Chapter 38

Combining Vector Planning With Wavefront Analysis to Optimize Laser In-Situ Keratomileusis Outcomes

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Introduction

Recent advances in laser technology are aimed at correcting ocular aberrations of the eye to improve visual outcomes. These new treatment paradigms, while offering advances for refractive surgery outcomes, do not take into account the possible mismatch between refractive and corneal astigmatism. Here we discuss both wavefront-guided laser in-situ keratomileusis (LASIK) surgery and the principles of vector analysis of astigmatism. The astigmatism outcomes of a series of patients treated with wavefront-guided LASIK are analyzed using the Alpins method of vector analysis.[1-3]

Principles of Wavefront Analysis

Introduction

The basic components of refraction, which are routinely measured, consist of myopia, hyperopia, and astigmatism. Traditionally, refractive surgery aims to correct errors of refraction, which are lower-order (second) aberrations. Higher-order aberrations include spherical aberration, coma, and foils. Even eyes with normal emmetropic vision can suffer from aberrations that affect vision.[4] The measurement of higher-order aberrations of the eye can be performed by wavefront analysis where the deviation of the wavefront from the ideal reference wave is measured. The quality of the visual system can also be described by determining how an object is imaged. Thus, the point spread function (PSF) or line spread function (LSF) can be used to measure the resultant blur from error in an optical system.

Shack-Hartmann Aberrometer

The aberrations of the eye can be measured using a Shack-Hartmann aberrometer to determine the wavefront. In Shack-Hartmann aberrometers, a small, focused beam of infrared light is shone into the eye (Figure 38-1A). The beam is reflected from the retina and passes through the optical system on the way out. This reflected beam is then captured by an array of lenslets and focused onto a charged-coupled device (CCD) array (Figure 38-1B). The wavefront is then measured from this reflected beam. The wavefront can be described by breaking down the map into component mathematical functions. The most commonly used system is to describe the wavefront in terms of Zernike polynomials of increasing order (Figure 38-2).

The Bausch & Lomb Zywave aberrometer (Rochester, NY) is Shack-Hartmann based. The Bausch & Lomb Zywave aberrometer is used to measure the wavefront deviation in prospective wavefront-guided (Zyoptix, Bausch & Lomb) LASIK patients both prior to and after surgery. It can also be used to determine the PSF. The Shack-Hartmann aberrometer has been used to measure the optical aberrations of the eye in patients with tear film abnormalities, corneal disease, and following LASIK.[5]

Aberrations and Visual Performance

Refractive techniques such as photorefractive keratectomy (PRK)[6] and LASIK,[7-9] while decreasing refractive errors have been shown to increase the optic aberrations of the eye. Performing LASIK surgery increases both coma-like and spherical-like aberrations, which are greater for larger myopic ablations.[9] The presence of optical aberrations after LASIK surgery may explain why some patients who have achieved 20/20 vision when measured on high contrast charts are not satisfied with their visual outcome after surgery. Since optical aberrations affect image contrast, measuring visual acuity on high contrast charts is not representative of the effect of optical aberrations on visual performance.[10]

These aberrations can result in a large PSF that reduces retinal image quality for large pupils.[5] In an optical system with aberrations, the larger the pupil, the greater the loss in image contrast.[11] Visual performance can be affected after LASIK, particularly in light conditions where a large pupil exists.[12,13]

It has been proposed that the increase in aberrations following LASIK surgery may be due to an increase in corneal asphericity, decentration of the ablation, corneal irregularities, interface corneal haze, and variability in wound healing.[9] Ocular aberrations also cause phase shifts and phase reversals that can affect image quality.[11] It was suggested in 1997 that "we need to move toward minimizing the eye's aberration at the same time we are correcting the eye's spherical and cylindrical refractive error."[14]

Wavefront-Guided Refractive Surgery

By correcting not only the spherical and cylindrical components of refraction but also the aberrations in the visual system that may affect vision performance, optimal visual outcomes beyond those currently achieved with "standard" laser ablations

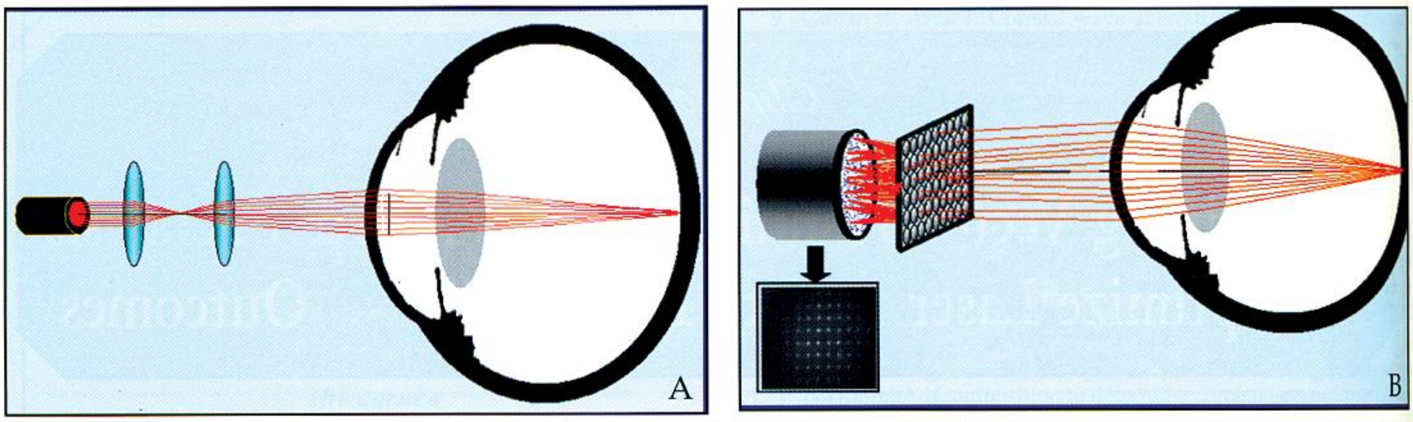

Figure 38-1. (A) A narrow beam is focused on the retina to generate a point source. (B) The outcoming rays experience the aberrations of the eye and their deviation is detected by an array of lenses. (Courtesy of Bausch & Lomb Surgical.)

may be possible. The first demonstration that the optical aberrations of the eye could be corrected was by Liang and colleagues.[15] Current laser refractive techniques have been developed to use wavefront analysis for determining LASIK customized ablations.

Recent results of patients treated with wavefront-guided LASIK are encouraging.[16-18] Mrochen and colleagues,[16] using a Tscherning wavefront sensor, reported on three eyes that had wavefront deviations reduced by an average of 27% following wavefront-guided LASIK. Consequently, uncorrected visual acuity (UCVA) of 20/12 or better was achieved. In a later series of 15 eyes by the same investigators using the Allegretto scanning spot excimer laser (WaveLight Laser Technologies AG, Erlanger, Germany), variable results were reported.[17] However, the majority of eyes gained one or more lines of best-corrected visual acuity (BCVA).

Arbelaez reported a series of patients where conventional and custom LASIK was performed using the NIDEK EC-5000 Multipoint excimer laser (Nidek, Gamagori, Japan) in which "more accuracy, better visual acuity, and more subjective satisfaction was achieved in the custom LASIK treatment group" than in the conventionally treated group.[18] Similarly, Panagopoulou and Pallikaris[19] reported that eyes that underwent Wavefront Aberration Supported Cornea Ablation (WASCA) (Asclepion-Meditec AG, Jena, Germany) demonstrated "improved outcomes" in comparison to conventionally treated eyes. Results like this have acted as a catalyst for claims of "supernormal" visual acuity and for the potential to use wavefront-guided LASIK on emmetropic eyes "aiming toward improved visual acuity only."[17]

While wavefront-guided LASIK is designed to correct higher-order aberrations, these impediments to a perfect outcome are still present after surgery. In a group of patients in which one eye was treated by conventional LASIK and the other by wavefront-guided customized ablation using the Nidek EC-5000 excimer laser system, no statistically significant difference was found in the postoperative higher-order aberrations or in the BCVA between the two groups 1 month after surgery.[20] In a study by Mrochen et al,[21] only 22.5% of eyes had a significant reduction in higher-order aberrations. On average, the optical aberrations were increased by a factor of 1.44 3 months after surgery.[21]

The limitations of refraction-based treatments only are:

1. Treatment is not regionally customized
2. There is potential for reduced contrast sensitivity, hence
3. There is potential for poor visual performance in low light conditions

$$W(x,y) = \sum_{n,m,\pi} A^{\pi}_{n,m} \times Z^{\pi}_{n,m}(x,y)$$

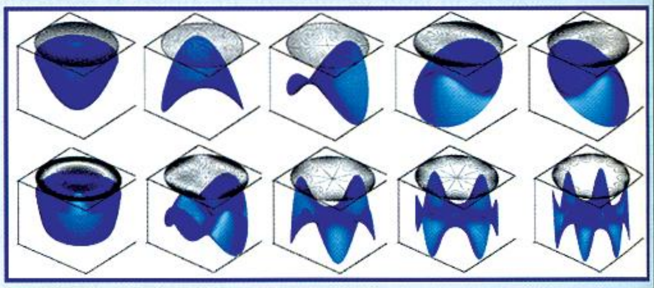

Figure 38-2. The shape of the wavefront is presented as a sum of a Zernike polynomial, each describing a certain deformation. (Courtesy of Bausch & Lomb Surgical.)

From the reported literature, it appears that wavefront-guided treatments achieve superior results to conventional treatments. The potential benefits of wavefront-guided treatments are:

1. Reduced aberrations in the optical system
2. Errors in spatial phase are corrected[11]
3. Improved contrast sensitivity and night vision
4. Better visual outcomes when compared to refraction-only based treatments

However, the potential limitations of wavefront-guided treatments are that they:

1. Do not take into account the amount of corneal astigmatism
2. Do not distinguish between corneal and lenticular aberrations
3. "Neutralize" internal aberrations of the eye onto the corneal surface
4. May increase irregularity of the cornea
5. Exclude the component of cortical perception of astigmatism, which would influence treatment with manifest refraction
6. Do not make allowances for internal aberrations that are likely to change with age

Table 38-1
Aggregate Data: Spherical Analysis of Treatment

Measurement	Manifest Refraction	Zywave Refraction
Preoperative spherical equivalent mean ± SD (D) (spectacle plane)	-3.65 ± 1.26	-3.78 ± 1.45
Postoperative spherical equivalent mean ± SD (D) (spectacle plane)	+0.27 ± 0.43	+0.17 ± 0.57
S.IOS (corneal plane)	0.14 ± 0.23	0.14 ± 0.12
S.CI (corneal plane)	1.07 ± 1.01	1.05 ± 1.02

S.IOS = Spherical Index of Success, S.CI = Spherical Correction Index

7. Utilize ablations to correct aberrations that may be small in comparison to the changes in corneal aberrations caused by creating a corneal flap

Principles of Vector Analysis of Astigmatism

Introduction

Refractive and corneal astigmatism, while usually related, seldom perfectly coincide. In many cases, they can be markedly different both in magnitude and orientation. Most current laser techniques aim for a zero refractive astigmatism outcome regardless of the amount or orientation of corneal astigmatism. Thus, the final shape of the cornea after surgery is seldom predetermined to target a spherical cornea. Surgical treatment of astigmatism determined by refractive means alone may result in an unfavorable distribution of astigmatism to the cornea.[22] Similarly, correcting astigmatism solely on corneal values could potentially lead to a gross overcorrection of manifest refraction and leave excessive refractive astigmatism remaining.

> Most current laser techniques aim for a zero refractive astigmatism outcome regardless of the amount or orientation of corneal astigmatism. Thus, the final shape of the cornea after surgery is seldom predetermined to target a spherical cornea.

By examining the relationship between surgery vectors, in particular the target-induced astigmatism vector (TIA), the surgically-induced astigmatism vector (SIA), and the difference vector (DV), outcomes of astigmatism treatment can be analyzed. In individual patients, the amount of correction achieved and the errors that occurred can be calculated. Aggregate data from a group of patients can be analyzed to determine systematic errors in laser application or surgical techniques and enable nomogram calculation for future adjustments to treatment.

Astigmatism Outcomes in a Group of Patients Treated by Wavefront-Guided LASIK

The results reported here are from the first series of patients with astigmatism treated with Zyoptix (Technolas 217z, Bausch & Lomb, Rochester, NY) at The Laservision Centre in Southport, Australia by Drs. Darryl Gregor and Peter Heiner. Patients were selected for Zyoptix treatment based on a number of set criteria. They had to have myopia of between -1 diopter (D) and -7 D combined with refractive astigmatism of not more than -3 D. The mean preoperative subjective refraction was -3.65 D ± 1.26 D for the spherical component and -1.01 D ± 0.6 D for the astigmatic component of the refraction.

The goal of surgery was a plano refractive outcome. Patients had to pass the usual criteria to be suitable for laser surgery. They had to have adequate corneal pachymetry, normal topography, better than 20/30 BCVA, and no signs of ocular pathology. Orbscan corneal topography and Zywave wavefront images were taken according to the manufacturer's (Bausch & Lomb) instructions.

Bilateral Zyoptix LASIK surgery was performed in all cases, except for the very first patient to be treated. In this case, Zyoptix was performed on one eye and a standard Planoscan (nonwavefront) treatment on the other. Corneal flaps were created with a Nidek MK 2000 microkeratome with heads designed to achieve either a 130 millimeter (mm) or 160.00 mm flap thickness depending on the preoperative pachymetry. Patients were reviewed at 1 day, 1 week, and at 1 and 3 months after surgery.

This initial cohort data has been previously analyzed by Bausch & Lomb Surgical (Germany). Based on the Bausch & Lomb analysis, a nomogram adjustment was made to alter future treatments by a factor of 90% of the spherical component of the refraction (this is in agreement with the results reported here). For the purposes of this paper, the 3 month postoperative data were analyzed using the Alpins Statistical System for Ophthalmic Refractive-Surgery Techniques (ASSORT) outcomes analysis program (ASSORT Pty Ltd, Victoria, Australia). The method and terminology followed in this paper have been published previously.[3] All refractive values were converted to the corneal plane and all calculations were performed using these values. Simulated keratometry readings were taken from Orbscan computer-assisted videokeratoscopy maps and values obtained were used for the corneal astigmatism analysis.

Aggregate Data Analysis

Spherical Analysis

The group data were analyzed based on subjective refraction spherical equivalents (Table 38-1). On average, eyes were overcorrected by 0.27 D ± 0.43 D. The Spherical Correction Index (S.CI = 1.07) indicates an overcorrection of 7%. A Spherical Index of Success (S.IOS) of 0.14 was achieved, indicating that the spherical correction was 86% successful.

Table 38-2
Aggregate Data: Simple and Polar Value Analysis of Astigmatism

Measurement	Manifest Refraction (D)	Zywave Refraction (D)	Topography (D)	Corneal/ Refractive Astigmatism*
Preoperative astigmatism mean ± SD	-1.01± 0.60*	-1.21 ± 0.75	1.33 ± 0.74*	1.32
Preoperative astigmatism, range	-0.25 to -3.00	-0.30 to -3.27	0.30 to 2.70	
Postoperative astigmatism, mean ± SD	-0.36 ± 0.23*	-0.43 ± 0.24	0.97 ± 0.47*	2.81
Postoperative astigmatism, range	0.00 to -0.75	-0.06 to -1.01	0.30 to 2.10	
Simple subtraction analysis mean ± SD	- 0.65 ± 0.61	- 0.78 ± 0.83	-0.36 ± 0.57	
Preoperative polar value mean ± SD	0.30 ± 1.04	0.33 ± 1.27	1.25 ± 0.86	
Postoperative polar value mean ± SD	0.25 ± 0.35	0.24 ± 0.44	0.97 ± 0.47	

Table 38-3
Aggregate Data: Surgical Vector Analysis of Astigmatic Treatment

	Manifest Refraction	Zywave Refraction	Topography
TIA, arithmetic mean ± SD	0.93 D ± 0.56	0.93 D ± 0.56	0.93 D ± 0.56
TIA, vector mean	0.22 D x 4	0.22 D x 4	0.22 D x 4
SIA, arithmetic mean ± SD	0.94 D ± 0.66	0.91 D ± 0.75	0.75 D ± 0.54
SIA, vector mean	0.11 D x 38	0.18 D x 23	0.18 D x 175
DV, arithmetic mean ± SD	0.36 D ± 0.24	0.49 D ± 0.21	0.53 D ± 0.36
DV, vector mean	0.21 D x 169	0.14 D x 157	0.08 D x 25
DV, vector mean/arithmetic mean	0.58	0.29	0.15

TIA = target-induced astigmatism, SIA = surgically-induced astigmatism, DV = difference vector

Astigmatism Analysis

Results for the group astigmatism analysis are shown in parallel for manifest refractive and Zywave measured refraction, and corneal (topographic) analysis. All patients except for one had -1.50 D or less of refractive astigmatism. The majority of patients only had a low or moderate amount of astigmatism (Table 38-2). Preoperative mean corneal astigmatism (1.33 D) exceeded mean subjective refractive astigmatism at the corneal plane (1.01 D) by a factor of 1.32. A greater reduction in refractive astigmatism (-0.65 D) than corneal astigmatism (-0.36 D) was achieved. Postoperative corneal astigmatism (0.97 D) exceeded subjective refractive astigmatism (0.36 D) by a factor of 2.81. This shows an excessive proportion of corneal, compared to refractive, astigmatism remaining. This phenomenon, which has been shown in other studies of astigmatism, is evident when employing refractive astigmatism parameters alone.[3]

Data analyzed using subjective refraction (subjective) data showed that a summated vector mean TIA value of 0.22 D x 4 (Table 38-3) was attempted. This indicates that the trend was to induce a net steepening along the horizontal meridian to result in a small net against-the-rule change. The arithmetic mean SIA by manifest refraction was 0.94 D and Zywave refraction was 0.91 D. These values were slightly lower than that aimed for (TIA = 0.93 D), suggesting a small undercorrection. An undercorrection was also evident for the corneal changes (SIA = 0.75 D). The summated vector mean values of SIA by refraction (subjective 0.11 D, wavefront 0.18 D) and topography (0.18 D) confirmed the trend for undercorrection by comparison with the TIA vector mean.

Consistent trends for treatment error are shown in both refractive and topographical measurements. The arithmetic mean magnitude of the DV by refraction (subjective 0.36 D [Figure 38-3A]; wavefront 0.49 D) was less than that by topography (0.53 D) (Figure 38-3B). When determined by subjective refraction data and topographical data, 58% and 15% of this error (0.21 D and 0.08 D, respectively) can be attributed to systematic treatment error (see Table 38-3).

Angle of error (AE) analysis for subjective refraction and topography show that both arithmetic means for the groups were close to zero (+1.57 degrees and -0.39 degrees) (slightly counterclockwise and clockwise, respectively). However, the spread of results is wide for both refractive (SD of AE = 14.45 degrees, absolute AE = 9.57 degrees) and corneal (SD of AE =

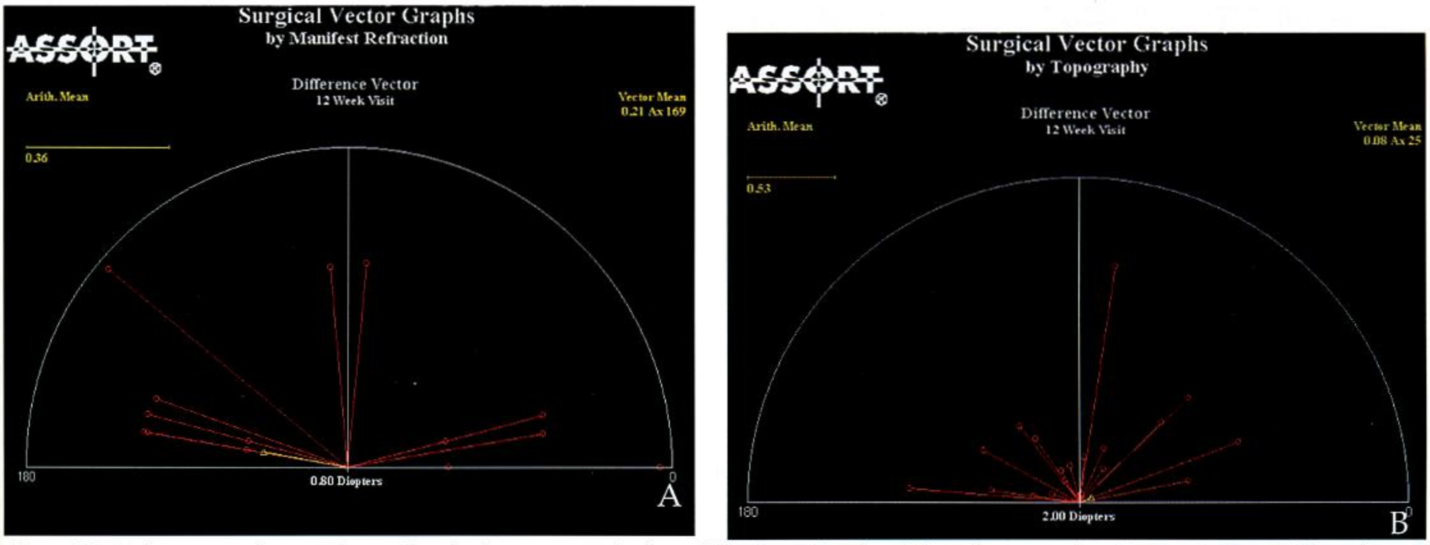

Figure 38-3. Aggregate data analyses. Surgical vector graphs for subjective refraction (A) and topography (B) are shown. Arithmetic and vectorial means are shown.

Table 38-4

Aggregate Data: Astigmatism Analysis of Vectors for Error and Treatment. A Comparison of Refractive and Topographical Values

	Manifest Refraction	*Zywave Refraction*	*Topography*
AE, arithmetic mean ± SD (degrees)	+1.57 ± 14.45	+2.07 ± 29.83	-0.39 ± 16.31
AE, absolute mean ± SD (degrees)	9.57 ± 10.93	18.81 ± 23.25	13.75 ± 8.77
ME, arithmetic mean ± SD (D)	0.01 ± 0.28	-0.02 ± 0.35	-0.18 ± 0.46
CI, geometric mean ± SD	0.96 ± 1.43	0.80 ± 1.83	0.74 ± 1.75
FI, geometric mean ± SD	0.79 ± 1.23	0.71 ± 1.28	0.62 ± 1.25
IOS, geometric mean ± SD	0.35 ± 0.12	0.61 ± 0.06	0.55 ± 0.06
CA	1.04 ± 1.43	1.26 ± 1.83	1.34 ± 1.75
ORA (D)		0.92 ± 0.47	

AE = angle of error, ME = magnitude of error, CI = correction index, FI = flattening index, IOS = index of success, CA = coefficient of adjustment, ORA = ocular residual astigmatism

16.31 degrees, absolute AE = 13.75 degrees) measures, with topographical results being more greatly spread. There was greater spread in the data when results were analyzed with wavefront-derived refractions than when analyzed with manifest refraction or corneal topography data, indicating a greater variability of wavefront measured values.

> There was greater spread in the data when results were analyzed with wavefront-derived refractions than when analyzed with manifest refraction or corneal topography data, indicating a greater variability of wavefront measured values.

The treatment (Table 38-4) was more successful when measured by subjective refractive measures (index of success [IOS] = 0.35, 65%) than by wavefront-derived refractive measures (IOS = 0.61, 39%) or objective corneal measurement (IOS = 0.55, 45%). This is supported by the correction index (CI) values of 0.96 for manifest refractive and 0.74 for topography measurements of astigmatism. It was interesting to note that wavefront-derived CI of 0.80 more closely parallels the corneal topographical value. The flattening index (FI) indicates that the treatment was less effectively applied at the treatment axis when measured by corneal (FI = 0.62) or wavefront derived refraction (FI = 0.71) than by subjective refractive (FI = 0.79) means. The values for nomogram adjustment indicate that an increase in the future magnitude of astigmatism treatment in the region of 26% (zywave) and 34% (corneal) would likely improve outcomes. However, this value should be modified down to some extent as manifest refraction showed a coefficient of adjustment (CA) of 1.04 (4%) only.

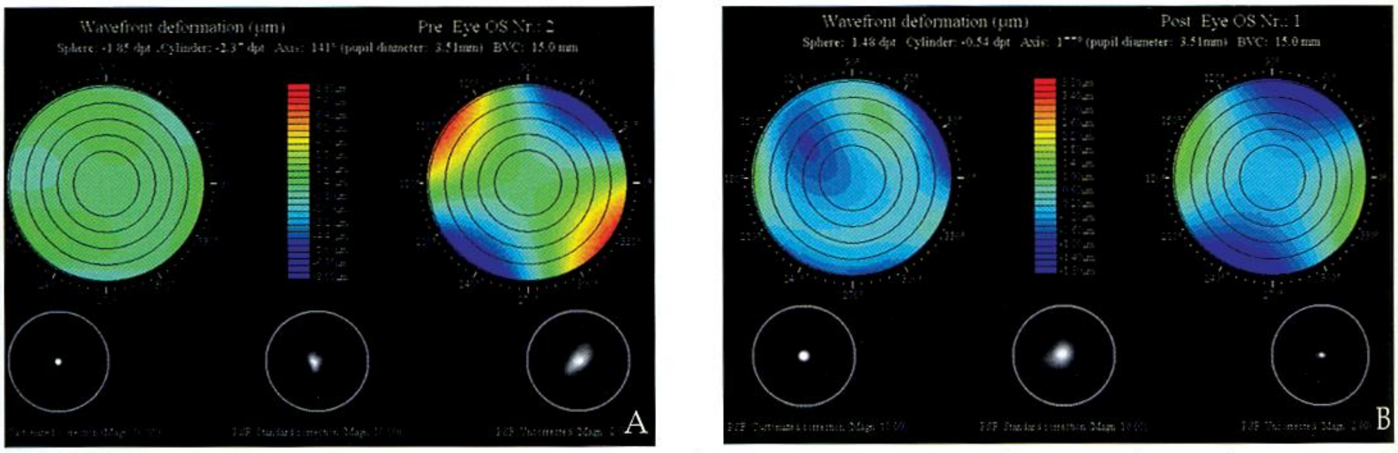

Figure 38-4. Single patient analyses. Preoperative (A) and 3-month postoperative (B) Zywave aberrometry data are shown.

Single Patient Analysis

The left eye of one patient was individually analyzed to determine changes in astigmatism. All calculations were performed on corneal plane values. The preoperative refraction was -2.00/-2.00 x 145 (UCVA = 20/200, BCVA = 20/20) and the Zywave refraction -1.85/-2.37 x 141 (Figure 38-4A). Three months after surgery, the refraction was +1.25/-0.75 x 180 (UCVA = 20/16-1, BCVA = 20/16+1) and the Zywave refraction +1.48/-0.54 x 177 (Figure 38-4B). Simulated keratometry values from the Orbscan (Figure 38-5) were 42.7/44.9 @ 67 preoperatively and 39.2/41.1 @ 90 at 3 months postoperatively.

Spherical Analysis

The preoperative spherical equivalent prior to surgery was -3 D and +0.88 D at 3 months postoperatively (Table 38-5). The S.IOS indicates that the surgery was 69% successful. The CI (1.31) shows that there has been an overcorrection in this patient of 31%.

Astigmatism Analysis

The refractive astigmatism prior to surgery was 2 D by refraction and 2.20 D by corneal values (Table 38-6). The astigmatic treatment (TIA) was 1.86 D x 145 at the corneal plane (Table 38-7). The SIA by refractive values was 1.75 D x 133 and by corneal values was 1.48 D x 124 (Figure 38-6). The DVs of 0.77 D x 0 (refractive) and 1.27 D x 171 (corneal) indicate that there was still remaining astigmatism.

Description of Astigmatism Analysis: Topography

Figure 38-6 displays corneal values for astigmatism and vectors, both on a double-angle vector diagram (DAVD). Also displayed in tables are all the astigmatism values, surgical vector values, and an analysis of errors and correction.

The DAVD is constructed by doubling all three meridian values of astigmatism and displaying these values (astigmatisms) at their respective double-angled location. The vectors are determined by joining the heads of the astigmatism displays with dashed lines.

To view the surgical vectors at their actual position, their axis value is halved and the tail of the vector is located at the origin of the polar surgical vector graph.

Both the refractive and corneal values indicate there has been an undercorrection of astigmatism. This is evidenced by CI values of 0.94 for refraction and 0.80 for corneal (Table 38-8). The AE shows that the treatment was off axis by 12 degrees clockwise for refraction and by 22 degrees clockwise when determined by corneal values. This could be due to alignment or healing factors. Thus, a significant loss of effect at the treatment meridian occurred as demonstrated by the FE (1.60 D and 1.09 D) and FI (0.86 and 0.58). The IOS shows that the treatment was 59% (0.41) successful in correcting refractive astigmatism and 31% (0.69) successful in correcting corneal astigmatism.

Torque Effect

While the FE and FI are measures of how effective the SIA has been in reducing astigmatism, the torque effect gauges the proportion of the SIA that did not reduce astigmatism. It occurs as a consequence of the effects of treatment being "off axis," and it results in the rotation of existing astigmatism and not its reduction. The torque effect is maximum when the AE reaches 45 degrees, so it is greater for corneal measurements (1.01 D) than for refractive (0.72 D) as the off-axis effect was greater (-22 degrees compared to -12 degrees).

Discussion

For the aggregate data, an average overcorrection of 7% of the spherical component of the treatment occurred (S.CI = 1.07). In comparison, the study of Alpins[3] found an undercorrection of 12% (S.CI = 0.88) for conventionally treated LASIK patients with a different laser device. This may be due to differences in individual lasers and treatment conditions. While it could indicate a trend for wavefront devices to overestimate the preoperative spherical component of refraction, this did not seem to be evident. The average spherical component was -3.65 D ± 1.26 D for the preoperative manifest refraction and -3.78 D ± 1.45 D when measured with the Zywave aberrometer.

The results reported here for a small group of patients treated with wavefront-guided LASIK compare favorably with conventional LASIK for the correction of low to moderate levels of astig-

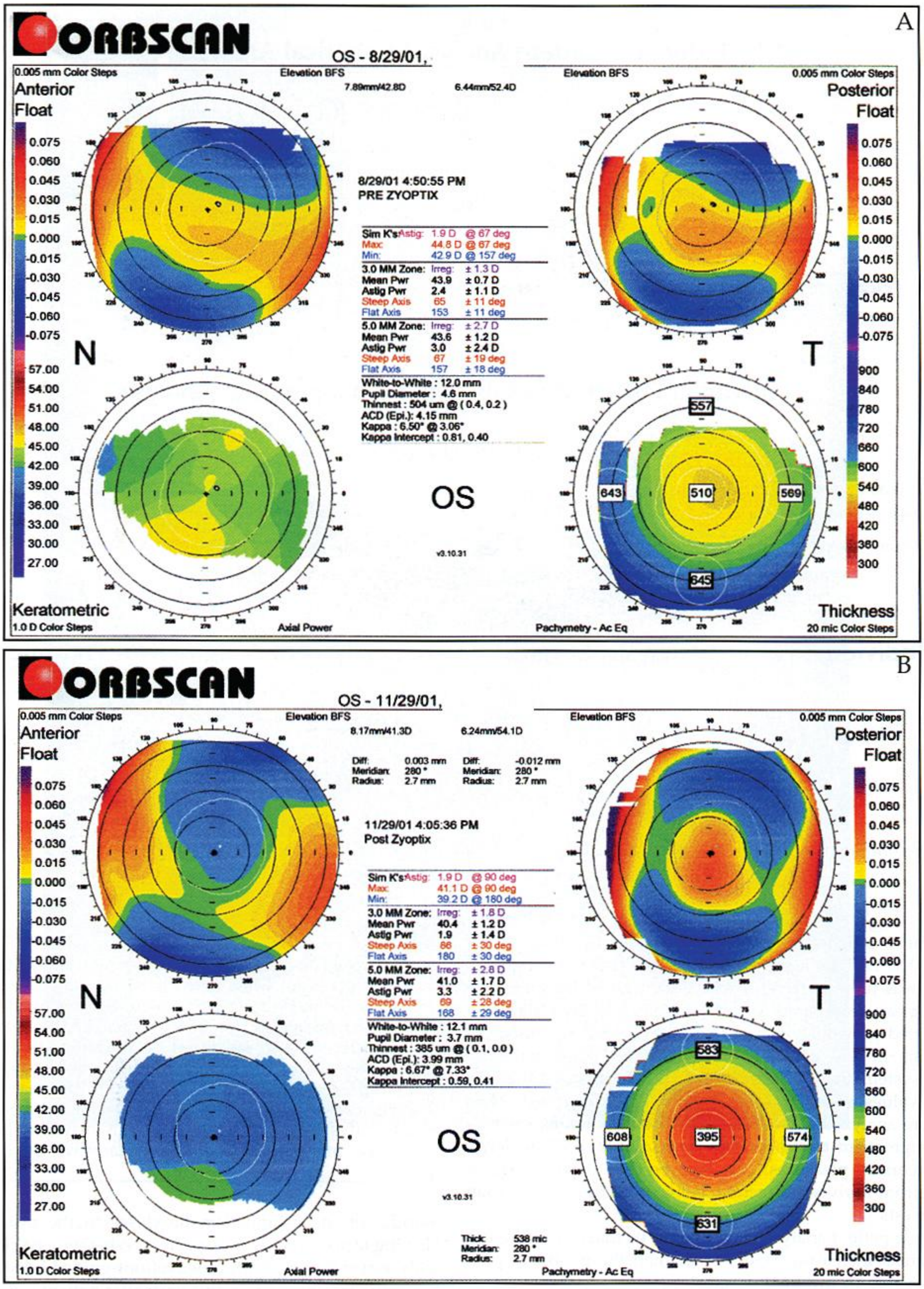

Figure 38-5. Single patient analyses. Preoperative (A) and 3-month postoperative (B) Orbscan computer-assisted videokeratoscopy maps are shown.

Table 38-5
Individual Patient Analysis: Spherical Analysis

	Refraction (Corneal plane)
Preoperative spherical equivalent (D)	-3.00 (-2.88)
Postoperative spherical equivalent (D)	0.88 (0.89)
S.IOS	0.31
S.CI	1.31

S.IOS = spherical index of success, S.CI = spherical correction index

Table 38-6
Individual Patient Analysis: Simple Astigmatism Analysis

	Refraction	Topography
Preoperative astigmatism (D)	2.00	1.90
Postoperative astigmatism (D)	0.75	1.90
Simple subtraction value	-1.25	0.00

Table 38-7
Individual Patient Analysis: Surgical Vector Analysis of Astigmatism Treatment

	Refraction	Topography
TIA (D)	1.86 x 145	1.86 x 145
SIA (D)	1.75 x 133	1.48 x 124
DV (D)	0.77 x 0	1.27 x 171

TIA = target-induced astigmatism, SIA = surgically-induced astigmatism, DV = difference vector

matism (mean astigmatism measured by manifest refraction of -1.01 D ± 0.60 D). The aggregate data show that the astigmatic treatment was more successful when determined by subjective refractive means compared to corneal measures. This trend has been reported previously for conventional LASIK treatments.[23] An analysis of 100 conventionally treated LASIK patients[3] showed a systematic undercorrection of astigmatism by 15% for refractive values and 30% for corneal values. However, when results were analyzed by wavefront-derived refraction, the success of astigmatism treatment was more similar to that determined by corneal measures. This may be due to both corneal- and wavefront-derived refraction being objective rather than subjective tests.

The single patient analysis data remind us that as the amount of astigmatism increases, factors other than the treatment plan may play a role in the final surgical outcome. As astigmatism magnitude increases, a small deviation in the meridian of treatment from that planned may have a more significant effect on the amount of treatment applied at the intended axis. Where oblique astigmatism exists, it is probably more likely that the analysis will show a misalignment of axes than when compared to against- or with-the-rule astigmatism in which the principal meridia of the astigmatism lie closer to the principal poles. Healing factors may also play a role. Whether a patient is treated with conventional LASIK or wavefront-guided LASIK, these factors remain important. In this particular patient's case, the visual outcome (UCVA = 20/15-1) was still extremely good as the best sphere was close to zero and an improvement in BCVA occurred (from 20/20 to 20/15+1), masking the less than perfect astigmatic outcome revealed by vector analysis. Ultimately, the subjective evaluation of the visual outcome is the most important measure of an individual patient's success.

The aggregate data show that the astigmatic treatment was more successful when determined by subjective refractive means compared to corneal measures. This trend has been reported previously for conventional LASIK treatments.[23] When results were analyzed by wavefront-derived refraction, the success of astigmatism treatment was more similar to that determined by corneal measures. This may be due to both corneal- and wavefront-derived refraction being objective rather than subjective tests. This may also be due to intrinsic inaccuracies in this particular wavefront device.

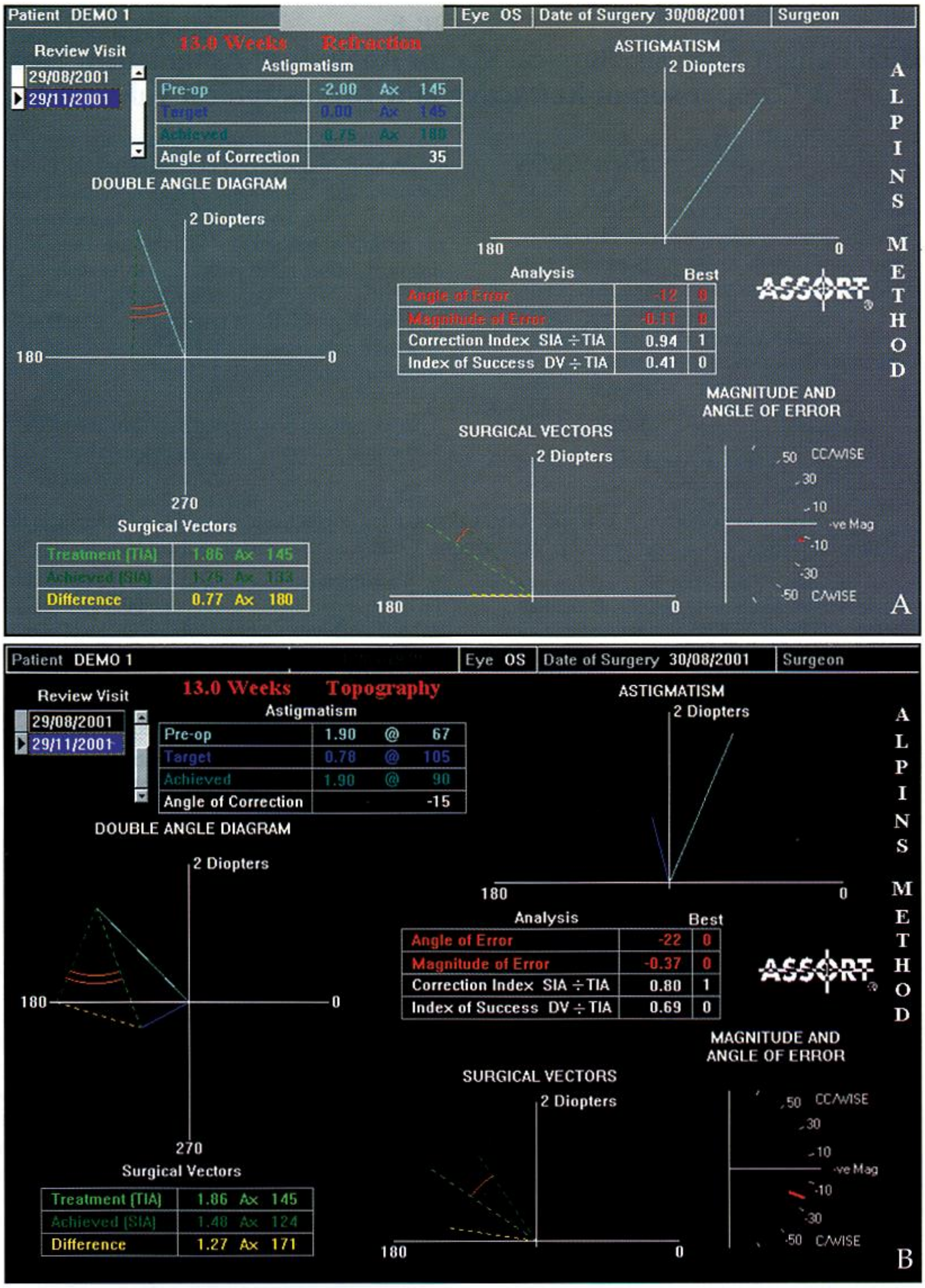

Figure 38-6. Single patient analyses. Surgical vector graphs for refraction (A) and topography (B) are shown.

Table 38-8

Individual Patient Analysis: Surgical Vector Analysis of Astigmatism Treatment. A Comparison of Refractive and Topographical Values

	Refraction	*Topography*
AE	-12.00	-22.00
ME	-0.11 D	-0.37 D
IOS	0.41	0.69
CI	0.94	0.80
FE	1.60 D	1.09 D
Torque effect (CCW)	0.72 D	1.01 D
FI	0.86	0.58
CA	1.06	1.25
ORA	0.78 D x 15	0.78 D x 15

AE = angle of error, ME = magnitude of error, IOS = index of success, CI = correction index, FE = flattening effect, CCW = counter clockwise; FI = flattening index, CA = coefficient of adjustment, ORA = ocular residual astigmatism

Optimizing Outcomes for Topography and Wavefront

When a LASIK flap is made on the eye, changes in corneal curvature and thickness occur outside of the ablation zone.[24,25] This biomechanical response causes a FE in the treatment zone, which enhances a myopic procedure but counteracts a hyperopic ablation.[24,25]

Creating a flap on the eye changes the structure of the cornea. Applying principles of spheric corneal topography may account for the differences in relative effect of creating a flap through an elliptical or conic section. It enables differences in the relative effect of laser treatment in the presence of corneal cylinder that is either greater or less than the refractive cylinder to be incorporated into the treatment plan.

Optimizing outcomes for topography and wavefront examinations takes into account both the corneal structure and refractive function. For individual patients this means that any discrepancy between refractive and corneal astigmatism can be taken into account in the treatment plan to avoid an excess residual amount of corneal astigmatism. Changes in corneal structure induced by LASIK surgery particularly can affect the lower-order aberrations of the eye.

Guiding the TIA, the meridian of maximum ablation, closer to the principal flat corneal meridian would result in less corneal astigmatism. The process of vector planning would reduce the excess amount of corneal astigmatism remaining demonstrated in this (2.81 versus 1.32) and other studies.[3] This needs to be further investigated and then incorporated into the treatment plan if a favorable influence is identified.

The potential benefits of vector planning of preoperative corneal and refractive astigmatism values are:

1. Corneal values are included in the treatment plan
2. The treatment can be optimized and balanced between corneal and refractive parameters
3. The potential for less "off-axis" effect on principal corneal meridia and a greater reduction in corneal astigmatism
4. There is the potential to bias the treatment to a more favorable with-the-rule astigmatism outcome (which usually has the least adverse impact on distance vision) or to any other orientation preferred by the surgeon
5. Reduced corneal astigmatism is likely to provide less low-order (second) aberrations and even some high-order (third and fourth) aberrations and enhanced contrast sensitivity

Conclusion

Wavefront-guided laser refractive surgery holds future promise for correcting higher-order aberrations of the eye. However, we must not lose focus of the importance of correcting both the spherical and cylindrical components of refraction quantified by the lower-order (second) aberrations. Nomogram adjustment of laser treatments remains an important factor in the surgical planning process. Vector planning would potentially be a valuable adjunct to treatments that are guided by wavefront aberrometry measurements. Optimizing outcomes by incorporating both corneal and refractive values into the treatment plan are necessary challenges for the imminent future of refractive surgery.

Editor's note:

Although the content of this chapter has been primarily focused on vector analysis and planning of wavefront vs refraction vs topographic cylinder, the possibility does exist to analyze the magnitude and axis of other higher-order aberrations as well. We reserve this topic for a later time, as the complexity of vector planning and astigmatism is sufficient for now. Further practical experience is needed to bring about more widespread acceptance of this method of analysis and planning.

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Definitions

Astigmatism Analysis

angle of error (AE): The angle described by the SIA and TIA vectors. The AE is positive if the achieved correction was counterclockwise to that intended and is negative if the achieved correction was clockwise to the intended axis.

coefficient of adjustment (CA): The coefficient required to adjust future treatments of astigmatism magnitude. It is calculated by dividing the TIA by the SIA, and is preferably 1.00.

correction index (CI): The CI is calculated by dividing the SIA by the TIA. The CI is ideally equal to 1.00. It is greater than 1.00 for an overcorrection and less than 1.00 if an undercorrection has occurred.

difference vector (DV): The induced astigmatic change needed for the initial surgery to have achieved its intended target outcome. The DV is preferably 0.

flattening effect (FE): The amount of astigmatism reduction achieved by the effective proportion of the SIA at the intended meridian.

flattening index (FI): The FI is calculated by dividing the FE by the TIA. The FI is ideally 1.00.

index of success (IOS): The IOS is calculated by dividing the DV by the TIA. The IOS is a measure of success and is preferably zero.

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

ocular residual astigmatism (ORA): The ORA represents the calculated minimum amount possible of astigmatism remaining in the system after treatment. It is the vector difference between the corneal and refractive astigmatisms.

surgically-induced astigmatism vector (SIA): The astigmatic change actually induced by the surgery.

target-induced astigmatism vector (TIA): The astigmatic change the surgery was intended to induce.

torque effect: The amount of astigmatic change induced by the SIA that has been ineffective in reducing astigmatism at the intended meridian but has caused rotation and a small increase in the existing astigmatism. Torque lies 45 degrees counter clockwise to the SIA if positive and 45 degrees clockwise to the SIA if negative.[2]

Spherical Analysis

spherical correction index (S.CI): The spherical equivalent correction achieved divided by the targeted spherical correction.

spherical difference (S.Diff): The absolute difference between the targeted spherical equivalent correction and the achieved spherical equivalent correction.

spherical index of success (S.IOS): The absolute difference between the achieved and targeted spherical equivalents divided by the targeted spherical equivalent correction.

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