Astigmatism analysis by the Alpins method

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ABSTRACT

Purpose: To determine the effectiveness of correcting astigmatism by laser refractive surgery by a vectorial astigmatism outcome analysis that uses 3 fundamental vectors: target induced astigmatism vector (TIA®), surgically induced astigmatism vector, and difference vector, as described by the Alpins method.

Methods: A data set of 100 eyes that had laser in situ keratomileusis to correct myopia and astigmatism (minimum preoperative refractive astigmatism 0.75 diopter) was analyzed. The data included preoperative and 3 month postoperative values for manifest refraction and standard keratometry. Using the ASSORT® or VectrAK® analysis program, individual and aggregate data analyses were performed using simple, polar, and vector analysis of astigmatism and an analysis of spherical change. Statistical analysis of the results was used for means and confidence limits, as well as to examine the differences between corneal and refractive astigmatism outcomes.

Results: At an individual patient level, the angle of error was found to be significant, suggesting variable factors at work, such as healing or alignment. A systematic error of undercorrection of astigmatism is prevalent in the treatment of these 100 patients by a factor of between 15% and 30%, depending on whether refractive or corneal values are examined. Spherical correction showed systematic undercorrection of 11%, and parallel indices demonstrated it to be more effective than the astigmatic correction.

Conclusion: This method of astigmatism analysis enables the examination of results of astigmatism treatment measured by both refractive and corneal measurements using vector analysis. By examining individual vector relationships to the TIA (ie, the correction index, index of success, and flattening index), a comprehensive astigmatism analysis is completed. Each index provides information necessary for understanding any astigmatic change. Astigmatic outcome parameters are more favorable when measured by subjective refractive than objective corneal methods. *J Cataract Refract Surg 2001; 27: 31–49 © 2001 ASCRS and ESCRS*

To determine the effectiveness of correcting astigmatism by laser refractive surgery, 3 fundamental vectors are examined. These are the target induced astigmatism vector (TIA®), surgically induced astigmatism vector (SIA), and difference vector (DV).[1] From various relationships among the 3 vectors, we are able to examine outcomes of astigmatism treatment. In individual patients, this is achieved by calculating the errors that occurred and gauging the amount of correction and flattening induced. The degree of success achieved can be determined using a standardized parameter.

The various relationships between the SIA and TIA tell whether the treatment was on axis or off axis and whether too much or too little treatment was applied. This information is also used to adjust nomograms to

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improve subsequent astigmatism outcomes. Systematic laser or surgical technique errors can be revealed by aggregate analysis. The TIA quantifies the intended astigmatism treatment at the corneal plane and is the key to enabling an integrated analysis to be performed by any modality of astigmatism measurement—corneal or refractive.

Patients and Methods

All calculations and graphical displays were performed using the ASSORT® outcomes analysis or VectrAK® astigmatism analysis program. Calculated values were exported to the SPSS program (SPSS Inc.) for statistical analysis. A valid analysis is achieved by converting all refractive astigmatism values to the corneal plane and performing all calculations on these corneal values.

Individual Patient Analysis

Simple Subtraction Analysis. Astigmatism analysis in its most basic but fundamentally important form is a comparison between the postoperative and preoperative magnitude of astigmatism without reference to axis. This is referred to as simple subtraction and determines, in its narrowest sense, that an increase (positive value) or a decrease (negative value) in the existing astigmatism of the eye has resulted from surgery.

Polar Analysis. This examines the steepening or flattening effect of the SIA occurring at the 90 degree reference meridian. A positive value indicates a with-the-rule (WTR) and a negative value an against-the-rule (ATR) change.

Vector Analysis of Treatment. The following are definitions of astigmatism vector terminology[1] used in this paper:

1. *Target induced astigmatism vector (TIA)*. The astigmatic change (by magnitude and axis) the surgery was intended to induce.
2. *Surgically induced astigmatism vector (SIA).* The amount and axis of astigmatic change the surgery actually induced.

   Correction index (CI). Calculated by determining the ratio of the SIA to the TIA by dividing SIA by TIA. The CI is preferably 1.0. It is greater than 1.0 if an overcorrection occurs and less than 1.0 if there is an undercorrection.

   Errors of treatment. The arithmetic difference between the SIA and TIA magnitudes and axes.

   Magnitude of error (ME). The arithmetic difference between the magnitudes of the SIA and TIA. The ME is positive for overcorrections and negative for undercorrections.

   Angle of error (AE). The angle described by the vectors of the achieved correction (SIA) versus the intended correction (TIA). The AE is positive if the achieved correction is on an axis counterclockwise (CCW) to where it was intended and negative if the achieved correction is clockwise (CW) to its intended axis.

3. *Difference Vector (DV)*. The induced astigmatic change (by magnitude and axis) that would enable the initial surgery to achieve its intended target. The DV is an absolute measure of success and is preferably zero.

   Index of success (IOS). Calculated by dividing the DV by the TIA. The IOS is a relative measure of success and is also preferably zero.

4. *Flattening Effect (FE)*. The amount of astigmatism reduction achieved by the effective proportion of the SIA at the intended meridian (FE = SIA Cos2.AE).

   Flattening index (FI). Calculated by dividing the FE by the TIA; preferably 1.0.[2]

5. *Torque*. The amount of astigmatic change induced by the SIA, due to nonalignment of the treatment, that has been ineffective in reducing astigmatism at the intended meridian but causes rotation and a small increase in the existing astigmatism. Torque lies 45 degrees CCW to the SIA if positive and 45 degrees CW to the SIA if negative.[2]

6. *Nomogram Calculator for Astigmatism*. An additional parameter is available from this method of astigmatism analysis that enables the achievement of a full correction of astigmatism magnitude in future treatments based on experience. This is

   Coefficient of adjustment (CA). Calculated by dividing TIA by SIA; the coefficient required to adjust future astigmatism treatment magnitudes (TIA). Its value is preferably 1.0 and it is the inverse of the CI.

Vector Analysis of Ocular Status. This analysis measures 2 components:

1. *Ocular residual astigmatism (ORA).* Dioptric measure of the noncorneal component of total refractive astigmatism; that is, the vector difference between refractive and corneal astigmatism.[3] It represents the amount of corneal astigmatism expected to remain after treatment using refractive astigmatism values.
2. *Topographic disparity (TD).* A vectorial measure of irregular astigmatism calculated as the dioptric distance between the displays of superior and inferior topographical values on a 720 degree double-angle vector diagram (DAVD).[4]

Analysis of Spherical Change (Corneal Plane). This analysis uses analogous parameters.[5]

1. Spherical correction index (S.CI):

$$\text{S.CI} = \frac{\text{Spherical equivalent correction achieved}}{\text{Spherical equivalent correction targeted}}$$

2. Spherical difference (SDiff):

$$\text{SDiff} = [\text{Spherical equivalent achieved} - \text{spherical equivalent targeted}] \text{ (absolute)}$$

3. Index of success for spherical change (S.IOS):

$$\text{S.IOS} = \frac{\text{Spherical difference}}{\text{Spherical equivalent correction targeted}}$$

To express indices as percentages, use the following calculations:

Percentage of astigmatism corrected: CI × 100
Percentage of astigmatism reduction at the intended axis: FI × 100
Percentage success of astigmatism surgery: (1.0−IOS) × 100
Percentage of sphere corrected: S.CI × 100
Percentage success of spherical surgery: (1.0 − S.IOS) × 100

Aggregate Data Analysis

When examining aggregate data of vectorial components, such as TIA, SIA, or DV, where magnitudes and axes are involved, 2 types of analysis are relevant.

1. An examination can be made of arithmetic means and the orientation of the vector disregarded to determine the mean vector magnitude.
2. Magnitudes of the vectors can be added with regard to each vector's orientation to determine a summated vector mean of the group.

The summated vector mean is always less than the mean vector magnitude, and the greater the difference between the 2 (ie, as the summated vector mean magnitude approaches zero), the less any overall trend is evident. In this situation, the changes are more likely due to random events than any discernible factor that may be prevalent. In the display of aggregate analysis, it is helpful to show the individual vectors (black) and the summated vector mean (red) in the same polar diagram as in Figures 3 to 7. Using this technique the vectors can be examined as they would appear on the eye, displayed at their own axes. In this way, when examining the treatment of irregular astigmatism, 2 displays can be used so that both halves of the cornea can be separately examined in a combined hemidivisional analysis of the whole cornea.

Statistical Methods

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

A further examination was performed for the correlation between analyses of changes between measurements by refraction and keratometry. The level of significance was set at a P value of 0.05 or less.

Examination of the distribution of the variables showed that all departed considerably from the normal distribution. They were, therefore, unsuitable for Pearson's correlation analysis. Thus, Spearman's correlation (rho value) was used to evaluate the distribution of the variables to find the degree of covariation between the 2 distributions.

Results

Individual Patient Analysis: Patient 25

This patient's refraction has changed from −9.25 −0.75 × 15 to −0.50 −1.00 × 67 and keratometry from 43.00/43.75 @ 95 to 38.17/38.83 @ 22. There was no significant reduction in astigmatism magnitudes, as shown by a comparison of the magnitude of astigmatism measured preoperatively and postoperatively (Table 1). However, by examination of the orientations of both pairs of astigmatism measurements preoperatively and postoperatively, there has been significant astigmatism change. Examining these astigmatism values alone does not assist greatly in revealing the errors.

The treatments were solely determined by refractive astigmatism values to eliminate myopic sphere and cylinder and achieve a plano refraction. The treatment applied to the cornea is the spectacle refraction (in negative cylinder notation) calculated to its corneal plane value by adjusting for back vertex distance. In this case (Figure 1, patient 25), the preoperative corneal plane refraction is -8.29 -0.60×15 so that the astigmatic treatment (TIA) is 0.60×15, intending to induce 0.60 diopter (D) of steepening at the 15 degree corneal meridian to achieve a refractive astigmatic target of 0.00 D. The calculated corneal target is 0.28 @ 71 when a TIA of 0.60×15 is applied to a corneal astigmatism value of 0.75 @ 95. The achieved values are the measured postoperative refractive and corneal astigmatism. The SIA is the calculated vectorial change between postoperative and preoperative astigmatism and is 1.26 D (refractive) and 1.35 D (corneal).

Figures 1 (refractive) and 2 (corneal) each contain 3 graphical displays. The polar diagram of astigmatism values displays the power meridian of the negative cylinder (which is the positive cylinder axis) for ease of comparison with the corneal (steep) astigmatism values. The DAVDs show these astigmatism magnitude values as a continuous line at twice their axis value and the respective surgical vectors as a dashed line connecting these astigmatism displays. The surgical vector polar diagrams show these same surgical vectors at their actual orientation, as they would appear on the eye, which is one half of their axis value on the DAVD display. The values of these calculated surgical vectors are tabulated in the box adjacent to the display.

The analysis facilitates the determination of the effectiveness of the astigmatism procedure by its individual components. The boxes titled "analysis" in Figures 1 and 2 display the AE, ME, CI, and IOS. Both refractive (Figure 1) and corneal (Figure 2) analyses show that there has been an overcorrection of astigmatism by more than double. This is evidenced by CI values of 2.11 for refraction and 2.26 for keratometry. The analysis of subjective values of refraction suggests that the treatment was off axis CW by 24 degrees but the objective analysis of corneal values (CW by 2 degrees) provides a cross check and balance, which indicates that the misalignment is likely to have been less than 24 degrees.

The DVs in both refractive (0.98 D) and corneal (0.75 D) cases are relatively large, each exceeding the TIA (0.60 D). An IOS of 0.00 indicates complete success in astigmatism treatment, a result of 1.00 shows no improvement on the preoperative status, and greater than 1.00 shows a deterioration in the astigmatic state. This result suggests that the astigmatic status postoperatively was worse than preoperatively by 63% (IOS = 1.63) by refraction and 26% (IOS = 1.26) by corneal measurements.

By corneal measurement, the FE at the treatment meridian (1.35 D [rounded up]; Table 2) was nearly equivalent to the SIA (1.35 D; Figure 2). The AE was small as treatment was off axis by 2 degrees (Figure 2). Hence, the corneal FI (2.25) was near to the CI (2.26 for keratometry) (Table 2) and negligible torque was created. By refractive values, however, the FE (0.83 D; Table 2) was one third less than the SIA (1.26 D; Figure 1) because the treatment was off axis by 24 degrees (AE) (Figure 1). Thus, a significant loss of effect at the intended (15 degree) meridian occurred. This is evidenced by a reduced FI (1.39; Table 2) compared to CI (2.11; Figure 1) for refraction and a significant proportion of the SIA being dissipated as CCW torque (0.95 D). This explains the significant rotation of the existing refractive astigmatism axis from 15 to 67 degrees (Figure 1).

Reduction in preoperative WTR astigmatism resulted in consistent ATR astigmatic changes in both modes by polar analysis (-1.20 D for refraction and -1.21 D for keratometry; Table 1). This is consistent with orientation of the SIA at axes of 171 degrees and 13 degrees, respectively (ie, close to the 0/180 axis) (Figures 1 and 2). Examining the FE at the 90 degree meridian results in precisely the same values as the polar analysis for WTR and ATR changes.

An ORA of 0.28×161 (Table 2) indicates relatively good correlation between preoperative refractive (-0.75×15) and corneal (0.75 @ 95) astigmatism

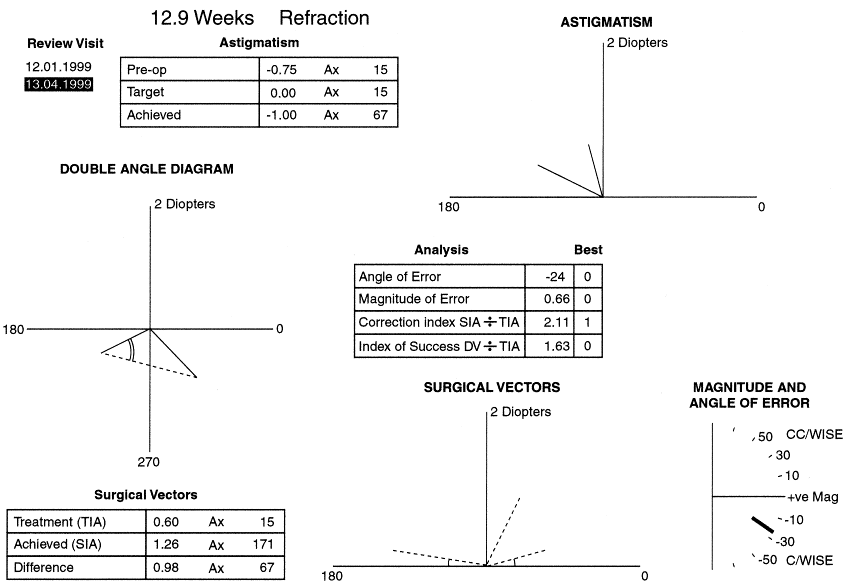

Figure 1. (Alpins) Individual vectorial analysis by refractive parameter for patient 25.

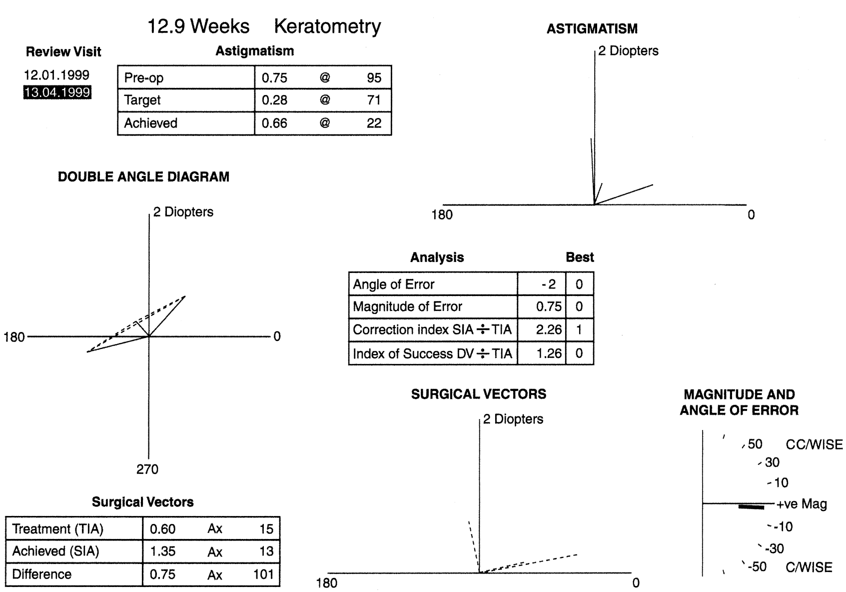

Figure 2. (Alpins) Individual vectorial analysis by corneal (keratometry) parameters for patient 25.

Table 1. Individual astigmatism analysis of patient 25, simple and polar values.

Measure	Refraction (D)	Keratometry (D)
Astigmatism		
Preop	0.75	0.75
Postop	1.00	0.66
Simple subtraction value	+0.25	−0.09
Polar value		
Preop	0.52	0.74
Postop	−0.68	−0.47
Polar change	−1.20	−1.21

Table 2. Individual astigmatism analysis of patient 25, vectors for treatment.

Measure	Refraction	Keratometry
Flattening effect (D)	0.83	1.35
Flattening index	1.39	2.25
Coefficient of adjustment	0.47	0.44
Torque effect (D CCW)	0.95	0.10
Ocular residual astigmatism (ORA) (D)	0.28 × 161	

D CCW = diopters counterclockwise

Table 3. Individual analogous spherical analysis of patient 25.

Measure	Refraction
S.CI	0.88
SDiff (D)	0.99
S.IOS	0.12

S.CI = spherical correction index; SDiff = spherical difference; S.IOS = spherical index of success

readings. Their corneal plane values (0.60 D and 0.75 D) are close to the same, with the separation being 10 degrees (Figures 1 and 2). Topographic disparity, the vectorial measure of corneal irregularity, was not assessed in this series as only 1 corneal value was available for each eye.

The preoperative spherical equivalent (corneal plane) was −8.59 D, which is also the targeted spherical equivalent of correction as plano was targeted for all eyes. The result was −0.99 D (corneal plane).

When an analogous spherical analysis is performed at the corneal plane (Table 3), the results show an S.CI of 0.88, indicating an undercorrection of spherical treatment by 12%, with the remaining absolute sphere being 0.99 D. The treatment shows an S.IOS of 0.12, indicating the spherical correction was 88% successful.

Aggregate Data Analysis

The following data analysis was performed on a group of 100 eyes that had laser in situ keratomileusis for myopia and astigmatism. Results are presented in parallel for refractive and corneal analysis 3 months after surgery. The mean spherical equivalent correction was −6.68 D (range −1.75 to −11.88 D) at the spectacle plane. The mean astigmatic correction was 1.24 D (range 0.40 to 3.04 D) at the corneal plane. Statistical analysis such as means, 95% confidence intervals, significance level, and Spearman's correlation (rho) are included in tables.

Changes in simple analysis of astigmatism values for both refraction and keratometry are shown in Table 4. Preoperative mean corneal astigmatism (1.57 D) was WTR and as is usually the case,[3] it exceeded mean re-

Table 4. Aggregate data, simple and polar value analysis.

Measure	Refraction (D)	Keratometry (D)	Significance (Spearman's Correlation)
Preoperative astigmatism			
Mean ± SD	1.24 ± 0.51	1.57 ± 0.71	<.000
Range*	1.23 to 1.25	1.56 to 1.58	(0.529)
Postoperative astigmatism			
Mean ± SD	0.39 ± 0.37	0.84 ± 0.50	.387
Range*	0.38 to 0.40	0.83 to 0.85	(0.087)
Simple subtraction analysis			
Mean ± SD	−0.85 ± 0.62	−0.73 ± 0.60	<.000
Range*	−0.87 to −0.84	−0.74 to −0.71	(0.485)
Preoperative polar value			
Mean ± SD	0.81 ± 0.99	1.28 ± 1.00	<.000
Range*	0.63 to 0.99	1.09 to 1.47	(0.812)
Postoperative polar value			
Mean ± SD	0.09 ± 0.43	0.63 ± 0.62	<.000
Range*	0.03 to 0.17	0.51 to 0.75	(0.454)
Polar analysis			
Mean ± SD	−0.72 ± 0.88	−0.65 ± 0.73	<.000
Range*	−0.89 to −0.55	−0.80 to −0.51	(0.737)

SD = standard deviation
*95% confidence interval

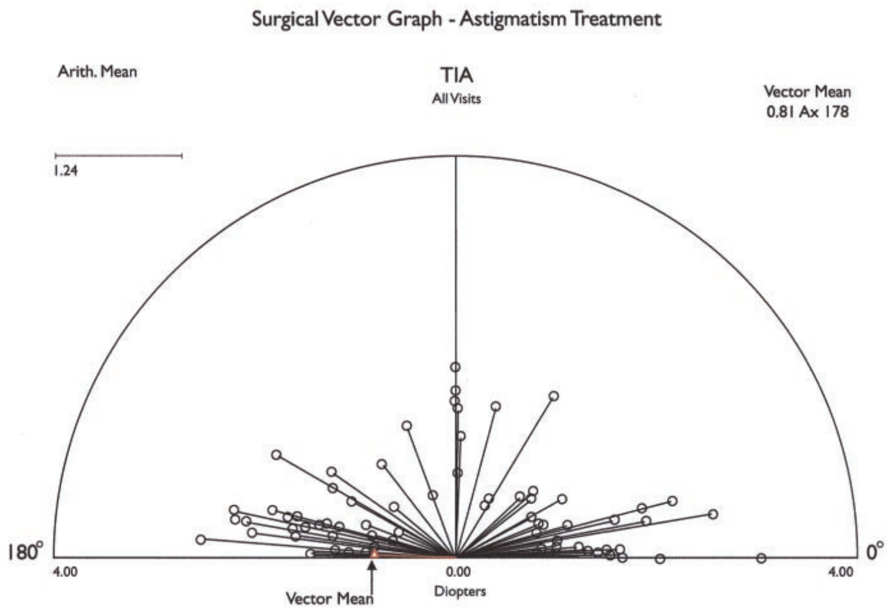

Figure 3. (Alpins) Vectorial display of targeted astigmatism treatments (TIA) at their own vector axis (of maximum ablation), with summated vector mean of group.

fractive astigmatism (1.24 D) by a factor of 1.27. A similar amount of astigmatism reduction occurred by refractive (0.85 D) and corneal (0.73 D) measures. Postoperative corneal astigmatism (0.84 D) exceeded refractive astigmatism (0.39 D) by an increased factor of 2.15. Astigmatism treatments were calculated using refractive astigmatism values after conversion to the corneal plane.

A summated vector mean TIA value of 0.81 × 178 shown in surgical vector graph (Table 5, Figure 3) was attempted, indicating that the overall trend of treatment was to induce a net steepening close to the horizontal meridian, resulting in an ATR change.

Values determined by vector analysis are shown in Table 5. The arithmetic mean SIA magnitude for both

Table 5. Aggregate data, surgical vector analysis of treatment.

Measure	Refraction	Keratometry	Significance (Spearman's Correlation)
TIA, arithmetic mean (D)			
Mean ± SD	1.24 ± 0.52		—
Range*	1.23 to 1.25		
TIA, vector mean (D)	0.81 × 178		—
SIA, arithmetic mean (D)			
Mean ± SD	1.14 ± 0.57	1.04 ± 0.50	<.000
Range*	1.13 to 1.15	1.03 to 1.05	(0.509)
SIA, vector mean (D)	0.72 × 179	0.66 × 179	—
DV, arithmetic mean (D)			
Mean ± SD	0.39 ± 0.37	0.72 ± 0.41	.166
Range*	0.38 to 0.40	0.71 to 0.73	(0.140)
DV, vector mean (D)	0.09 × 172	0.16 × 172	—
DV – $\frac{\text{vector mean}}{\text{arithmetic mean}}$	0.23	0.22	—

TIA = target induced astigmatism vector; SD = standard deviation; SIA = surgically induced astigmatism vector; DV = difference vector
*95% confidence interval

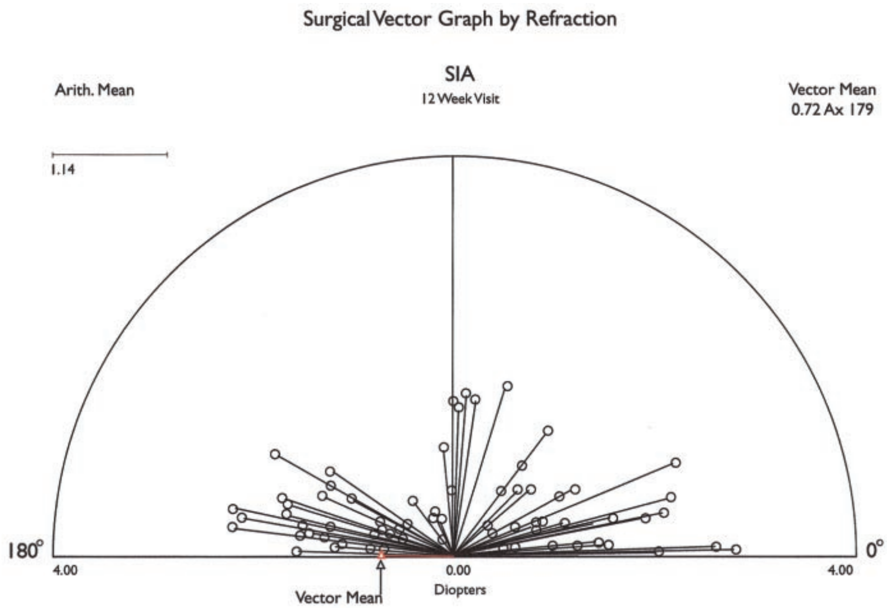

Figure 4. (Alpins) Vectorial display of achieved treatments (SIA) measured by refractive parameters at their meridian of maximum ablation, with the summated vector mean of the group.

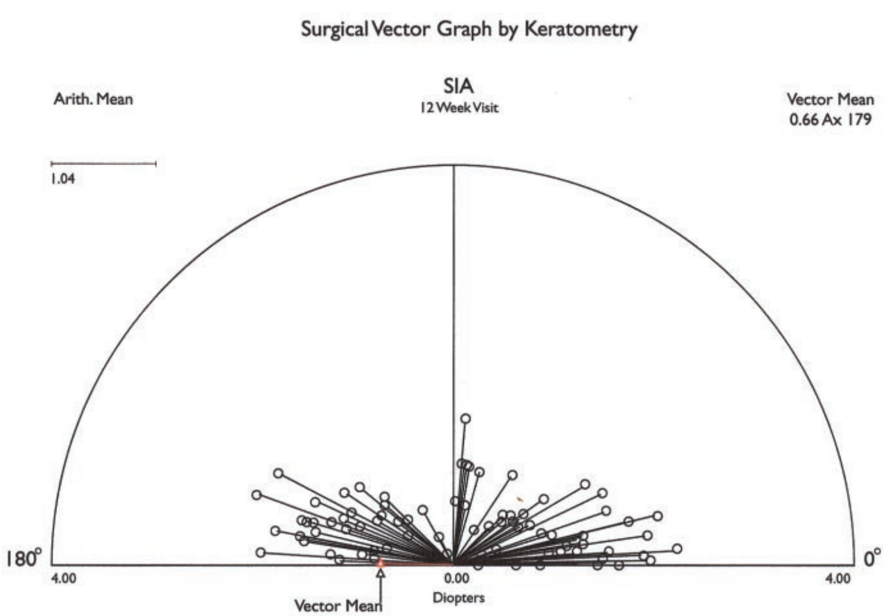

Figure 5. (Alpins) Vectorial display of achieved treatments (SIA) measured by corneal parameters at their meridian of maximum ablation, with the summated vector mean of the group.

refraction (1.14 D) and keratometry (1.04 D) were less than the arithmetic mean TIA (1.24 D); overall undercorrection was more pronounced in the corneal than in the refractive analysis. The SIA surgical vector graphs are shown in Figure 4 for refraction and Figure 5 for keratometry. The summated vector mean values of SIA by refraction (0.72 D) and keratometry (0.66 D) compared with the TIA (0.81 D) followed the same trend of greater undercorrection by corneal analysis.

Analysis using the difference vector showed consistent trends for treatment error in both measurement modes. The arithmetic mean magnitude of the DV by refraction (0.39 D) was substantially less than that by keratometry (0.72 D). A little under 25% of this error (0.09 and 0.16 D) can be attributed to systematic treatment error (Table 5) by examining the summated vector mean. Both refraction and keratometry results show similar trends when summated vector means of the DV are examined on the surgical vector graphs shown in Figure 6 for refraction and Figure 7 for keratometry.

Angle-of-error analysis for refraction (Figure 8) and keratometry (Figure 9) show that both arithmetic means

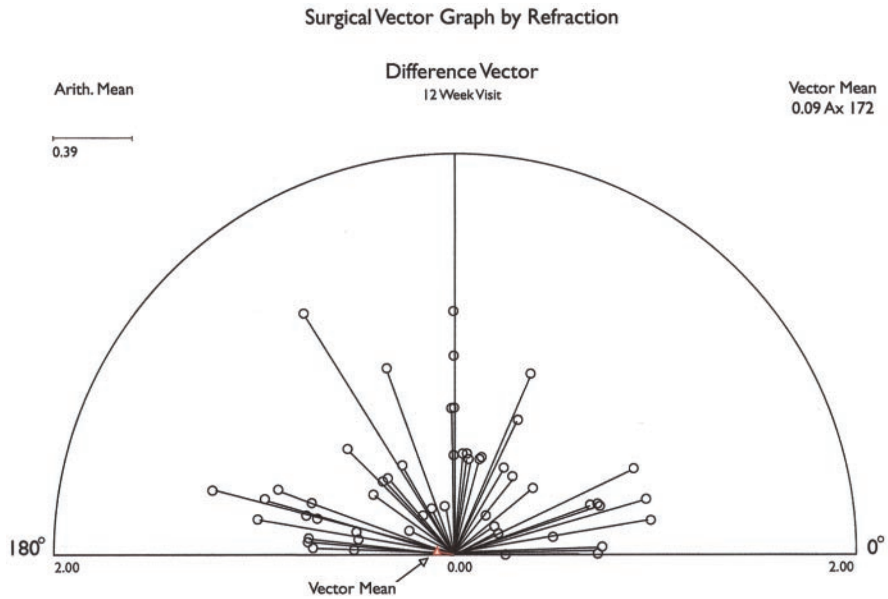

Figure 6. (Alpins) Vectorial display of the treatment errors (DVs) calculated by refractive values at their own axes to achieve the targeted result. The vector mean (0.09 × 172) is a proportion (23%) of the arithmetic mean (0.39 D), indicating a small error caused by systematic correctable trends.

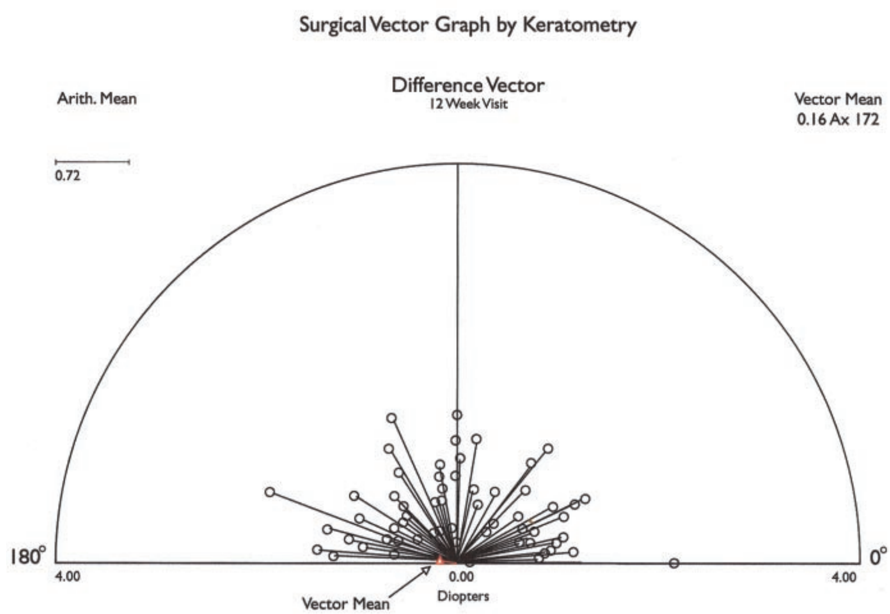

Figure 7. (Alpins) Vectorial display of the treatment errors (DVs) calculated by corneal values at their own axes to achieve the targeted result. This vector mean (0.16 × 172) is larger than that measured refractively and is also a similar proportion (22%) of the arithmetic mean (0.72 D), suggesting a small correctable systematic error is present.

for the group were slightly CW (−1.1 degrees and −0.2 degrees) and close to zero (Table 6). However, the spread of results is wide, and by examining the absolute means, the objective corneal measure (16.6 degrees) shows a less favorable outcome on alignment with a wider spread of results than that of the mean refractive value (6.7 degrees). A significant finding reveals that analysis for AE of zero was present in 3 eyes by corneal analysis and in 42 eyes by refractive analysis (Table 6, Figures 8 and 9). The negative MEs (−0.11 D refraction and −0.20 D keratometry), where the mean SIA magnitude is less than the mean TIA magnitude, confirm a trend of undercorrection for the group.

Correction index polar diagrams are shown in Figure 10 for refraction and Figure 11 for keratometry. The ratio of SIA/TIA for each individual treatment is displayed at the meridian of maximum ablation (axis of each respective TIA). Scatter plots of SIA versus TIA are shown in Figure 12 for refraction and Figure 13 for keratometry. The general undercorrection of astigma-

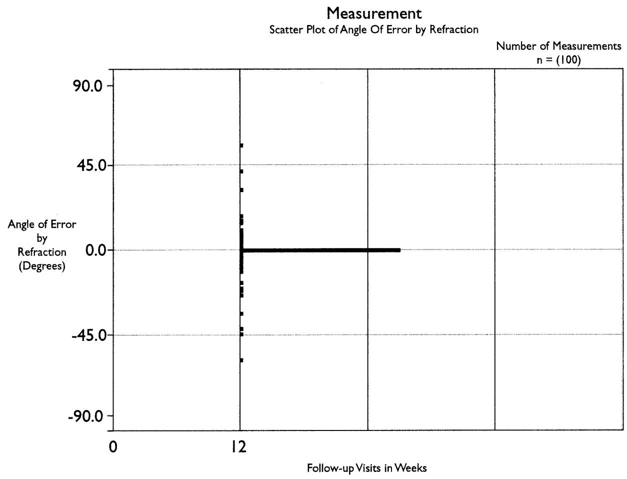

Figure 8. (Alpins) The AE by refraction value shows the amount each treatment applied was off axis. By subjective means, a significant proportion of these occur at 0 degree.

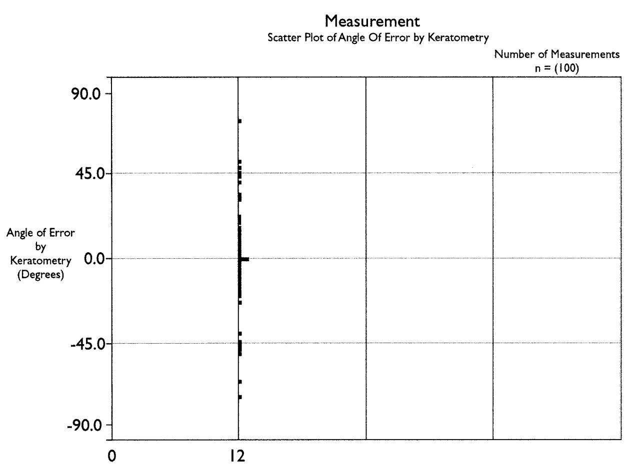

Figure 9. (Alpins) The AE by corneal values shows the amount each treatment applied was off axis. In this analysis, the spread is wider than by refractive values and there is no bias to any 1 coincident value.

tism is less evident by refraction (0.87) than by keratometry (0.77) (Table 7), as is usually the case.[5]

Index of success polar diagrams are shown in Figure 14 for refraction and Figure 15 for keratometry, displaying the ratio of DV/TIA at the meridian of maximum ablation (axis of each respective TIA). The treatment is less successful when measured by objective corneal measures (IOS = 0.59; 41%) than by subjective refractive measures (IOS = 0.21; 79%) (Table 6). Comparing the CI and AE (absolute) values for the 2 measurement modes shown in Tables 6 and 7 supports this finding. Geometric means of IOS for this data set were calculated by taking a mean of the individual square root values, then squaring this calculated mean value.

The FI (Table 7) indicates that the treatment is less effectively applied at the treatment axis when measured by corneal (0.72) than by refractive (0.86) means. This value quantifies the proportion of SIA treatment that has been effectively applied as flattening. This value decreases in a sinusoidal manner with larger angles of error.[2] The FI is shown as a polar diagram in Figure 16 for refraction and Figure 17 for keratometry. These values cannot exceed the CI for any 1 eye and as with the CI, the best result for the FI is 1.00.

The values for nomogram adjustment (Table 7) indicate that an increase in the future magnitude of astigmatism treatment (TIA) by between 15% (refractive) and 30% (corneal) would likely improve outcomes. The geometric mean CA (TIA/SIA) is derived by taking the mean of the individual logarithmic values followed by the antilog of this calculated mean value.

The analogous spherical analysis (at the corneal plane) is shown in Table 8. There has been a prevailing undercorrection of spherical equivalent treatment. More success was shown by spherical treatment (0.13 = 87%) than by astigmatic treatment (0.21 = 79%) using parallel indices.

The mean ORA for the group was 0.73 D. Twenty-one eyes had a value greater than 1.00 D. As all patients were treated by refractive astigmatism parameters, the ORA is the amount of astigmatism expected to remain on the cornea after surgery if all refractive astigmatism were corrected. The mean remaining amount of corneal astigmatism for the group was 0.84 D (Table 4).

Discussion

Results

In the results of this data set detailing refractive values first and keratometric values second, the principal reason for the failure to correct all the astigmatism is the systematic undercorrection of the magnitude of astigmatism by a factor of between 15% for refractive values and 30% for corneal values (CA). This trend is confirmed in aggregate analysis of a vector mean SIA (179 degrees and 179 degrees) for refraction and keratometry, respectively, in very close alignment with the TIA (178 degrees) but with substantially smaller vector mean

Table 6. Aggregate data, analysis of vectors for error.

Measure	Refraction	Keratometry	Significance (Spearman's Correlation)
AE – arithmetic mean (degrees)			
Mean ± SD	−1.10 ± 13.65	−0.20 ± 23.56	.575
Range*	−3.80 to 1.57	−4.80 to 4.88	(0.057)
AE – absolute mean (degrees)			
Mean ± SD	6.70 ± 11.98	16.60 ± 16.72	.151
Range*	4.36 to 9.07	13.30 to 19.89	(0.145)
AE – mean plus			
Mean ± SD	+10.35 ± 13.49	+18.33 ± 16.34	
Range*	5.27 to 15.43	13.49 to 23.03	—
n	27†	45‡	
AE – mean minus			
Mean ± SD	−12.65 ± 14.46	−16.11 ± 17.29	
Range*	−17.74 to −7.56	−20.80 to −11.42	—
n	31†	52‡	
ME – arithmetic mean (D)			
Mean ± SD	−0.11 ± 0.40	–0.20 ± 0.53	.000
Range*	−0.11 to −0.10	−0.21 to −0.19	(0.406)
IOS – geometric mean			
Mean ± SD	0.21 ± 0.15	0.59 ± 0.07	0.052
Range*	0.20 to 0.21	0.58 to 0.60	(0.195)

AE = angle of error; SD = standard deviation; ME = magnitude of error; CI = correction index; IOS = index of success
*95% confidence interval
†AE = 0 (n = 42)
‡AE = 0 (n = 3)

magnitudes of the SIA (0.72 D for refraction and 0.66 D for keratometry) compared to that of the TIA (0.81 D). Undercorrection of astigmatism only occurs when the TIA exceeds the SIA and is not a result of measured astigmatism remaining after surgery. When off-axis treatment occurs, it does not alter the effective power of the SIA magnitude, so that any remaining astigmatism does not occur as a result of undertreatment of astigmatism power.

That the mean AE (−1.1 degrees and −0.2 degrees) was close to zero is consistent with the closeness of the aggregate vector mean TIA and SIA axes detailed above, so no significant systematic error of misaligned treatment is evident. However, at an individual patient level, each AE is significant as is shown by mean absolute values (6.7 degrees and 16.6 degrees), suggesting variable factors at work such as healing or alignment. The mean astigmatic IOSs (0.21 and 0.59) demonstrate the failure to successfully correct astigmatism on an individual basis. This becomes more evident when examined by corneal (objective) means than by refractive (subjective) means. Either way, the success in spherical treatment (S.IOS 0.13), when examined by analogous means, is greater. The refractive value for IOS (0.21) compares favorably with that in other published series using the Alpins method of astigmatism analysis.

The effect of the significant mean absolute AEs (6.7 degrees and 16.6 degrees) is a loss of FE of the SIA (reduced to 1.07 D and 0.87 D) and reduced FI (0.86 and 0.72). The prevailing undercorrection of astigmatism also influences these values. When calculated by vector analysis, the proportion of loss of FE is 1.5% when treatment is 5 degrees misaligned, 13.4% when 15 degrees, 50% when 30 degrees, and total loss of FE when 45 degrees showing a sinusoidal form.[2]

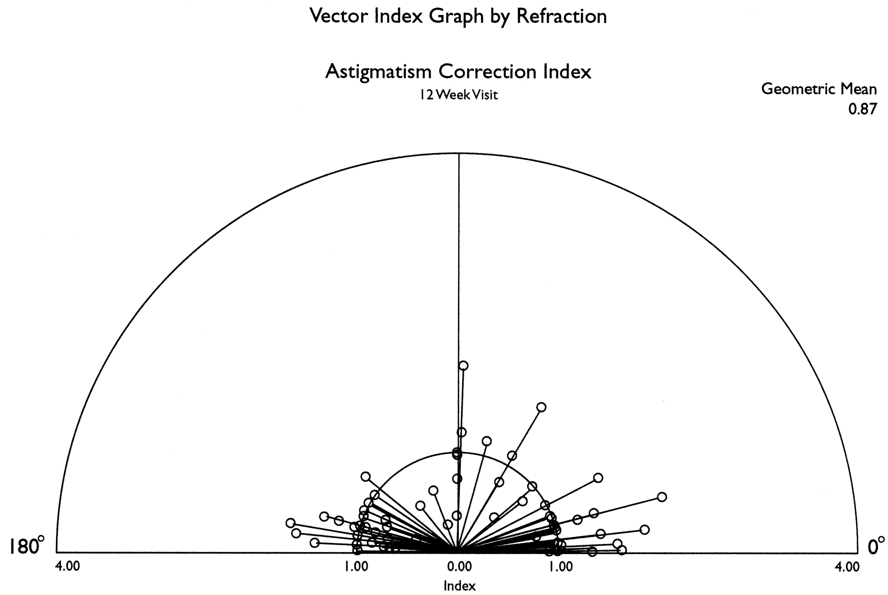

Figure 10. (Alpins) The astigmatic correction index (SIA/TIA) calculated by refractive values displayed at the meridian of their respective treatments (TIA). This shows the proportion of astigmatic treatment achieved at the meridian of maximum ablation. The information on efficacy of treatment in the various sectors of the cornea can be fed back to the laser for future sectorial tuning of the laser's performance. The semicircular line indicates the line of desired astigmatism correction.

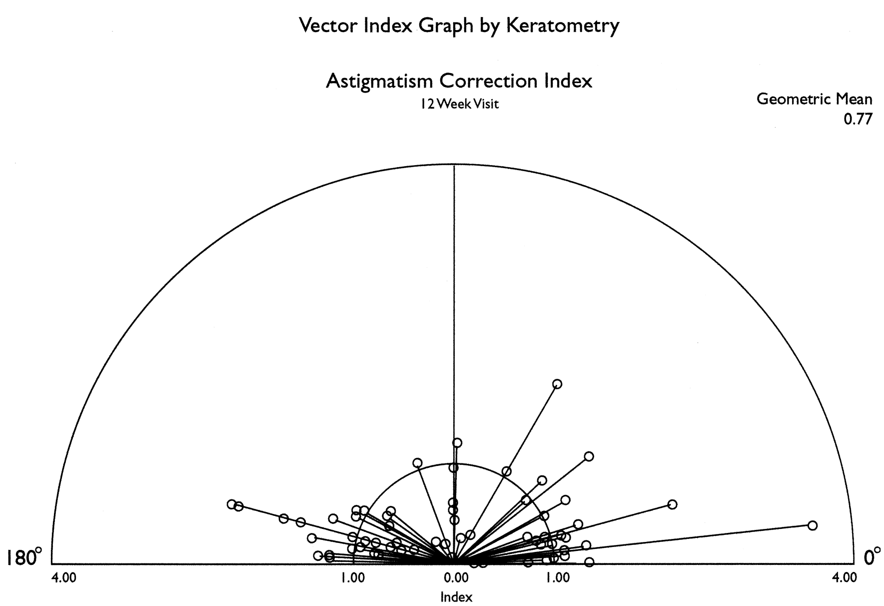

Figure 11. (Alpins) The astigmatism correction index (SIA/TIA) calculated by corneal values displayed at the meridian of their respective treatments (TIA). This shows the proportion of astigmatic treatment achieved at the meridian of maximum ablation. Outliers can be detected on this analysis (eg, patient 94 @ 6 degrees) so that review of measurements and data recording can be made to ensure axis reversal has not occurred.

The DV is a useful vectorial measure of uncorrected astigmatism. Mean magnitude values show significant amounts of uncorrected astigmatism present (0.39 D and 0.72 D). This suggests objective (corneal) measurements for uncorrected astigmatism were more indicative of treatment errors.

The summated vector mean of the DV shows that the orientations of refractive and corneal values are equivalent (172 degrees) and that both vector mean magnitudes (0.09 D and 0.16 D) are 23% and 22% of their respective arithmetic mean magnitude values (Table 5). This suggests some error trend in the treatments, and any cause for the systematic errors should be identified when possible. Theoretically, if all individual future laser treatments (TIA) were adjusted by vectorially adding to each the summated DV mean by an amount between these 2 vector means of 0.09 D and 0.16 D at an axis of 172 degrees, one would expect an overall improvement in future results. In practice its value is relatively small, and addressing the separate systematic factors of undercorrection and misalignment causing the error is simpler and potentially more effective by addressing the causative factors for the failure to completely correct astigmatism.

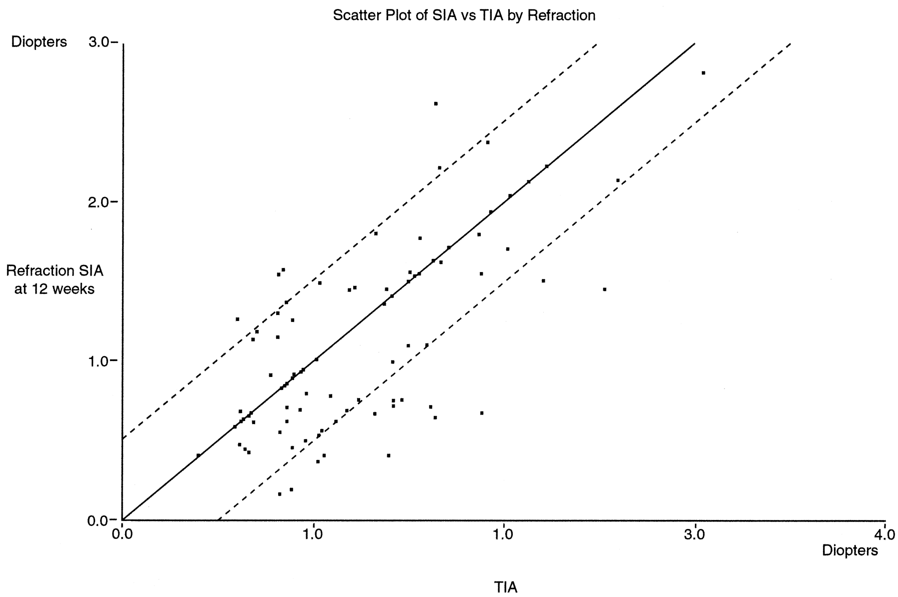

Figure 12. (Alpins) Examination of individual refractive values of correction. Above the unity line is an overcorrection, and below is an undercorrection. The dashed line indicates ±0.50 D limits. Many data points coincide with the unity line.

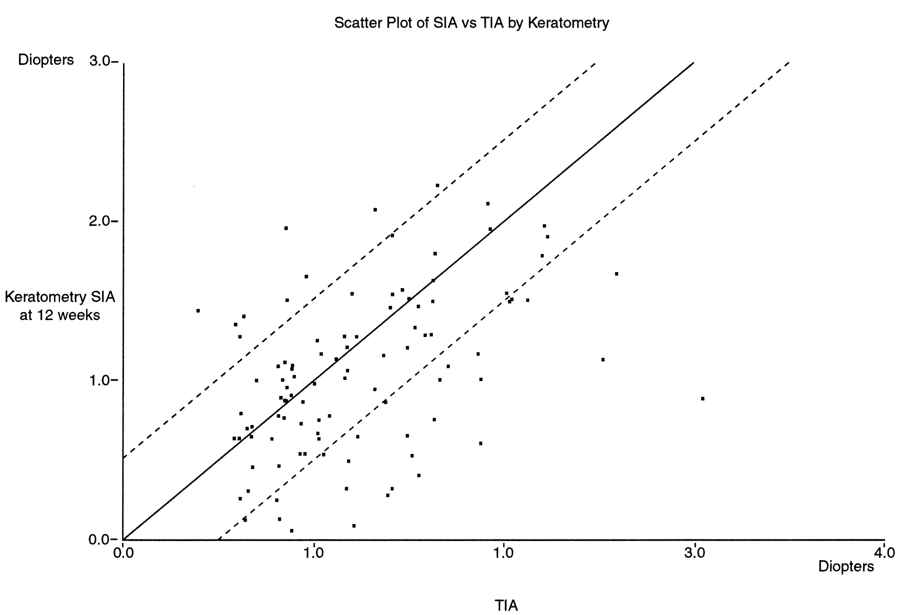

Figure 13. (Alpins) Examination of individual corneal values of correction. Above the line is an overcorrection, and below is an undercorrection. The dashed line indicates ±0.50 D limits. Few values coincide exactly on the unity line.

Preoperative mean corneal astigmatism (1.57 D) was greater than refractive astigmatism (1.24 D) by a factor of 1.27. This preoperative astigmatism was overall WTR as polar values were positive (+0.81 D and +1.28 D). The TIA vector mean axis is orientated at 178 degrees, inducing the ATR polar change (−0.72 D and −0.66 D) by reducing WTR astigmatism. The existing astigmatism was reduced by refractive and corneal means by similar amounts (0.85 D and 0.73 D). Treatment parameters emphasized the elimination of refractive astigmatism (target 0.00 D) in this series, so that the mean target corneal astigmatism is represented by the mean ORA (0.73 D). Postoperatively, the mean corneal astigmatism in the group decreased to 0.84 D and refractive astigmatism decreased to a mean of 0.39 D. Thus, the resulting mean corneal astigmatism exceeded refractive astigmatism by a factor of 2.15. This trend is opposite to the usual, in which corneal astigmatism tends to exceed refractive astigmatism when WTR prevails, and the reverse so that refractive exceeds corneal when ATR.[3] The change in this ratio is so great that examining and comparing the individual keratometry to

Table 7. Aggregate data, analysis of vectors for treatment.

Measure	Refraction	Keratometry	Significance (Spearman's Correlation)
CI − geometric mean			
Mean ± SD	0.87 ± 1.84	0.77 ± 0.91	<.000
Range*	0.86 to 1.06	0.76 to 0.78	(0.373)
FE (D)			
Mean ± SD	1.07 ± 0.62	0.87 ± 0.60	<.000
Range*	1.06 to 1.09	0.85 to 0.88	(0.595)
FI − geometric mean			
Mean ± SD	0.86 ± 0.41	0.72 ± 0.57	<.000
Range*	[0.84 to 0.86]	0.72 to 0.74	(0.469)
CA − geometric mean			
Mean ± SD	1.15 ± 1.54	1.30 ± 1.91	<.000
Range*	1.06 to 1.26	1.29 to 1.32	(0.371])
ORA (D)			
Mean ± SD	0.73 ± 0.43		–
Range*	0.72 to 0.74		

D = diopters, SD = standard deviation
CI = correction index, FE = flattening effect; FI = flattening index; CA = coefficient of adjustment; ORA = ocular residual astigmatism
*95% confidence interval

refraction ratios preoperatively and postoperatively shows there is no significant correlation between the 2 (rho = 0.042; $P = .675$).

This imbalance in excessive corneal astigmatism remaining after treatment can be attributed to refractive astigmatism values being the sole consideration in treatment planning. If corneal astigmatism values were included in the treatment plan using vector planning,[3,4] the corneal astigmatism reduction would have been proportionately and absolutely greater, with less corneal astigmatism remaining after surgery. This could occur without necessarily increasing the mean postoperative refractive astigmatism so that an overall greater reduction in astigmatism (topographic plus refractive) would have been achievable.

Scatter plots of the astigmatic correction, SIA/TIA (Figures 12 and 13), and AE (Table 6, Figures 8 and 9) show a greater bias toward unity and zero, respectively, when examined by refractive values. The objective values of keratometry are more evenly and widely distributed, suggesting less potential for measurement bias where the target value is unknown during the examination process.

Examination of the display graphs of CI, IOS, and FI (Figures 10, 11, and 14 to 17) might display a trend for more accurate correction and greater success in the regions closer to treatment on the horizontal axes. Statistical analysis revealed a number of univariate outliers in the data analyzed that had the effect of lowering correlation between refractive and corneal groups. These 6 display graphs were extremely useful in identifying those outliers that required verification and correction of any aberrant recording of corneal values, such as axis reversal. An example of this is seen on the displays at the 6 degree meridian (patient 94) where the correction index by refraction is 1.00 and by keratometry is 3.58. This inconsistency is also evident for this patient's IOS (0.00 and 2.61) and FI (1.00 and 3.50).

Benefits of Method

This method of astigmatism analysis enables the examination of results of astigmatism treatment by both refractive and corneal measurements. The approach uses vector analysis, which is used in this series for examining regular astigmatism. This can be further applied to irregular astigmatism by separately examining the 2 halves

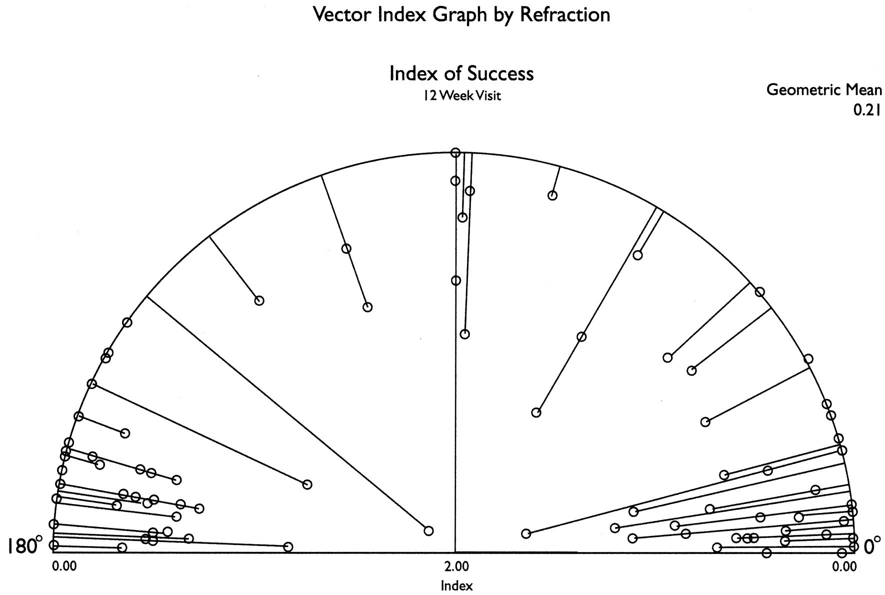

Figure 14. (Alpins) The IOS using refractive data peripherally displayed at the meridian of maximum ablation (axis of TIA). The longest lines indicate the least successful astigmatic outcome. Circles alone indicate an IOS of zero.

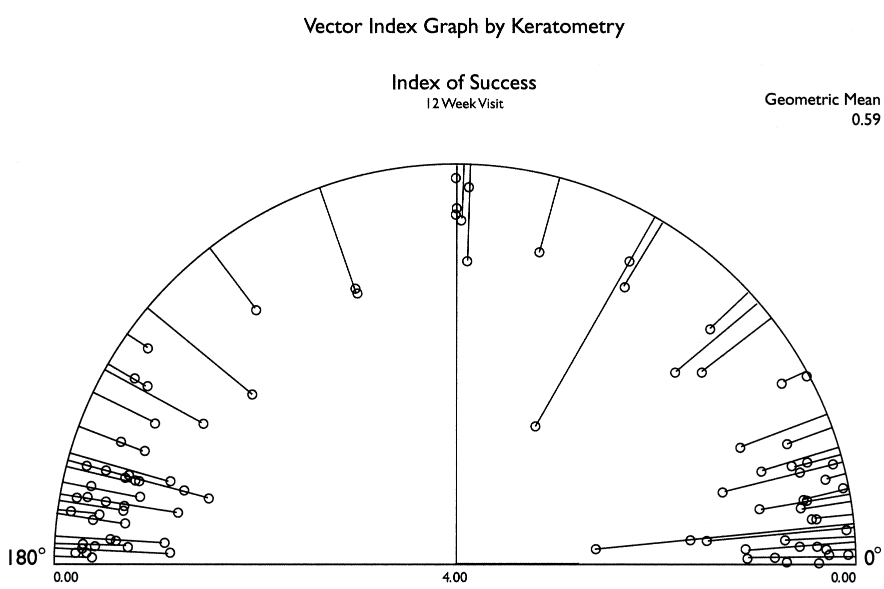

Figure 15. (Alpins) The index of success by corneal data peripherally displayed at the meridian maximum ablation (axis of TIA). The longest lines are the least successful. Circles alone indicate an IOS of zero.

of the cornea by adding a second analysis between 181 and 360 degrees and displaying both together on a 360 degree polar diagram as they would appear on an eye or topography map. The method, principles, and functionality have been explained in detail.[1,2,3,5]

Furthermore, a comprehensive astigmatism analysis is completed by using 3 indices: CI, IOS, and FI. Each index examines individual vector relationships to the TIA and provides the valuable and separate information necessary for understanding the clinical relevance of any astigmatic change.

The value of statistical analysis demonstrates the sensitivity of this method of astigmatism analysis to detect outcome variations, as statistical significance is achieved in a high proportion of the parameters examined in the 2 measurement groups. Comparing only postoperative resultant astigmatism values did not reveal any significant differences.

Multiple eyes can be examined in a number of ways:

1. The arithmetic means of vector magnitudes can be calculated.

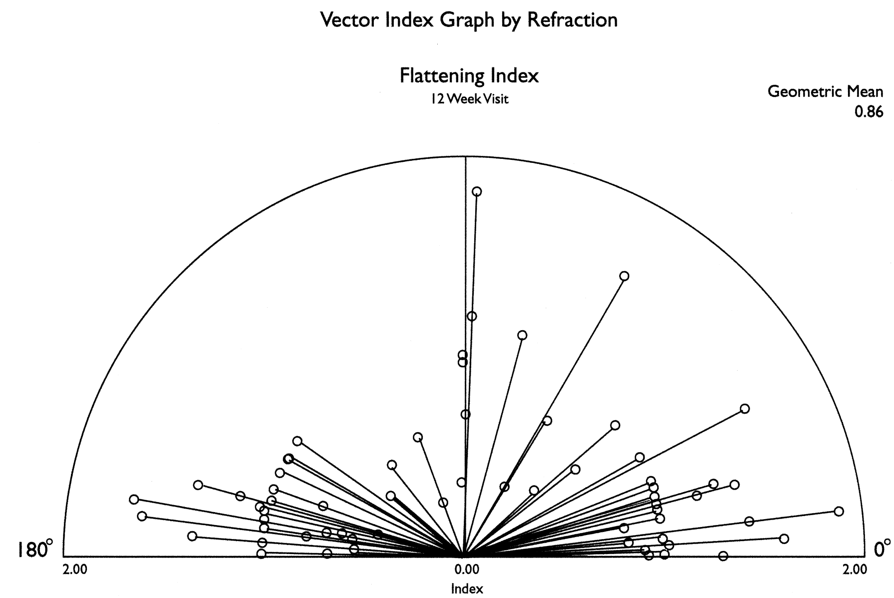

Figure 16. (Alpins) The FI by refraction displayed at the meridian of maximum ablation. For any 1 treatment, the flattening index decreases as the treatment becomes increasingly off axis. It equals the CI when the SIA is on axis and becomes zero when the SIA is 45 degrees off axis.

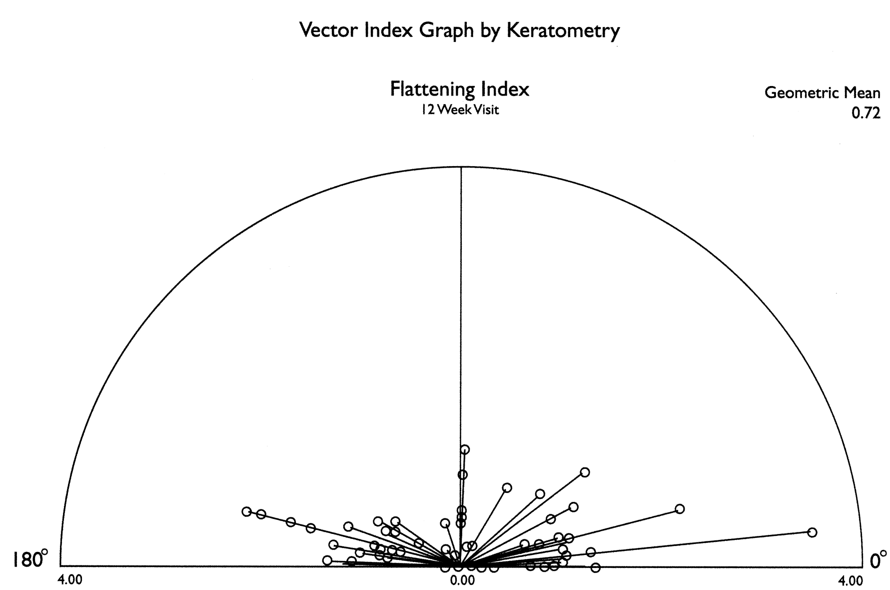

Figure 17. (Alpins) The FI by corneal values displayed at the meridian of maximum ablation. Any lack of correlation between FI by keratometry and refraction (eg, patient 94 @ 6 degrees) is a useful means of examining outliers requiring review of measurements and data recording values.

2. The arithmetic differences and ratios between SIA and TIA vector magnitudes can be compared.
3. The arithmetic differences between SIA and TIA axes can be compared.
4. The individual and aggregate values of any 1 of the 3 principal vectors determine individual and group trends that can be displayed on surgical vector graphs.
5. Calculated index values can be displayed at their meridia of treatment (the axis of the TIA) on vector index graphs to determine general trends of laser and surgical performance.
6. Statistical analysis can be performed effectively on arithmetic values of the aggregate vectorial parameters.

The analysis performed on this data set is comprehensive for single and aggregate data, examining all aspects of astigmatic change and comparing outcomes with analogous indices for spherical change. However, for a study that examines a particular facet of astigmatism treatment, the researcher need only select the necessary section of this analysis method to support the relevant conclusion derived from the data set.

Table 8. Aggregate data, analogous spherical analysis.

Measure	Refraction
S.CI − geometric mean	
Mean ± SD	0.89 ± 1.19
Range*	0.85 to 0.91
SDiff − arithmetic mean (D)	
Mean ± SD	0.75 ± 0.66
Range*	0.72 to 0.76
S.IOS − geometric mean	
Mean ± SD	0.13 ± 0.04
Range*	0.13 to 0.13

S.CI = spherical correction index; SD = standard deviation; SDiff = spherical difference; S.IOS = spherical index of success
*95% confidence interval

Advantages of Method

All vectorial calculations and summations are performed using DAVDs. This mode of calculation is an essential part of the process for this method of vector analysis of astigmatism. Doubling the astigmatism meridian and vector axis values is an analytical and mathematical necessity that gains clinical meaning only when halved at the conclusion of the analysis. For this reason, all results are displayed on polar (0 to 180 degree) diagrams. This preferable mode of display is simpler and more clinically intuitive. A vector, such as the SIA, displayed in this way indicates the actual meridian of the eye at which maximum ablation effect occurred and the TIA at which maximum ablation was intended.

When examining results of treatment of irregular astigmatism, the whole cornea can be examined in a 360 degree display. The unnecessary complexity created by displaying vectors at twice their actual position could cause greater confusion when examining irregular astigmatism outcomes as it would be necessary to display a 720 degree view.

The errors and necessary adjustments gleaned from 180 degree (or 360 degree) corneal analysis can be performed using refractive and corneal data. By examining both sets of data, suitable adjustments to correction can be fed back into the laser algorithm at their corresponding corneal orientations to correct and refine treatments over time to an increasingly accurate end point. Using advanced planning and analysis techniques,[1,4] the 2 diagnostic modalities of corneal topography and wavefront refraction can be combined to provide a single integrated module to refine the treatment of refractive errors associated with regular and irregular astigmatism.

For incisional surgery, the FE, measured in diopters, is equivalent to the with- and against-the-wound values of Holladay and coauthors[6] and with- and against-the-power values of Naeser and coauthors[7] that have been used extensively for the analysis of cataract incisions. The astigmatic changes of small incision cataract surgery are relatively small, and the predominant goal for any 1 incision type is constancy of effect seeking astigmatic neutrality or reduction. In this case, the FE varies with the amount of SIA as well as the amount the incision is placed off axis (AE).

However, in laser refractive surgery, the TIA is larger and becomes a third variable. Therefore, the FE also varies according to the amount of astigmatism treatment at this intended treatment meridian. For this reason, the mean FE (and the 2 equivalent parameters of Holladay and coauthors[6] and Naeser and coauthors[7]) is less useful when examining average changes induced by multiple refractive surgeries. Its value lies in examining individual patient's outcomes, but calculating its arithmetic or aggregate mean is of limited interest. This obstacle can be overcome by relating the amount of flattening to the attempted change (TIA) by using the FI, which is also influenced only by 2 variables—SIA and AE—but independent of the amount of treatment.

Clinical Relevance of Methodology

Every parameter used in this methodology has clinical relevance pertinent to the treatment or outcome of an eye after cataract or refractive surgery. These have been discussed comprehensively in this paper to explain their relevance to laser in situ keratomileusis. The effects of incisional cataract surgery can be effectively addressed using parameters such as AE, FE, and SIA, in addition to simple and polar value analysis.

Manifest refraction is a subjective test that depends on observer and patient responses. These responses may vary according to ambient conditions, such as inconsistencies in lighting, chart distance, or illumination. The inadequacy of refraction as the sole measurement parameter for astigmatism is accentuated by the large changes in spherical equivalents induced by refractive surgery, which may cause less attention than warranted to be paid to remaining astigmatic refractive errors.

Trends detected through the use of conventional keratometry in this series, and corneal topography when available, provide an objective balance to the subjective analyses derived from refractive astigmatism values. When examining astigmatic outcomes, it is valuable to look at all the modes used to measure astigmatism. This yields a more precise examination of the differing treatment trends revealed by these parameters.

The measure of intended astigmatic change is the TIA. This induced astigmatism treatment vector is common to all modes of astigmatism measurement for any single surgical procedure. The TIA provides the necessary link for a valid, integrated astigmatism analysis. In this way, all means of measurement, keratometry, topography, manifest refraction, and wavefront refraction can be used to determine success, the errors that are occurring, and the adjustments that might be necessary to improve future results.

The DV is a precise vectorial measure of the unplanned astigmatic change. It is a valuable measure of absolute success. For aggregate analysis, the summated vector mean of the DVs can be used to examine the overall trend for error in a patient group. The CI, IOS, and FI measure the effectiveness of astigmatism surgery; the CA can be used to refine nomograms. All these parameters can be calculated using corneal or refractive parameters to achieve parallel analyses. Analogous spherical analyses (at the corneal plane) can be performed using the S.CI, SDiff, and S.IOS. Inverting the S.CI provides a parameter for spherical nomogram adjustment analogous to the CA for astigmatism.

Another advantage of the polar display used in this astigmatism analysis method and the manner in which it has been displayed in this paper is that it can be used for hemidivisional analysis of the entire cornea. This is necessary because most patients display differences in the corneal topography values, providing 1 astigmatism value for each of the 2 halves before and after refractive surgery. The manifest refraction provides only 1 refractive astigmatism value applicable for both sides of the cornea; however, wavefront refraction, like corneal topography, can provide 2 fundamentally important values and, when necessary, many more.

In all cases of corneal irregularity, vector analysis can be applied separately to each hemidivision of the cornea to examine outcomes for each of the 2 asymmetrical treatments by corneal and refractive means. Furthermore, the irregularity of any cornea can be quantified by the TD, a vectorial value for magnitude and axis calculating the separation between the 2 opposite semimeridian astigmatism values.[4] The changes in the TD value induced by surgery can also be calculated and observed.

Refining Future Treatments Using the Analysis

Corneal analysis showed the undercorrection of astigmatism treatment to be more evident by 30% than the refractive 15%. The systematic proportion of the errors, displayed by the summated DV mean, fell between 22% and 23% of the total error gauged by the arithmetic mean DV magnitude. These 2 pairs of numbers independently suggest a nomogram adjustment to future treatments (TIAs) should be used by an additional factor (CA). The choice of their common midpoint of 22.5% (CA 1.225) would seem appropriate for the task until the analysis on the next group of treated eyes is performed to incrementally refine outcomes. This is a useful and easily implemented alternative that, in this series, better serves the same purpose as the vectorial adjustment using the summated DV mean discussed earlier. No axis adjustment for treatment is required in view of the insignificant trend of mean arithmetic AE. Improvement in axis alignment for individual cases could be achieved as shown by the mean absolute AE.

Just as corneal values deserve emphasis when examining outcomes and nomogram refinement, they should also be regarded in planning. In my experience, astigmatic outcomes could be improved by reducing the remaining postoperative corneal astigmatism without necessarily increasing remaining refractive astigmatism. This could be achieved by using vector planning to link the preoperative topographic measurements into the treatment plan with the refractive values, using the method of treatment optimization previously described.[3,4] This inclusion of corneal values into the treatment plan would redress the imbalance in the planning process commonly practiced and used in this series, in which refractive values are employed exclusively. The immediate benefit would be less corneal astigmatism after surgery and consequently less overall (topographic plus refractive) astigmatism, as little or any increase in resultant refractive astigmatism is likely to occur.

One would expect after the treatment adjustments and other refinements have been added to the astigmatism treatment paradigms, the success in treating astigmatism measured by most parameters is likely to improve and more closely parallel the higher levels of success achieved in spherical treatment outcomes. This may have the additional benefit of reducing the wide discrepancy in outcome scores between corneal and refractive values.

Studies of future treatments could confirm the control of systematic treatment errors identified by this analysis. Subsequently, these studies could seek other means for improving the alignment of treatment, such as preoperative limbal marking, using a parameter such as AE used for this study, to gauge the effectiveness of this suggested step.

Conclusion

A systematic error of undercorrection of astigmatism is prevalent in the treatment of these 100 eyes so that their outcomes are less favorable than is otherwise achievable. Other significant problems are a proportionate excess of corneal astigmatism remaining over refractive astigmatism and a prevalent AE that appears in a CW or CCW sense, whose arithmetic mean shows no apparent trend. Astigmatic outcome parameters are less favorable when measured by objective corneal, than subjective refractive, astigmatism values. The success of spherical correction is greater than astigmatic correction when using analogous indices for comparison.

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The author has a proprietary interest in the treatment and analysis of astigmatism and the ASSORT® and VectrAK® computer programs.

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