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Measuring Astigmatism
Planning Surgery and Tracking Results

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Measuring Astigmatism

Limbal relaxing incisions (LRIs) are used to change the shape of the cornea and reduce astigmatism both on the cornea and in the resulting refractive cylinder. Numerous clinical devices are available to determine corneal and refractive astigmatism values. Both modes of measurement—corneal and refractive—may be assessed and considered when determining the amount of astigmatism that needs to be reduced and at which meridian to place the LRIs.

Topography Systems

Corneal topography, which uses computer-assisted video keratography (CAVK), measures and calculates 8000 to 10,000 points on the anterior corneal surface to determine elevation and power. Many topographers also measure the posterior corneal surface. This permits the determination of regional corneal thickness, as well as the posterior corneal shape, so that irregular conditions and ectasias can be detected. The simulated keratometry (Sim K) gauge of astigmatism is calculated using the central 3-mm region of the cornea. This parameter was introduced in the 1980s to parallel manual keratometry readings. The more recent description of corneal topographic astigmatism now provides a more accurate means to quantify corneal astigmatism.[1]

Corneal topography is an essential component to the work-up and assessment of the astigmatic surgical candidate for both the measurement of cylinder and for the detection of subtle pathology, such as keratoconus or pellucid marginal degeneration; conditions that might preclude the use of incisional surgery, such as LRI procedures.

Manual Keratometry

Corneal curvature using traditional manual keratometry entails measurement at only 4 points *within 3 to 4 mm of the central anterior corneal surface. Distortion of the keratometry mires indicates corneal irregularity—the greater the distortion of the mires, the greater the corneal unevenness.*

Nichamin LD.
Limbal Relaxing Incisions: A Practical Guide (pp 15-25).

Manifest Refraction

The manifest refractive cylinder represents a subjective means of measurement. It incorporates perceptual astigmatism, as well as whole eye astigmatism. In many cases, the refractive cylinder will be different in magnitude and/or orientation to the corneal astigmatism; however, in the case of planning LRIs, the surgeon may want to base the surgical parameters on a combination of both. The manifest refractive cylinder is usually expressed in steps of 0.25 diopters (D).

Wavefront Refraction

Wavefront (aberrometry) refraction is an ocular measurement of astigmatism, independent of subjective and central neural processing. Although the second-order spherocylinder can be measured in 0.01-D steps, utilizing this modality, compared with 0.25-D steps in manifest refraction, must correlate closely with the manifest refraction for both spherical and astigmatic components before its accuracy can be confirmed.

To achieve high accuracy with wavefront measurements, it is important to avoid excess accommodation. To this end, the patient should avoid near work for approximately 15 minutes before a measurement is taken, and it is preferable to spend this period of time in a darkened room to promote pupillary dilation, thereby maximizing the detection of higher-order aberrations.

Regardless of which measurement is adopted for clinical use, it is recommended that the same instrument be used to measure both the preoperative and the postoperative parameters for analysis. Ideally, it is also recommended that the same clinician or technician perform these measurements.

Planning Surgery

The planning of LRI procedures performed at the time of cataract surgery is best based on and more highly weighted toward corneal parameters. Measures of manifest or wavefront refractive astigmatism may not be accurate due to the coexisting cataract, and subsequent removal of the natural crystalline lens of the eye will impact the final refractive outcome. Furthermore, the amount of corneal astigmatism requiring correction and its orientation must take into account the induced effect of the phaco incision. This can most accurately be determined by analyzing previous phaco incisions of the same size and calculating a mean flattening effect at the appropriate corneal meridia around the eye (Figure 2-1).

Different techniques can be applied when LRIs are used to correct corneal astigmatism:

1. **Using the Phaco Incision as One of the Pair of LRIs.** With this method, the position of the phaco incision will vary, depending on the steep meridian of the preoperative corneal astigmatism. The phaco incision needs to "mimic" the effect of the opposing LRI. Therefore, it will need to be made wider and, in some cases, be positioned slightly more centrally to gain a more pronounced flattening effect than typically induced when phaco incisions are used solely to remove the natural lens or to insert an intraocular lens (IOL).

   The LRI will then be placed 180 degrees away from this phaco incision. It is recommended that the LRI be performed prior to the phaco incision, as the eye is firmer at this stage, thereby allowing for a more accurate length and depth of the LRI.

   With this technique, there is no need to allow for any "off-axis" effects[2] due to the phaco incision—the phaco incision is positioned precisely on the steep corneal meridian.

   The theoretical reduction effect is calculated arithmetically when placed at the steep meridian (Figure 2-2). This technique requires 2 incisions in total.

2. **Using a Phaco Incision Together With Paired LRIs.** Placing a phaco incision away from the steepest corneal meridian will have an "off-axis" rotational effect on the preoperative corneal

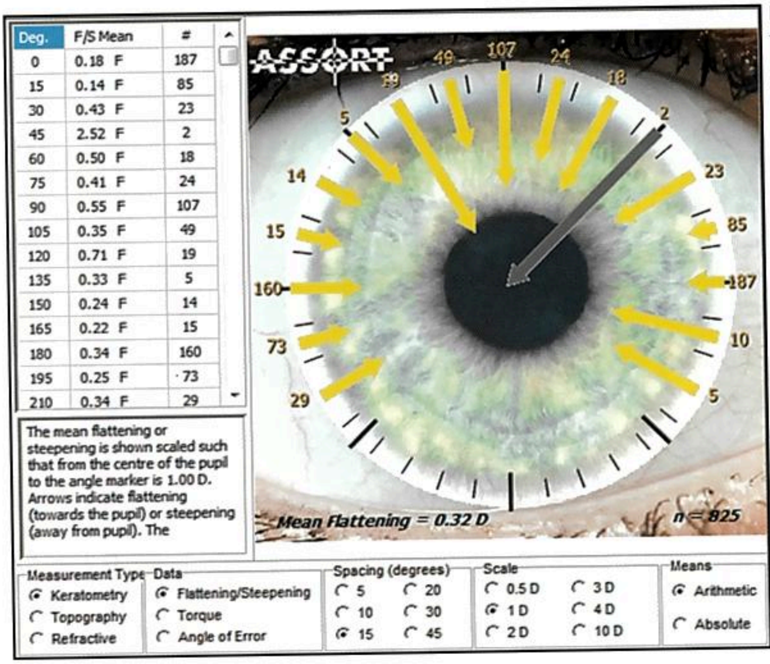

Figure 2-1. Display of the flattening effect by keratometry of 2.2-mm phaco incisions for both the left and right eyes where the incision is placed at the steepest corneal meridian. The varying sizes of the arrows indicate the varying amounts of flattening—the longer the arrow, the greater the flattening.

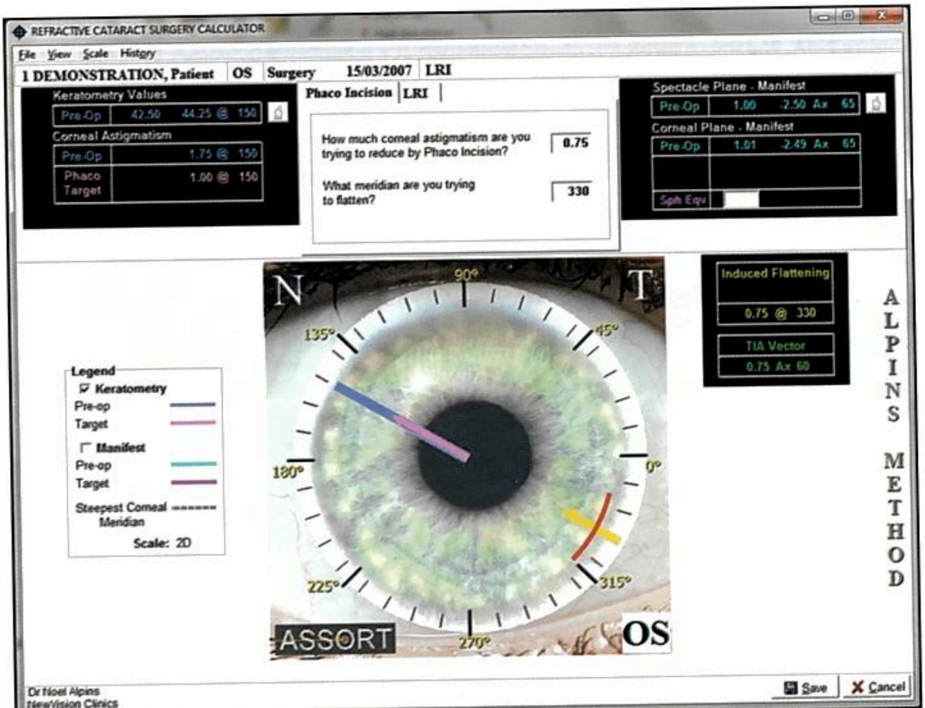

Figure 2-2. The phaco incision is placed on the steepest corneal meridian at 150 degrees, thus reducing the corneal astigmatism from the preoperative amount of 1.75 to 1.00 D. The red line indicates phaco incision and the yellow line is the amount of associated flattening. Abbreviation: N, nasal; T, temporal.

astigmatism (Figure 2-3A). This must be taken into account when planning for the effect required from the additional pair of LRIs and their positioning (Figure 2-3B). This technique requires a total of 3 incisions.

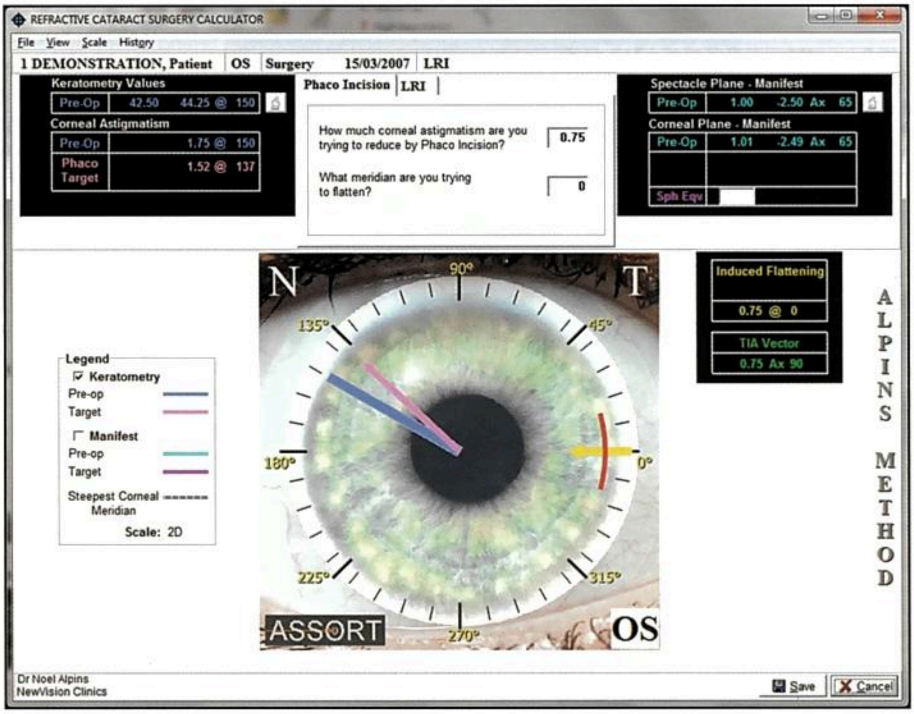

Figure 2-3A. The phaco incision is placed temporally at a meridian of 0 degrees, reducing the preoperative corneal astigmatism of 1.75 to 1.52 D. Note that the steepest corneal meridian has now rotated 13 degrees from 150 degrees clockwise to 137 degrees. Abbreviations: N, nasal; T, temporal.

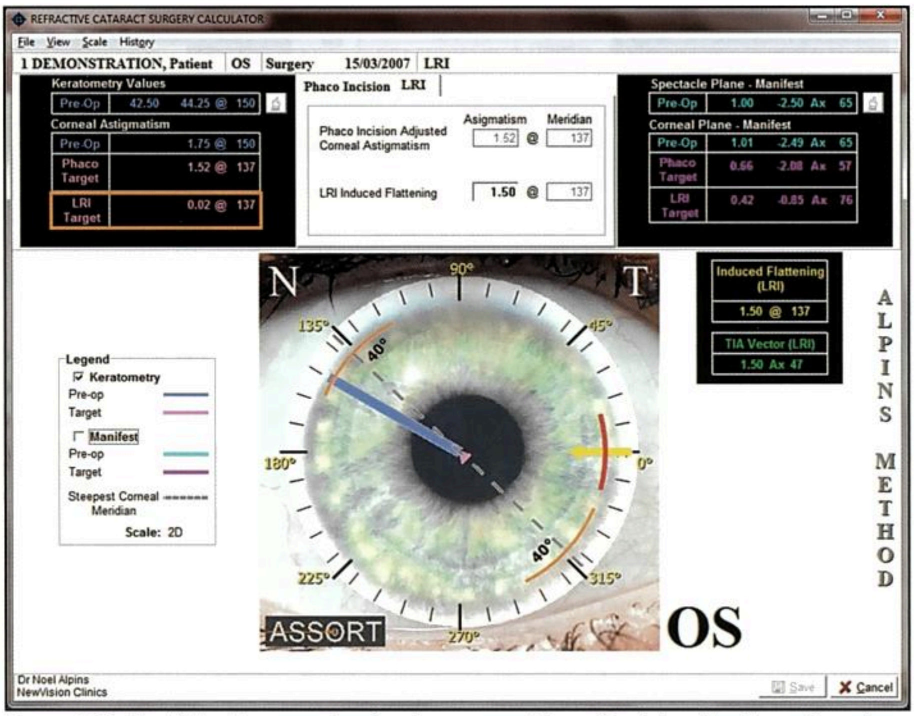

Figure 2-3B. The LRI incisions are placed at the steep meridian of the (phaco) incision-adjusted corneal astigmatism at 137 degrees, instead of the preoperative steep meridian of 150 degrees. The red line indicates phaco incision, the yellow line is the amount of associated flattening, and the orange lines indicate the LRI incisions. Abbreviations: N, nasal; T, temporal.

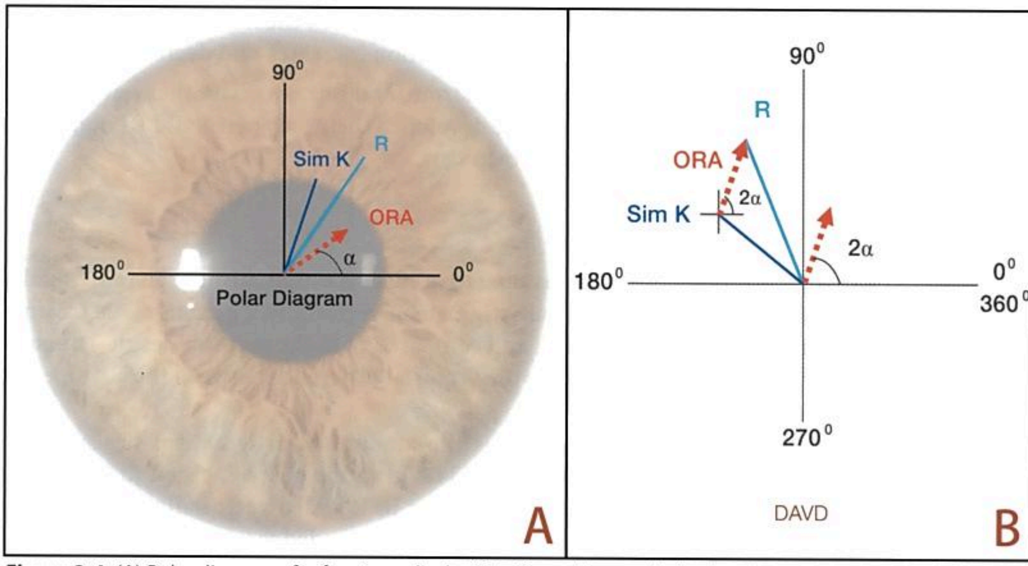

Figure 2-4. (A) Polar diagram of refractive cylinder (R in figure) (corneal plane) at its positive axis, simulated keratometry steep meridian and ORA as they would appear on the eye. (B) Double-angle vector diagram (DAVD) showing a "doubling" of both the positive cylinder axes without a change in the astigmatic magnitudes.

3. **Paired LRIs Not Associated With a Phaco Incision.** If the natural lens of the eye is clear and will not be removed and if correction of the total astigmatism of the eye is required, then both the corneal and refractive astigmatism (corneal plane) can be considered when planning the effect of the LRIs; the most effective magnitude and position of the LRI will lie somewhere between the 2 corneal and refractive astigmatisms. Using this optimization method, it is important to calculate ocular residual astigmatism (ORA) preoperatively. The ORA is the vectorial difference between the corneal astigmatism and the refractive cylinder at the corneal plane and is expressed in diopters (Figure 2-4).[3,4] The greater the ORA, the more astigmatism will be left uncorrected postoperatively in the optical system of the eye, regardless of how precisely the procedure was performed. A routine assessment of the ORA preoperatively allows the surgeon to advise the patient accordingly on the expected visual outcome. If the ORA is high (>1.00 D), depending on the amount of preoperative astigmatism, the visual outcome may not meet the patient's expectations. Therefore, the patient should be advised accordingly prior to surgery so that he or she is able to achieve realistic expectations regarding the likely outcome of surgery.

Limbal Relaxing Incision Nomograms

A number of nomograms currently exist that determine the length of the LRIs:

1. *The NAPA (Nichamin Age and Pachymetry-Adjusted) Nomogram* (Dr. Louis D. "Skip" Nichamin) in which the length of the incision decreases with age and increases with the magnitude of astigmatism requiring correction.
2. *The DONO Nomogram* (Dr. Eric D. Donnenfeld) in which the length of the incision increases with increasing magnitude of astigmatism correction.
3. *The Gills LRI Nomogram* (Dr. James P. Gills) titrates surgery by the length and number of LRIs.

4. *The Wallace LRI Nomogram* (Dr. R. Bruce Wallace III) in which the number of LRIs and their length increases as the amount of astigmatism correction increases and decreases with age.

Many other surgeons, such as Drs. Thornton, Lindstrom, and Buzzard, have their own variation of one of these commonly used nomograms or have developed their own personal LRI nomograms determined from retrospective analyses of their own data.

Tracking Results

To analyze LRI astigmatic outcomes, the postoperative corneal astigmatism of an individual eye must be compared with its preoperative corneal astigmatism vectorially. The astigmatic treatment intended by the LRIs must be known, recorded, and compared with the vectorial result—the surgically induced astigmatism vector (SIA), which is the vectorial difference between the postoperative and preoperative corneal astigmatism.

The target-induced astigmatism vector (TIA) is the amount of astigmatism the surgeon is attempting to correct, using either paired LRIs or the TIA from the phaco incision (if this is being used as one of the LRIs) plus the TIA from the opposing LRI, added vectorially. The difference vector is the correction that would be required to achieve the intended target of the initial surgery. If the initial surgery is successful, then the difference vector is zero.

The various relationships between these 3 vectors form the basis of the Alpins method and allow for a basic analysis that determines whether the astigmatism was overcorrected or undercorrected and whether the treatment was on- or off-axis.[5-7]

Correction Index

The correction index (CI) is the amount of astigmatism correction achieved. It is calculated by dividing the SIA by the TIA; the ideal value is 1.0. Correction index values greater than 1.0 indicate an overcorrection, and values less than 1.0 indicate an undercorrection.

Angle of Error

The angle of error (AE) is the angle between the TIA and the SIA on a polar diagram. The AE is positive if the SIA is counterclockwise to the TIA, and it is negative if the SIA is clockwise to the TIA.

Magnitude of Error

The magnitude of error (ME) is the arithmetic difference between the magnitudes of the SIA and the TIA. ME is positive for an overcorrection and negative for an undercorrection.

Index of Success

The index of success (IOS) is calculated by dividing the difference vector by the TIA. The IOS is a relative measure of success. It takes into account the targeted amount of astigmatism correction preoperatively. Ideally, when the target is achieved at the first application of a corrective procedure, the IOS is zero.

Coefficient of Adjustment

The coefficient of adjustment (CA) is the factor required to adjust future astigmatism treatment magnitudes and is calculated by dividing the TIA by the SIA. Ideally, the value is 1.0; it is the inverse of the CI. The CA of 1.0 is the nomogram adjustment that is applied to either the angular length of the arcuate incisions or to the position (optical zone) of the arcuate incisions relative to the center of the cornea.

Flattening Effect

The flattening effect (FE) of the phaco incision must be calculated over time to improve accuracy. This is done by using a double-angle vector diagram (DAVD), where the effect of the SIA on

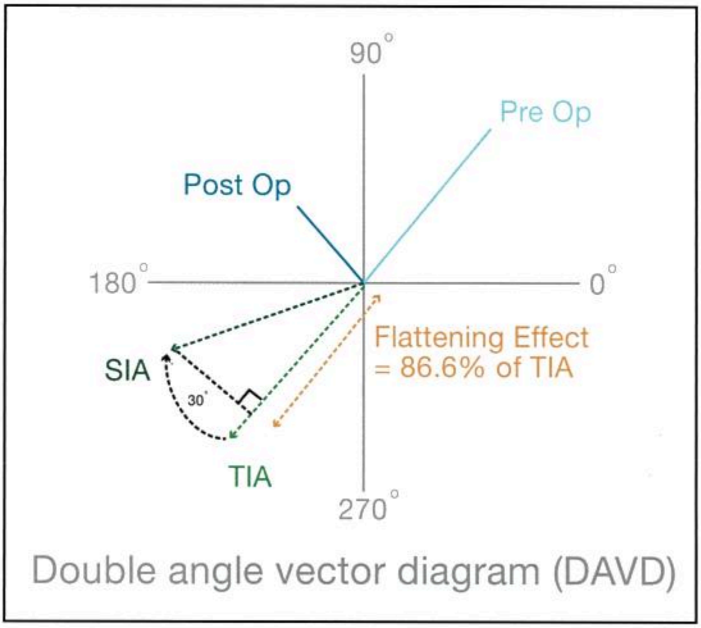

Figure 2-5. The FE demonstrates the effect of the SIA at the intended astigmatic treatment meridian when misaligned by 15 degrees and is expressed in diopters with a loss of effect of 13.4%.

the TIA axis is calculated using trigonometric principles (Figure 2-5). The DAVD is then converted to a polar diagram to display how the FE would appear on an eye. The average flattening for any particular meridian can then be used for future phaco procedures to determine the expected effect on the preoperative corneal astigmatism at that position on the cornea.

The FE is defined as: FE = SIA cos 2.AE[2,6]

Individual Outcomes

A single LRI procedure can be analyzed using vector analysis; however, no nomogram adjustment can be performed without aggregating data from multiple eyes. A one-by-one case analysis can determine the magnitude of the additional astigmatic treatment required and can determine at what meridian any further surgical enhancement should occur, as well as the relative success indicators of any one procedure.

Astigmatism Sign Convention

To assist with the following examples, it is useful to be aware of sign convention as it applies to astigmatism and vectors.

The convention sign "@" refers to the steep corneal meridian and the greatest power. The "Ax" or "x," representing the axis notation, refers to a position 90 degrees away from the steep corneal meridian, which is zero or the least refractive power of a cylindrical lens, such as the negative cylinder axis in a manifest refraction. Vectors, which must always be positive, are aligned with this negative cylinder axis, so their notation is always "Ax" and never "@." An incision that flattens the steep meridian and an ablation that steepens the flat meridian 90 degrees away will share the same TIA (treatment vector) axis because they are having the same net astigmatic effect.

For example, we assume a scenario where the preoperative corneal astigmatism has been measured as 2.50 D Ax 68 (minus cylinder) in the left eye, and the LRI procedure has been planned to correct 2.00 D of this astigmatism. The analysis is based on a resultant target of 0.50 D corneal astigmatism as the aim of this corrective procedure.

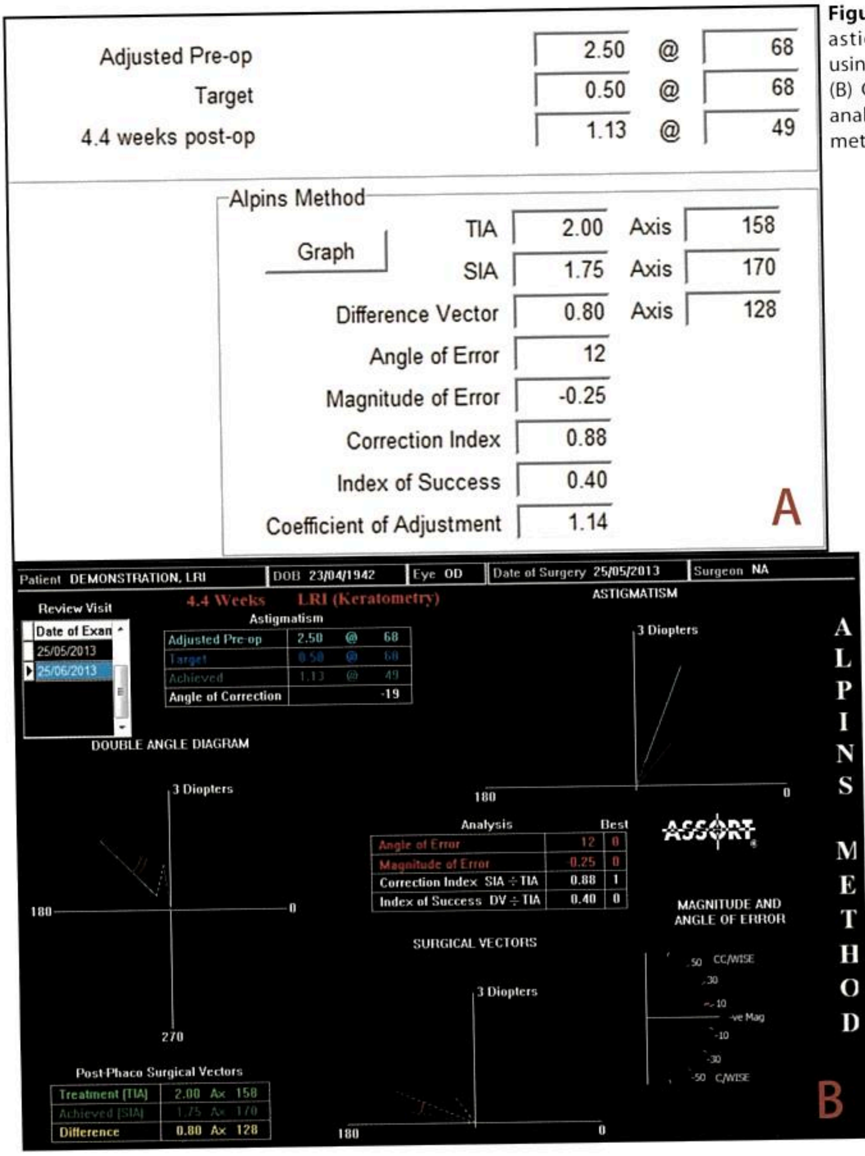

Figure 2-6. (A) Numerical astigmatism analysis using the Alpins method. (B) Graphical astigmatism analysis using the Alpins method.

The achieved (postoperative) corneal astigmatism is measured at 1.13 D @ 49.

Figure 2-6A displays the numerical astigmatism analysis and Figure 2-6B shows the graphical astigmatism analysis, using the Alpins method for the previous example.

The TIA is 2.00 D, which is the planned correction of the LRIs. It is at an axis of 158 degrees, that is, 90 degrees away from the planned meridian to be flattened, as vectors create a steepening change.

The SIA was calculated to be 1.75 D Ax 170.

Did the LRI Procedure Over- or Undercorrect the Astigmatism?

This is determined by calculating the CI as CI = SIA/TIA = 1.75/2.00 D = 0.88. The astigmatism was therefore undercorrected by 12%.

Were the LRIs On- or Off-Axis?

This can be determined by using the AE between the TIA and the SIA. In the previous example, it is 12 degrees counterclockwise. The LRIs were planned to be at 68 degrees, but postoperative analysis determine that they were in fact functionally placed at 80 degrees.

The FE of this LRI procedure is 1.61 D Ax 158, which is less than the intended effect of 2.00 D (TIA). It is also less than the SIA, as it is off-axis by 12 degrees, causing loss of effect.

Aggregate Outcomes

Aggregate Analysis Data

When adjusting nomograms, it is important to have at least 50 cases, with 3-month postoperative data that can be analyzed. This is to ensure that any trends observed are statistically valid and consistent, and the effect of isolated outliers is minimized. Two types of analysis are relevant:

1. Arithmetic means: astigmatism vector magnitudes are averaged, irrespective of their orientation.
2. Summated vector means (SVM): head-to-tail summation of vectors.

Systematic errors can be gauged by comparing the SVM and the arithmetic mean magnitudes. The greater the difference between the arithmetic and the SVM's magnitudes, the more likely it is that the changes occurring are a result of random events. A ratio above 0.6 and close to 1.0 indicates that the trend achieved by the surgery is consistent and predictable.

Non-Zero Targets

When analyzing outcomes of LRIs, one must consider the difference between preoperative corneal astigmatism and the amount of astigmatism the procedure is able to correct. Note that it is the intended corneal astigmatism that the procedure will correct, so if the nomogram used indicates that only 1.50 D and not 2.00 D of astigmatism can be corrected by using a particular degree of arc, the analysis should be based on a non-zero astigmatic target of 0.50 D. The nomogram is calculated on the amount of astigmatism intended and not on what might have been unrealistically desired.

Misalignment of Limbal Relaxing Incisions

If an LRI is misaligned with the intended meridian, the cause for the loss of astigmatic effect may be misleading when calculated vectorially. A misalignment of 15 degrees will actually result in a 13.4% loss in the astigmatic effect of the treatment; a 30-degree misalignment will result in a loss in astigmatic effect of 50%.[2] This can be demonstrated by postoperatively measuring the astigmatism at the same intended preoperative treatment meridian and NOT at the postoperative steep meridian. This measurement is acquired by using a keratometer and comparing this *measured value* to the preoperative astigmatism at its meridian (Figure 2-7). Note that this is a magnitude-only comparison. Complete loss of effect occurs at 45 degrees off axis. At this position, the SIA, which is still prevailing, is acting wholly as torque; it rotates the astigmatism rather than reducing it.

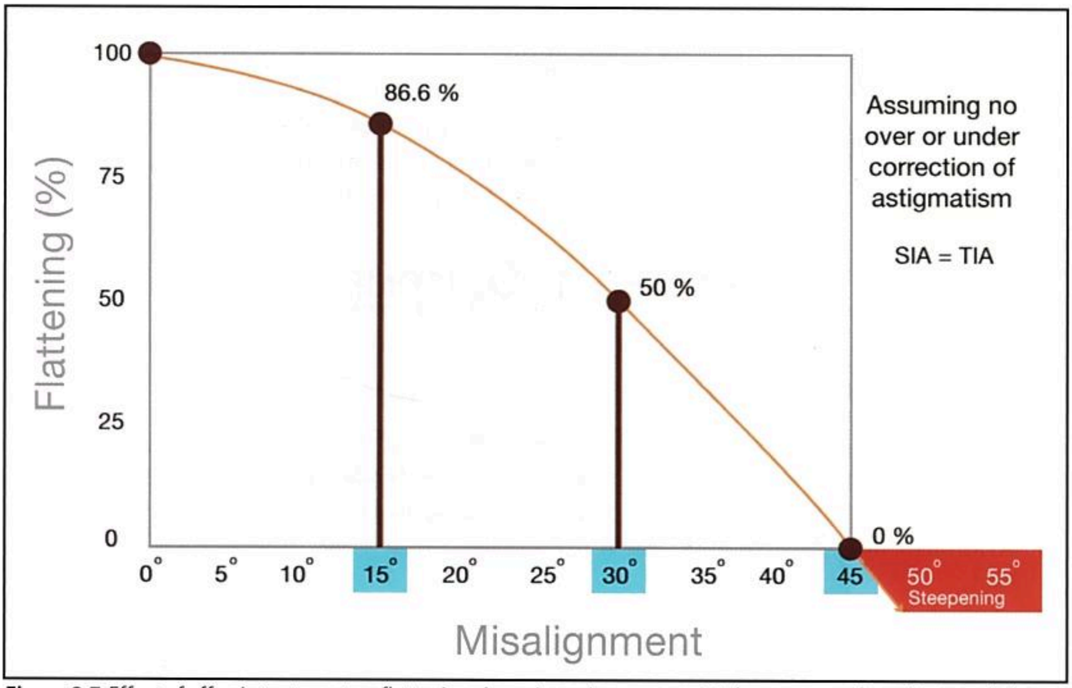

Figure 2-7. Effect of off-axis treatment on flattening. An astigmatic treatment 30 degrees away from the *intended* treatment meridian will result in a 50% loss in flattening at the intended meridian.

Conclusion

Astigmatism can be measured by using both corneal and refractive modalities—consistency of both equipment and operator is the key to accuracy, but in practice, these commonly differ, contributing in part to our inability to completely eliminate astigmatism.

Planning LRI procedures should incorporate all available astigmatism measurements together with surgeon-specific outcome data to help predict the effect of the phaco and/or the LRI incisions. An understanding of the vectorial changes that occur will assist in the refinement and optimal application of nomograms. Regular postoperative astigmatic analyses of LRI procedures allow for ongoing nomogram refinement and hence potential for continual improvement in visual outcomes of future surgery.

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