CHAPTER 1

ASTIGMATISM: LASIK, LASEK, AND PRK

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Astigmatism occurs concomitantly with myopia and hyperopia in a high proportion of refractive corrections attempted with LASIK, LASEK, and PRK. Consequently, accurate measurement and analysis of preoperative astigmatism is an essential step in further understanding and determining appropriate corneal ablations for its surgical treatment.

THE ASTIGMATISM PHENOMENON

The total amount of correction required to eliminate the astigmatism within an eye's optical system is gauged subjectively by a manifest refraction. This measurement is the sum of all astigmatic components, optical and perceptual, and is known as the refractive astigmatism.

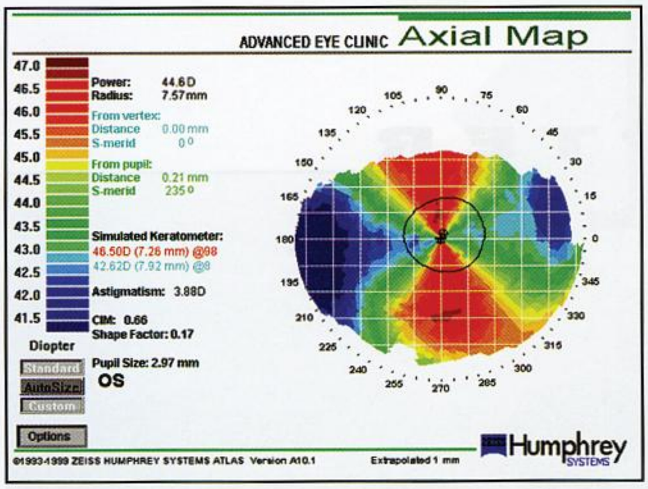
The principal refractive surface of the eye, the cornea, can contribute an element of astigmatism, both from its anterior and posterior surfaces. The shape of the anterior corneal surface can be objectively quantified using manual keratometry or corneal topography methods and is described as corneal astigmatism.

Corneal astigmatism arising from the anterior corneal surface can be grouped into regular and irregular forms. Regular corneal astigmatism occurs when the principal meridians, flattest and steepest, of the anterior corneal surface are both orthogonal and symmetrical (Figures 1-1 through 1-3).[1]

Irregular corneal astigmatism describes the situation where there is a difference in the steepest corneal meridian across the hemi-division of the cornea—ie, where the astigmatism across the hemi-division is different in magnitude (asymmetry); not aligned across 180 degrees (non-orthogonal); or a combination of both of these factors.[2] The corneal irregularity itself can be idiopathic or occur secondary to:[3]

- Irregularity on the anterior corneal surface (eg, keratoconus [Figure 1-4], pellucid marginal degeneration, and keratoglobus)
- Trauma (eg, corneal incisions, excision or burns)
- Posttherapeutic healing or scarring
- Surgery (eg, keratoplasty, PRK, LASIK, LASEK, RK, or AK)

Residual astigmatism is a measure of the difference between the refractive and corneal astigmatism.[4] The amount of residual astigmatism can be measured directly from a spherical RGP contact lens overrefraction or mathematically calculated by vectorially subtracting the topographic from the refractive astigmatism at the corneal plane.[1] Both surfaces of the crystalline lens, any misalignment or tilt within the optical system, and an element of visual cortical perception[1,5] contribute to the amount of residual astigmatism present within an optical system.


ADVANCED EYE CLINIC Axial Map

Power: 44.6D
Radius: 7.57mm
From vertex:
Distance 0.00 mm
S-merid 0°
From pupil:
Distance 0.21 mm
S-merid 235°
Simulated Keratometer:
46.50D (7.26 mm) @98
42.62D (7.92 mm) @8
Astigmatism: 3.88D
CIM: 0.66
Shape Factor: 0.17
Pupil Size: 2.97 mm
OS

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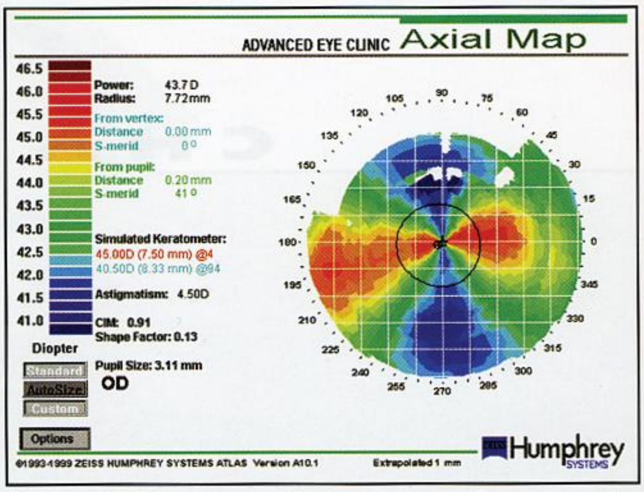
Extrapolated 1 mm

Figure 1-1. Regular with-the-rule astigmatism. The steepest axis of the anterior corneal surface is aligned along the vertical meridian.


ADVANCED EYE CLINIC Axial Map

Power: 43.7D
Radius: 7.72mm
From vertex:
Distance 0.00 mm
S-merid 0°
From pupil:
Distance 0.20 mm
S-merid 41°
Simulated Keratometer:
45.00D (7.50 mm) @4
40.50D (8.33 mm) @94
Astigmatism: 4.50D
CIM: 0.91
Shape Factor: 0.13
Pupil Size: 3.11 mm
OD

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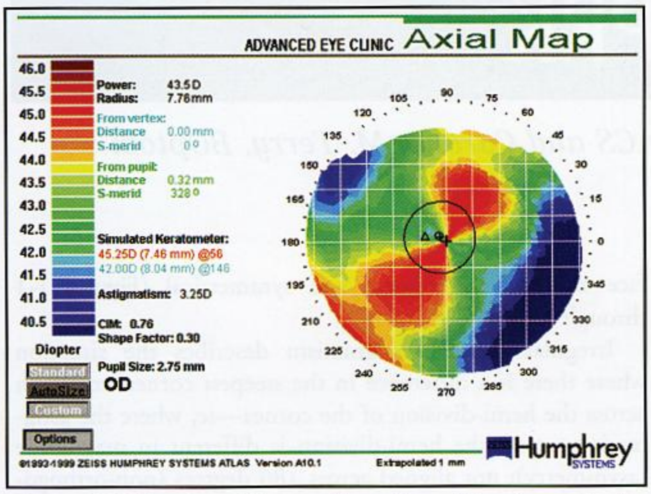
Extrapolated 1 mm

Figure 1-2. Regular against-the-rule astigmatism. The steepest axis of the anterior corneal surface is aligned along the horizontal meridian.


ADVANCED EYE CLINIC Axial Map

Power: 43.5D
Radius: 7.76mm
From vertex:
Distance 0.00 mm
S-merid 0°
From pupil:
Distance 0.32 mm
S-merid 328°
Simulated Keratometer:
45.25D (7.46 mm) @56
42.00D (8.04 mm) @146
Astigmatism: 3.25D
CIM: 0.76
Shape Factor: 0.30
Pupil Size: 2.75 mm
OD

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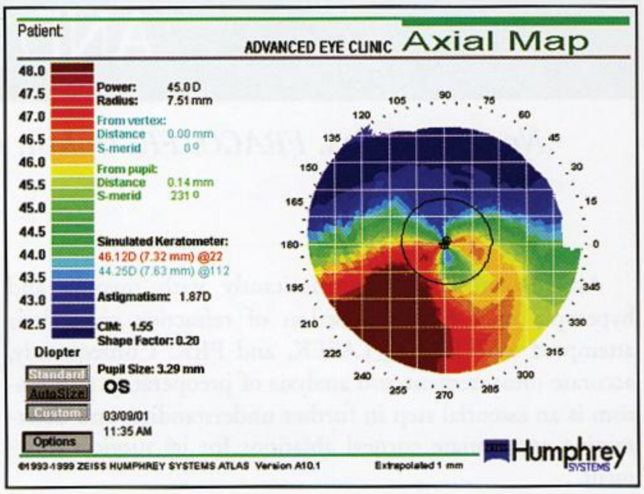
Extrapolated 1 mm

Figure 1-3. Regular oblique astigmatism. The steepest axis of the anterior corneal surface is aligned along an oblique orientation.


Patient:
ADVANCED EYE CLINIC Axial Map

Power: 45.0D
Radius: 7.51mm
From vertex:
Distance 0.00 mm
S-merid 0°
From pupil:
Distance 0.14 mm
S-merid 231°
Simulated Keratometer:
46.12D (7.32 mm) @22
44.25D (7.63 mm) @112
Astigmatism: 1.87D
CIM: 1.55
Shape Factor: 0.20
Pupil Size: 3.29 mm
OS
03/09/01
11:35 AM

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Extrapolated 1 mm

Figure 1-4. Irregular astigmatism. This anterior corneal display of keratoconus shows nonorthogonal and asymmetric astigmatism with steepening in the inferior hemidivision of the cornea.

MEASUREMENT OF ASTIGMATISM

Optical Astigmatism

MANIFEST REFRACTION

The spherocylindrical result established from a manifest refraction determines how much optical correction is required to establish a single, clear focused image on the retina. The manifest refraction not only quantifies the amount of astigmatism due to the refracting surfaces of the eye, but also incorporates the component of astigmatism due to the perception of the retinal image by the visual cortex.[6]

This subjective mode of testing is largely dependent on observer response and testing conditions and subsequently can be prone to inconsistencies between individuals. Variations in ergonomics due to differences in ambient lighting conditions and chart type, distance, illumination, and contrast can lead to unreliable comparison between data.[7]

WAVEFRONT ABERROMETRY

Wavefront assessment devices are useful diagnostic tools that provide objective information regarding the optical aberrations within an ocular system. Small decentrations in all optical surfaces and shapes can produce optical aberrations even in "normal" eyes and cannot be corrected effectively by spectacles or contact lenses.[8] The wavefront devices available in clinical practice utilize the principle of outgoing reflection aberrometry (Shack-Hartmann, Adaptive Optics Associates, Cambridge, Mass), retinal imaging aberrometry (Tscherning) or ingoing adjustable refractometry (spatially resolved refractometer).[9] The Shack-Hartmann aberrometer is the most widely implemented technique.[9] In this technique, a beam of light is focused upon the retina from which a reflection passes backward through the media of the eye.[10] As the wavefront emerges from the entrance pupil, it is detected by a sensor and the resultant image is analyzed and compared to the uniform distribution produced by a perfect wavefront.[11]

The ensuing wavefront pattern provides a profile for the refractive error and expresses the ocular aberrations in terms of Zernike polynomials.[10] Second-order aberrations provide a measurement of defocus and astigmatism, not unlike the information derived from a manifest refraction. However, unlike a manifest refraction, a wavefront device is unable to provide effective information regarding cortical perception.[12] Third-order (trefoil, coma, and coma-like aberrations), fourth-order (spherical aberration and spherical-like aberrations), and higher order aberrations are also detected by these devices.[10]

Corneal Shape

KERATOMETRY

Keratometry provides a basic curvature measurement of the anterior cornea's 2 principal meridians. The resultant average corneal astigmatism value applies to a limited central area of the anterior cornea and cannot quantify any corneal irregularity that may be present on that surface.

CORNEAL TOPOGRAPHY

Corneal topography mapping by computer-assisted videokeratography (CAVK) affords a more advanced technique of appraising corneal astigmatism by measuring values at multiple reference points over the anterior corneal surface. This objective measurement modality provides useful information regarding corneal irregularity and assists the quantitative and qualitative analysis of astigmatism.

The CAVK is also capable of producing an average curvature value for the whole cornea, not unlike a keratometry reading. However, these simulated keratometry values are a best-fit compromise. As the various commercially available CAVK devices establish these values using varied proprietary methods, variability between values can exist and render standardization difficult.

SURGICAL TREATMENT OF ASTIGMATISM

Most excimer lasers in use today possess the ability to treat myopic, hyperopic and mixed astigmatism by LASIK, LASEK, and PRK up to a maximum ranging from 4.00 to 6.00 D.[13] The pattern of ablation application has varied widely with previous and current methods including scanning spots or slits, ablatable masks, expanding blades, rotating slits, and rotating masks.[13]

Refraction and Wavefront Versus Topography and Keratometry

Situations where corneal and optical astigmatism precisely coincide are relatively uncomplicated to treat surgically by LASIK, LASEK, or PRK. In reality, individuals commonly display some variance between the refractive and corneal astigmatism parameters.

Upon first consideration, it seems feasible to achieve a plano spherical and astigmatism result by targeting either a spherical corneal shape or manifest refraction. However, when differences exist between these 2 parameters, either in their magnitude, orientation, or both, there will be some remaining astigmatism within the optical system of the eye following surgical treatment. This astigmatism will exist entirely on the cornea or the resultant manifest refraction depending on the initial emphasis for correction by the astigmatism treatment. Either way, there is the possibility that such a surgical approach at either extreme could create an inferior functioning optical system and lead to a poorer quality of vision.

For example, many think that if the aim of refractive surgery is to reduce or eliminate the requirement for spectacle correction, then the corneal ablation—for both the spherical and cylindrical components—should be solely defined by the manifest refraction. Disregarding the initial corneal shape means that there is the potential to leave excessive levels of corneal astigmatism remaining[5,6,7] and the chance of reduced quality of vision secondary to an increase in aberrations such as spherical aberration[14] or lower order astigmatism.

Conversely, an ablation guided entirely by topography, with the intention of generating a spherical anterior corneal surface, could potentially leave residual manifest refractive error from the other internal refracting surfaces of the eye.

The advent of wavefront analysis devices has added an additional dimension to consider when treating astigmatism. Much of today's research efforts have been placed on the development of customized corneal ablations to correct higher order aberrations. The majority of conventional ablations correct the lower order aberrations of blur and defocus by altering the natural prolate shape of the cornea. It is widely documented that the resulting postoperative oblate corneal shape may give rise to an increase in higher order monochromatic aberrations such as coma and spherical aberration, particularly under scotopic conditions.[15-18] This can subsequently lead to a decline in postoperative visual performance.

By evaluating these aberrations and applying individual customized treatments to the corneal surface, an increase in visual performance may result. In other words, all aberrations regardless of their origin—be they corneal, lenticular or retinal—would be compensated for on the anterior corneal surface. This theory, however, places little importance on the impact of any induced irregularity that could result from correcting all these aberrations on the corneal surface alone.[12]

There is some concern that the healing characteristics of the cornea, particularly the corneal epithelium, may negate the correction accomplished with wavefront ablations by reducing or masking its effectiveness.[19] Furthermore, the biomechanical and healing effects of the cornea following wavefront-guided treatments are yet to be determined or nomograms developed,[20] which could potentially improve visual results while reducing induced aberrations.[21] It is also likely that the aberrations within an optical system are not static[22] but may in fact be dynamically changing over time. These alterations can occur in the crystalline lens with age[12] and accommodation,[22] or via the nonoptical components of the visual system (ie, the cerebral integration of images).[12]

Consequently, in order to effectively treat astigmatism as part of the overall spherocylindrical correction, there is merit in considering both corneal and optical astigmatism components to formulate an integrated treatment strategy. Wavefront data adds another dimension to this treatment strategy and can be considered in conjunction with the parallel technology of corneal topography,[12,20] and integrated using vector planning for the ultimate determination of surgical astigmatic treatments.[12]

In an attempt to perform successful astigmatism surgery it is important to consider:

1. Optimizing surgical treatments according to prevailing corneal and optical parameters[6]
2. Targeting less overall corneal astigmatism by orientating the maximum ablation closer to the principal corneal meridian
3. Conducting valid analyses of astigmatic results using both corneal and refractive measurements. This is accomplished by predetermining the target values for the treatment of astigmatism[5-7]

Vector Planning

The analytical approach of vector planning[5] provides a technique of implementing these objectives by incorporating each patient's unique corneal and refractive parameters in a customized treatment plan.

As astigmatism is described both by magnitude and direction, the mathematical approach of vectors can be used to assist the surgeon design astigmatic corrections with an associated spherical component. The basic principal of vector analysis assists the development of customized treatment plans by integrating corneal astigmatism and refractive astigmatism values. With the assistance of vectors, treatment parameters can be calculated and determined for the "maximal treatment" of astigmatism by complete elimination of refractive astigmatism (100% refraction), topographic astigmatism (100% topographic), or any combination of both that totals 100% and leaves the minimum possible remaining.

The Optimal Result

The optimal result of any given customized eye treatment can be determined by employing the following principles:[5,6]

1. Less astigmatism remaining is preferable to more
2. When remaining astigmatism is unavoidable after correction, then a WTR orientation for distance vision is more favorable to an ATR orientation

With the steepest meridian lying vertically, a WTR orientation places the clearest retinal image along this vertical orientation. This is likely to be associated with an increase in visual acuity with vertical strokes dominating the English alphabet.[23] It is probable that any oblique orientation would be least favorable.[6]

VECTOR PLANNING PARADIGM: AN EXAMPLE

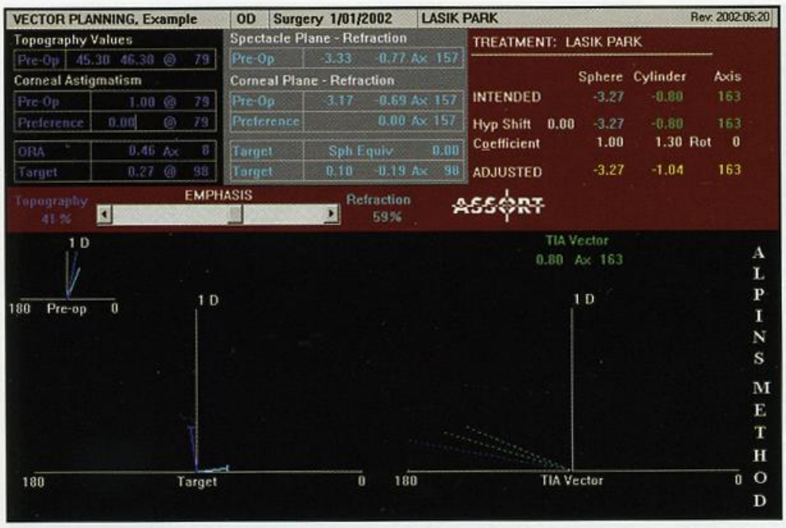
The ASSORT program treatment-planning module (ASSORT Pty Ltd, Australia) is used to illustrate the steps required in the calculation of surgical parameters for the symmetric and orthogonal treatment of astigmatism. This example shows small magnitude changes in conjunction with a minor astigmatism treatment but effectively represents the principles involved in vector planning (Figure 1-5).

Ocular Residual Astigmatism

The vectorial value of ocular residual astigmatism (ORA) refers to the discrepancy that exists between the corneal and refractive astigmatism at the corneal plane. In other words, in cases where a discrepancy exists between corneal and refractive astigmatism, then the ORA represents the amount of astigmatism that cannot be eliminated from the optical system following the photorefractive treatment of astigmatism.[6] The best theoretical outcome or the maximal reduction in astigmatism possible following surgery occurs when the astigmatism remaining is equivalent to the ORA.[5] The astigmatism remaining can be refractive, topographic or any combination of both parameters. By using vector planning to determine the treatment, the surgeon has the ability to chose the proportion of any of the ORA remaining in the theoretical refraction, while reducing the targeted corneal astigmatism.[6]

Planning the Treatment Using Surgical Vectors

The values of measured preoperative refractive and corneal astigmatism are used to generate the optimized treatment plan. Figure 1-6 shows the simulated keratometry val-



VECTOR PLANNING, Example | OD | Surgery 1/01/2002 | LASIK PARK | Rev: 2002:06:20

Topography Values
Pre-Op 45.30 46.30 @ 79
Corneal Astigmatism
Pre-Op 1.00 @ 79
Preference 0.00 @ 79
ORA 0.46 Ax 8
Target 0.27 @ 98

Spectacle Plane - Refraction
Pre-Op -3.33 -0.77 Ax 157
Corneal Plane - Refraction
Pre-Op -3.17 -0.69 Ax 157
Preference 0.00 Ax 157
Target Sph Equiv 0.00
Target 0.10 -0.19 Ax 98

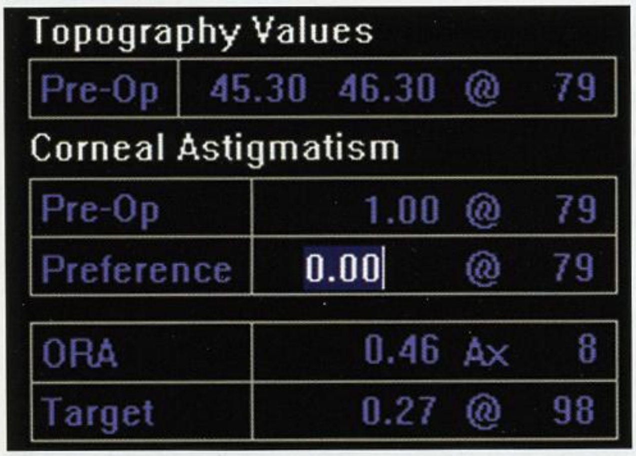
TREATMENT: LASIK PARK

		Sphere	Cylinder		Axis
INTENDED		-3.27	-0.80		163
Hyp Shift	0.00	-3.27	-0.80		163
Coefficient		1.00	1.30	Rot	0
ADJUSTED		-3.27	-1.04		163

Topography 41 %
EMPHASIS
Refraction 59%

TIA Vector 0.80 Ax 163

Figure 1-5. ASSORT treatment planning module. This example displays an optimized plan for the treatment of astigmatism.



Topography Values
Pre-Op 45.30 46.30 @ 79
Corneal Astigmatism
Pre-Op 1.00 @ 79
Preference 0.00 @ 79
ORA 0.46 Ax 8
Target 0.27 @ 98

Figure 1-6. Topography: preoperative measurements and postoperative goals. As seen in Figure 1-5, the top left-hand side of the ASSORT screen shows the pre-operative corneal astigmatism extracted from the corneal topography, the preferred spherical outcome, the ORA, and the target corneal values.

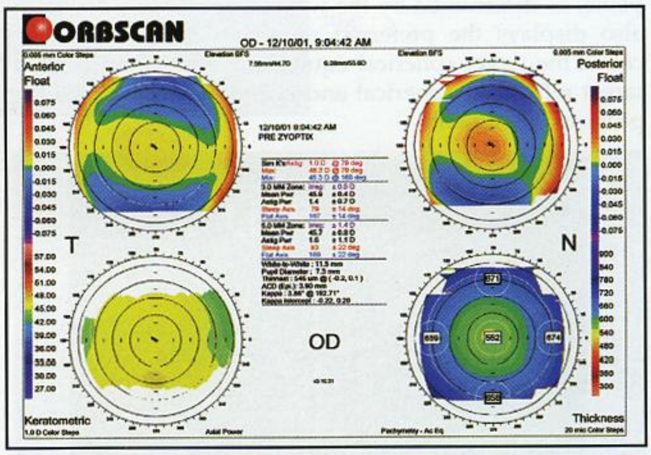


Figure 1-7. Vector-planning example: preoperative topography data. This Orbscan (Bausch & Lomb, Rochester, NY) indicates the preoperative corneal topography illustrated in the vector-planning example.

ues as determined by topography (Figure 1-7), the preference for remaining corneal astigmatism and target values. Figure 1-8 displays the refractive values, preferences, and targets as determined by manifest refraction or a wavefront analysis device (Figure 1-9). The preoperative refraction data is converted to the corneal plane for planning and analytical purposes. The facility also allows for a nonzero spherical equivalent to be targeted postoperatively.

A polar display of these preoperative measurements is displayed in Figure 1-10, the preoperative astigmatism for topography (dark blue line) of +1.00 D at a meridian of 79 degrees and refractive astigmatism of +0.69 D at 67 degrees being the power axis of the negative cylinder (light blue line).

Determining Surgical Emphasis

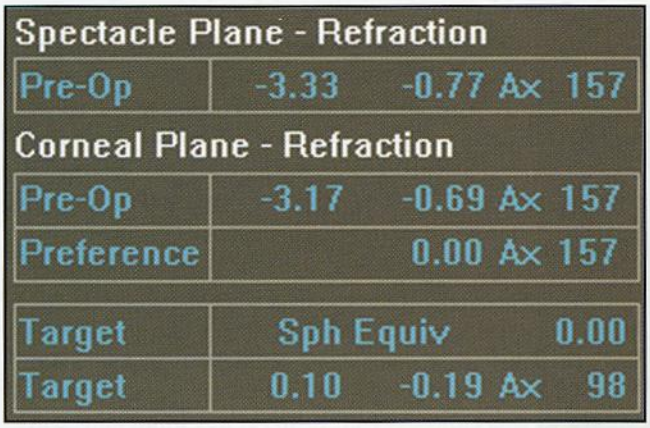
The surgical emphasis bar defines the relative treatment preferences for a spherical cornea, spherical refraction, or any treatment at an intermediate point to these extremes. This adjustment apportions the ORA that is to be corrected in the corneal and refractive modalities.

100% Correction of Refractive Astigmatism

Although, a spherical refraction will be achieved at this treatment emphasis, the topographic target will be at its maximum level and equivalent to the ORA but at 90 degrees to it in order to neutralize it. In this case, +0.46 D at a meridian of 98 degrees (Figure 1-11).

100% Correction of Corneal Astigmatism

Despite a spherical equivalent of zero and a resultant spherical cornea, such treatment emphasis will result in a



Spectacle Plane - Refraction

Pre-Op	-3.33	-0.77 Ax 157

Corneal Plane - Refraction

Pre-Op	-3.17	-0.69 Ax 157
Preference		0.00 Ax 157
Target	Sph Equiv	0.00
Target	0.10	-0.19 Ax 98

Figure 1-8. Refraction: preoperative measurements and postoperative goals. As displayed in Figure 1-5, the central top section of the ASSORT screen shows the preoperative refraction data converted from the spectacle to the corneal plane, as determined by the wavefront analysis device. It also displays the preferred refractive astigmatism outcome, the target spherical equivalent, and the calculated target refractive (spherical and cylindrical) values for the proposed treatment.

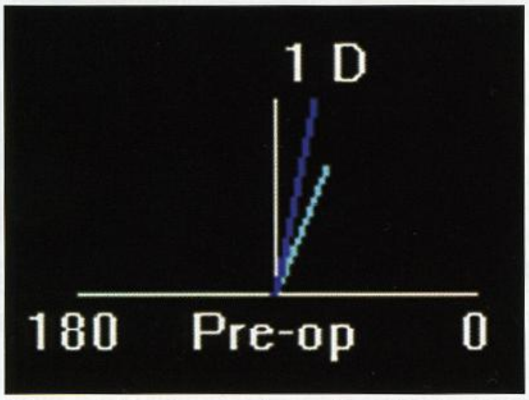


Figure 1-10. Preoperative polar display. The polar display of preoperative corneal astigmatism (dark blue line) and refractive astigmatism (light blue line) at the power axis of negative cylinder values

refractive target of sphere +0.23 D, cylinder -0.46 D, and axis 98 degrees (Figure 1-12).

THE OPTIMAL RESULT

A treatment emphasis of 41% corneal astigmatism and 59% refractive astigmatism provides a surgical balance of the 2 targeted zero-astigmatism goals. The resultant topographic target is +0.27 D at a meridian of 98 degrees and a refraction target of sphere +0.10 D, cylinder -0.19 D at an axis of 90 degrees (Figure 1-13).

Target Induced Astigmatism Vector

The target induced astigmatism vector (TIA) describes the amount and orientation of dioptric steepening force required to achieve a desired astigmatic goal. Its axis coincides with the meridian of maximum ablation and relative steepening effect. Figure 1-14 shows the TIA necessary to achieve the astigmatic results targeted in Figure 1-13. To achieve a zero-refractive astigmatism target (light blue line) a TIA of 0.69 D Ax 157 would be required. Conversely, a TIA of 1.00 D Ax 169 is required to achieve a zero topographic target (dark blue line). The green line displays the TIA required to achieve the proposed astigmatic treatment that lies at an intermediate point between the corneal and refractive extremes. The magnitude of the astigmatic treatment is 0.80 D at a maximum ablation meridian of 163 degrees.

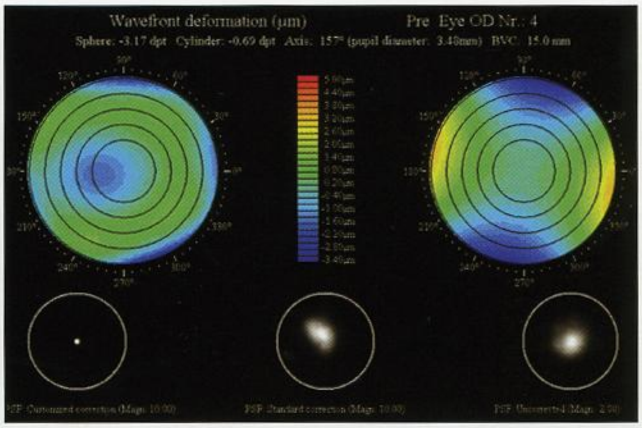


Figure 1-9. Vector planning example: preoperative refraction data. This figure exhibits the preoperative spherocylindrical error and point-spread function as determined by a wavefront analysis device.

The maximum correction of astigmatism is achieved at all positions of treatment emphasis (0% to 100%) using this method of vector planning. Any remaining topographic or refractive astigmatism is at a minimum and orientated at 90 degrees to each other, when their sum is equivalent to the ORA.

Where possible, excessive corneal astigmatism (above 0.75 D) should be avoided by moving the emphasis left towards the full topography correction. Moving the maximum treatment closer to the principal flat corneal meridian can assist in minimizing lower order aberrations. In instances where the ORA is in excess of 1.50 D, due to larger differences between corneal and refractive values, it is advisable to share this load between the cornea and refraction by placing the emphasis at the midpoint (50%). A recent study showed that 33% of eyes have an ORA greater than 1.00 D, and 7% have an ORA greater than the preoperative astigmatism therefore resulting in an increase in corneal astigmatism postoperatively if refractive treatment parameters are used exclusively.[5]

Determination of Treatment

The treatment required to achieve the desired corneal and refraction targets is displayed by the ASSORT nomogram

ORA	0.46 Ax 8	Target	Sph Equiv 0.00
Target	0.46 @ 98	Target	0.00 0.00 Ax 157

Topography 0 %
EMPHASIS
Refraction 100%

Figure 1-11. Surgical emphasis: 100% correction of refractive astigmatism.

ORA	0.46 Ax 8	Target	Sph Equiv 0.00
Target	0.00 @ 79	Target	0.23 -0.46 Ax 98

Topography 100 %
EMPHASIS
Refraction 0%

Figure 1-12. Surgical emphasis: 100% correction of topographic astigmatism.

ORA	0.46 Ax 8	Target	Sph Equiv 0.00
Target	0.27 @ 98	Target	0.10 -0.19 Ax 98

Topography 41 %
EMPHASIS
Refraction 59%

Figure 1-13. Surgical emphasis: optimal result with minimum astigmatism remaining.

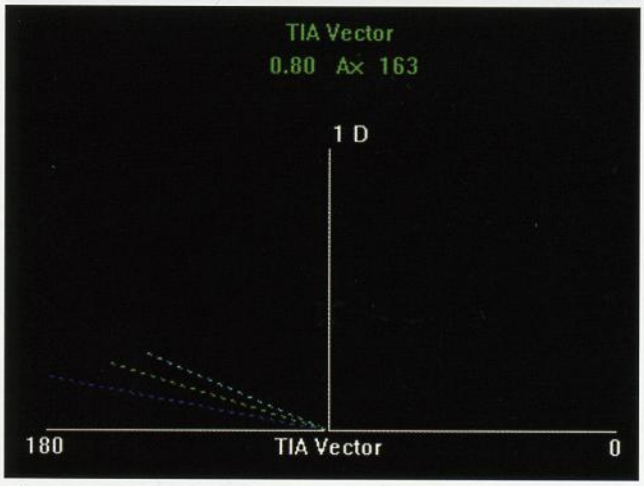


Figure 1-14. TIA polar diagram: optimal result. The treatment (TIA) vector (light green) applied to this eye lies between the treatment required to sphericize the refraction (light blue) or to sphericize the cornea (dark blue). In this example, the TIA lies closer to the refractive astigmatism correction line.

TREATMENT: LASIK PARK

		Sphere	Cylinder	Axis
INTENDED		-3.27	-0.80	163
Hyp Shift	0.00	-3.27	-0.80	163
Coefficient		1.00	1.30 Rot	0
ADJUSTED		-3.27	-1.04	163

Figure 1-15. Treatment. The intended treatment at the corneal plane comprises the spherical treatment required to achieve a zero spherical equivalent and the astigmatism treatment (TIA). The adjusted treatment, which will be applied to the cornea, has been modified for any spherical shifts or spherical and astigmatic nomogram adjustments.

adjustment table (Figure 1-15). The intended treatment should be mathematically adjusted according to the laser type used for the ablation, its manufacturers recommendations or the surgeon's previous experience and other prevailing conditions.

Following allowances for spherical shifts as a consequence of astigmatism changes, and nomogram adjustment for under- or overcorrection, an adjusted treatment appears detailing the corneal plane treatment plan. In this example, the nomogram adjustments, based on past experience, allow for a full correction of sphere and 30% of commonly found astigmatic undercorrection.

By using this approach of targeting less overall resultant corneal astigmatism, the optimization process can provide an advantageous surgical outcome without increasing the resultant refractive astigmatism present.

ANALYSIS OF ASTIGMATIC OUTCOMES

Examination of surgical outcomes following treatments for astigmatism is an essential step in ascertaining the success of individual treatments and for the further development and refinement of treatment nomograms.[5] Fine adjustments in surgical nomograms may be necessary for under and overcorrections of sphere and cylinder and for the associated spherical shifts that accompany astigmatic treatments. Such surgical technique or systematic laser errors can be determined from the analysis of aggregate data.[7]

Concepts and Terms of Analysis

The effectiveness of astigmatism surgery can be determined from the relationships between 3 fundamental vector quantities—the TIA, surgically induced astigmatism vector (SIA) and the difference vector (DV).[6,7]

The TIA, as mentioned previously, is the astigmatic change (magnitude and orientation) intended from surgery. The SIA, reflects the magnitude and orientation of corneal steepening that has been induced by surgery. When the SIA equals the TIA in both magnitude and orientation, the surgical astigmatic goal has been achieved. In cases where this has not been accomplished, the DV represents the astigmatic change that would be required to allow the initial surgery to achieve its target.[6,7]

The effectiveness of the astigmatic treatment can be gauged by comparing individual vector relationships to the TIA. The index of success (IOS) is a relative measurement of success that relates the magnitude of the difference vector to the magnitude of the TIA. Ideally, the IOS is zero. The correction index (CI) is the ratio of the SIA to the TIA. In situations where the CI is greater than 1.0, an overcorrection has occurred, whereas, a CI less than 1.0 indicates that an undercorrection has resulted. The inverse of the CI is the coefficient of adjustment (CA). When resolved from aggregate analysis, the CA can be used to gauge if any modifications to the surgical nomograms are required.[6,7]

Furthermore, arithmetic differences between the SIA and TIA can be calculated. The magnitude of error (ME) is the discrepancy between the magnitude of the SIA and the TIA. A positive ME indicates an overcorrection, while a negative ME an undercorrection. The angle of error (AE) quantifies the difference between the angle of the achieved correction compared to the angle of the intended correction. A positive AE implies that the achieved correction falls on an axis counterclockwise to the intended orientation while conversely, a negative AE denotes an achieved correction in clockwise orientation from that which was intended.

Single Patient Analysis: An Example

It is valuable to perform parallel analysis of astigmatism outcomes, using all measurement methods. This assists the establishment of valid trends of relative success, error, and adjustment so the effectiveness of the astigmatic procedure can be analyzed in detail. This is particularly useful in comparing aggregate outcomes and in calculating retreatment parameters.

Postoperative results are shown by topography (Figure 1-16) and wavefront analysis (Figure 1-17). The corresponding corneal and refractive analyses for this individual data are calculated at the corneal plane using the ASSORT outcomes analysis program as displayed in Figures 1-18 and 1-19 respectively.

The treatment used in this example was determined with a surgical emphasis of 100% refraction, in order to achieve a plano refraction. That is, the astigmatic treatment TIA is 0.69 x 157 intending to induce 0.69-D steepening along the 157 degree corneal meridian to achieve a refractive astigmatic target of 0.00 D. The corneal target under these circumstances is 0.46 D at 98 degrees changed from a preoperative value of 1.00D at 79 degrees. From the resultant pre- and postoperative data the SIA can be determined. This vectorial change between these astigmatism values is 0.31 D (corneal) and 0.39 D (refractive).

The analysis display generated using the ASSORT program contains 3 graphical representations while the tabulated data within Figures 1-18 and 1-19 shows the AE, ME, CI, and IOS. Refractive and corneal analysis both show that there has been an undercorrection of astigmatism. This is evidenced in the CI values of 0.56 for refraction and 0.45 for topography. Although refractive data indicates that the treatment was 26 degrees off axis, the comparative topographic data shows a smaller 5-degree angle of error. The IOS for both data sets demonstrates that an improvement in astigmatism status was achieved.

IRREGULAR ASTIGMATISM

The development of highly sophisticated diagnostic equipment, including CAVK and wavefront aberrometry analysis devices, has highlighted a higher prevalence of corneal irregularity existing within the population. Even individuals with otherwise "normal" eyes may exhibit some degree of irregularity.[3]

In addition to differences between refractive and corneal astigmatism, irregularity may exist across the corneal hemidivision either as a difference in dioptric magnitude (asymmetry) or orientation (nonorthogonal) or both.[2] The vectorial value of TD is a valuable tool for quantifying corneal irregularity. Topographic disparity represents the dioptric separation between the 2 corneal hemidivisions as displayed on a 720-degree double-angle vector diagram (DAVD). Significant irregularity is present cases where the TD is greater than 1.00 D and occurs in approximately 44% of eyes with treatable astigmatism.[2,3]

The theory behind vector planning can be applied with increased complexity to predetermine separate surgical plans and unique TIAs for each hemidivision. Despite the treatment options for irregular astigmatism having expanded with the advent of tailored corneal excimer laser ablations,

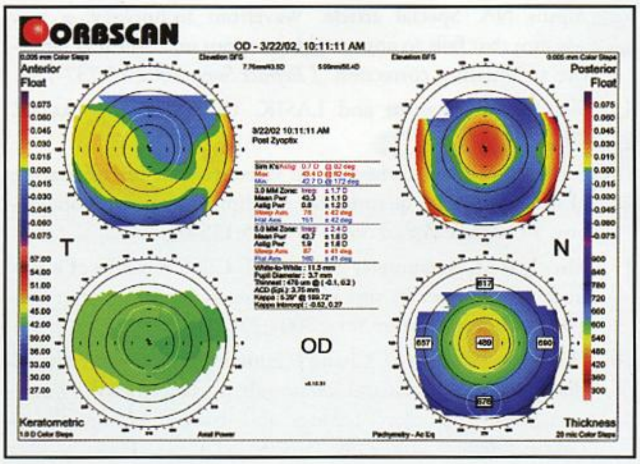


Figure 1-16. Vector planning example: postoperative topography data. This postoperative topography result is analyzed as part of the vector-planning example.

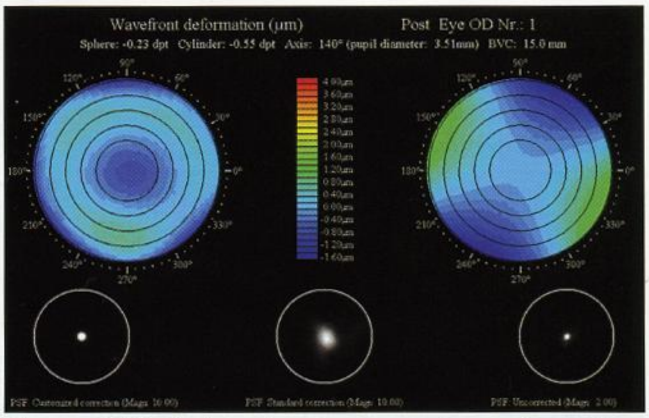
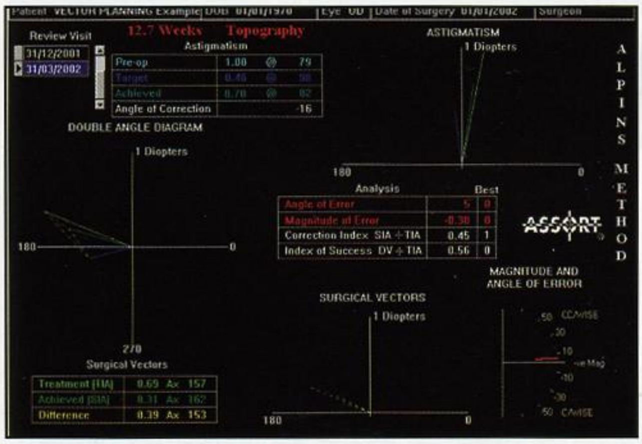


Figure 1-17. Vector planning example: postoperative refraction data. The refraction data for analysis has been determined from postoperative wavefront analysis.



Astigmatism

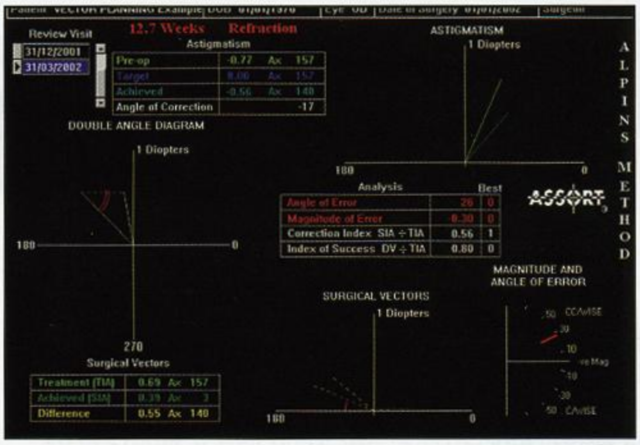
Pre-op	1.00	@	79
Target	[illegible]	@	[illegible]
Achieved	0.70	@	82
Angle of Correction			-16

Analysis		Best
Angle of Error	5	0
Magnitude of Error	-0.30	0
Correction Index SIA ÷ TIA	0.45	1
Index of Success DV ÷ TIA	0.56	0

Surgical Vectors

Treatment (TIA)	0.69 Ax 157
Achieved (SIA)	0.31 Ax 162
Difference	0.39 Ax 153

Figure 1-18. Individual analysis topography using ASSORT and the Alpins' method.



Astigmatism

Pre-op	-0.77	Ax	157
Target	0.00	Ax	157
Achieved	-0.56	Ax	140
Angle of Correction			-17

Analysis		Best
Angle of Error	26	0
Magnitude of Error	0.30	0
Correction Index SIA ÷ TIA	0.56	1
Index of Success DV ÷ TIA	0.80	0

Surgical Vectors

Treatment (TIA)	0.69 Ax 157
Achieved (SIA)	0.39 Ax 3
Difference	0.55 Ax 140

Figure 1-19. Individual analysis refraction using ASSORT and the Alpins method.

the patterns required for customized asymmetrical toric ablations are not yet readily available. The challenge exists to apply different treatments over 2 corneal hemidivisions while maintaining a smooth transitional zone over this ablated surface.[3]

Such asymmetrical treatments can be applied with the aim of[2,3]:

1. Reducing or rearranging the existing astigmatism
2. That is, the least favorable corneal meridian may be rotated toward the more favorable meridian to obtain alignment topographically. Alternatively this may be achieved by changing both in opposite cyclical directions without necessarily needing to alter the overall refractive state
3. Reducing the magnitude of remaining astigmatism and its meridian
4. Providing a combination of the above-listed objectives to obtain the minimum amount of regular astigmatism remaining

The ability to treat irregular astigmatism in such a way provides the potential to improve both best-corrected and unaided visual acuities while significantly enhancing overall visual performance.[2,3]

CONCLUSION

It is important to consider and address differences between corneal shape and function to maximize the visual potential of the eye's optical system and improve visual results after photorefractive surgery. These differences in astigmatic status may occur between manifest refraction and keratometry or wavefront analysis and corneal topography or all of these. Therefore, addressing this conflict using vector planning may provide a method of developing improved customized treatment plans. Furthermore, the analysis of astigmatism results using vector analysis can help surgeons compare outcomes and develop more accurate nomograms for the effective treatment of astigmatism.

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Note: Dr. Alpins has a proprietary interest in the ASSORT program used in this chapter for calculating and displaying treatment and analysis of astigmatism parameters.