Measuring Astigmatism

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"Keratometry, topography, and refraction are fundamental determinants of astigmatic status, and disagreement in magnitude and/or axis is prevalent."—N. Alpins

Corneal shape and refractive power are the basic means to measure astigmatism. Each measurement can be utilized in incisional surgery (ie, cataract, astigmatic keratotomy, limbal relaxing incisions), refractive laser procedures, and postkeratoplasty for suture removal or intraocular lens (IOL) power calculations. Accurate measurement of the magnitude and orientation of astigmatism may improve visual outcomes and patient satisfaction through more effective treatment.

Astigmatism can be measured in the consulting room using one of several methods, including corneal topography, manual or automated keratometry, manifest refraction, and wavefront refraction.

Corneal Topography

This measurement provides qualitative and quantitative evaluations of the corneal curvature. Most topographers evaluate 8000 to 10,000 specific points over the entire cornea and center the acquisition on the corneal apex. This method of measuring astigmatism identifies multiple steep and flat meridians at 3-, 5-, and 7-mm optical zones. Topographers incorporating scanning slit photography also measure the power and the astigmatism of the posterior corneal surface, which may improve correlation with the refractive astigmatism. Topography values are imperative for IOL power calculations following previous corneal surgery, and are also useful when postsurgically examining the cornea for signs of irregularity.

Manual Keratometry

In contrast to topography measurements, manual keratometry only has 4 data points within 3 to 4 mm of the central anterior surface of the cornea. The reading does not provide data from the central or peripheral cornea, and therefore conditions such as keratoconus or pellucid marginal degeneration (PMD) may not be detectable. The measurements, like topography, are obtained by centering the cross-hairs on the corneal apex. In cases of irregular astigmatism, manual keratometry measurements may be quite difficult due to the distorted appearance of the mires that do not allow for accurate superimposition. In such cases, the contours of topography are more meaningful than the mild variations shown between the orthogonal steep and flat meridia in keratometry. Naturally occurring lenticular astigmatism, astigmatism of the corneal posterior surface, or tilted IOL is not taken into account. Despite this, keratometers are more readily available in most consulting suites and provide a quick, reliable means of gauging corneal astigmatism magnitude and its meridian with an experienced observer. Automated keratometers can be a useful screening device, although not as sensitive with low magnitudes of astigmatism for accuracy of axis.

Manifest Refraction

Subjectively measuring astigmatism extending from the anterior cornea to the perceptual levels at the visual cortex, manifest refraction considers the total amount of astigmatism the patient accepts or rejects, despite what has been measured objectively on the cornea or by wavefront aberrometry. Refraction can identify only one steep and one flat refractive axis orthogonal to each other (ie, regular astigmatism).

An experienced observer is the key to accuracy. For moderate to high astigmatism, retinoscopy may be a useful starting point for manifest refraction and as a crosscheck against the refraction.

Wavefront Refraction

These measurements are done by centering the mires on the middle of the pupil. It measures the aberrations within the optical system and does not deal with the nonoptical com-

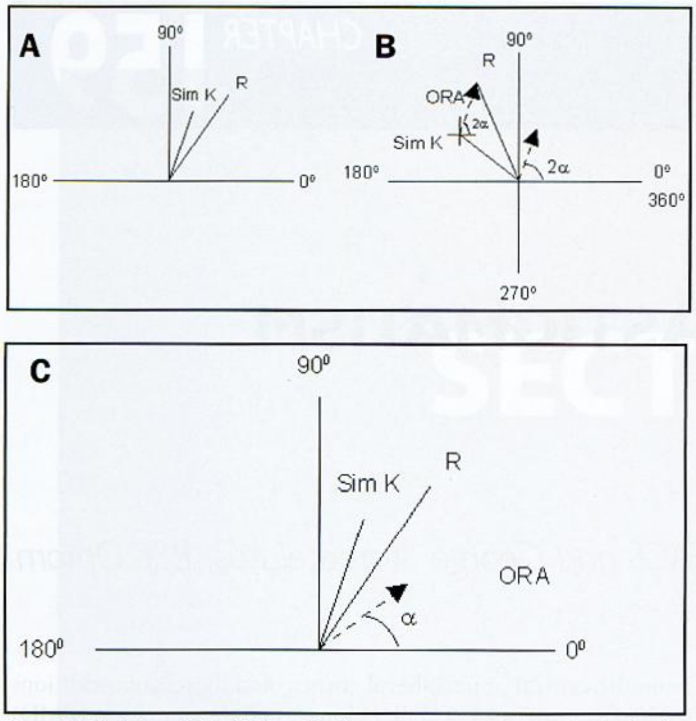

Figure 1. Calculation of ORA. (A) The polar diagram represents the corneal and refractive astigmatism as they appear on the eye. (B) The DAVD shows these same parameters with the angles doubled and the magnitudes the same; the ORA is the vectorial difference between the refractive and corneal astigmatism. It is also shown in its translocated position at the origin. (C) This displays the ORA calculated as it would appear on the eye.

ponent of refractive astigmatism (ie, cerebral integration of visual images). The second-order astigmatism magnitude and axis must be within a certain range of that measured by manifest refraction to be acceptable for use as treatment. Advising patients not to read in the waiting area and leaving them in a dark room for approximately 10 minutes before the aberrometry measurement may improve the accuracy of a wavefront refraction. Obtaining at least 3 captures of each eye is recommended for consistency.

Furthermore, it is a very useful exercise to cross-check the manifest refraction obtained with the wavefront refraction, particularly for the cylinder magnitude and axis. If they differ, repeat manifest refraction may be in order. Using the same instruments pre- and postoperatively and similar lighting conditions, where possible, adds to the accuracy of any postsurgical outcome analyses.

Astigmatic Discrepancy

The treatment of astigmatism would be considerably simpler if refractive and corneal astigmatism always coincided in magnitude and axis. Variance between manifest or wavefront refraction and keratometry or topography is widely prevalent, however, and the consequence is that an inevitable amount of astigmatism remains in the eye after treatment.

Refractive laser surgery conventionally relies on manifest refraction. Incorporating corneal and refractive parameters into this treatment plan using vector planning may potentially improve visual outcomes,[2,3] principally by reducing the amount of remaining corneal astigmatism. During cataract surgery, preferential reliance is on keratometry or topography. Subjective refraction information is inaccurate because of the cataract and its subsequent removal. Incisional surgery including astigmatic keratotomy (AK) or limbal relaxing incisions (LRIs) to correct pre- or postoperative astigmatism may be based upon keratometry, topography, refraction, or a combination of corneal and refractive parameters using vector planning. Keratometry, refraction, and topography parameters can guide suture removal or laser surgery retreatment following penetrating keratoplasty.

To quantify the discrepancy between corneal and refractive astigmatism measurements, calculate the vectorial difference between the refractive cylinder (ie, measured by wavefront or manifest refraction) and the corneal astigmatism (ie, measured by topography or keratometry). This vectorial difference is known as the ocular residual astigmatism (ORA), and is expressed in diopters (D).[2,3] The greater its magnitude, (1) the greater the astigmatic difference between the refractive and corneal astigmatism in magnitude and/or axis, and (2) the more postoperative astigmatism will remain. Eyes with irregular astigmatism (ie, keratoconus, keratoglobus, PMD) generally have a poorer correlation between corneal and refractive values. Hence, they have a higher ORA than a normal astigmatic eye. Studies have shown that ORA in healthy astigmatic eyes is between 0.73 and 0.81 D.[2,3] In keratoconic eyes, it has been calculated to be 1.34 D—derived from a series of 45 eyes with myopic astigmatism treated using photoastigmatic refractive keratectomy (PARK) in an ongoing study at NewVision Clinics.[4] The ORA has also been referred to as intraocular, lenticular, and noncorneal astigmatism.

CALCULATING OCULAR RESIDUAL ASTIGMATISM

Figure 1A displays (1) refractive astigmatism measured by manifest or wavefront refraction and (2) simulated keratometry measured by topography. To calculate the difference between these two parameters, the axes are doubled and the magnitudes remain unchanged (Figure 1B). The ORA, which has a direction from the simulated keratometric reading (SimK) to the refractive astigmatism, is then calculated using basic trigonometric principles, and the ORA vector is transferred to the origin ($x = 0$, $y = 0$) and halved to simulate how it would exist within the eye (Figure 1C).

TOPOGRAPHIC DISPARITY

Topographic disparity (TD) is a precise vectorial measure of corneal irregularity. The greater the topographic disparity, the greater the ORA.[4] The TD quantifies both the nonorthogonal and asymmetrical component of corneal irregularity as a single number with an axis. It is a precise, convenient way of assessing the variable of irregularity. The TD is calculated as the dioptric distance between the displays of superior and inferior topographical values on a 720-degree double-angle vector diagram (DAVD).

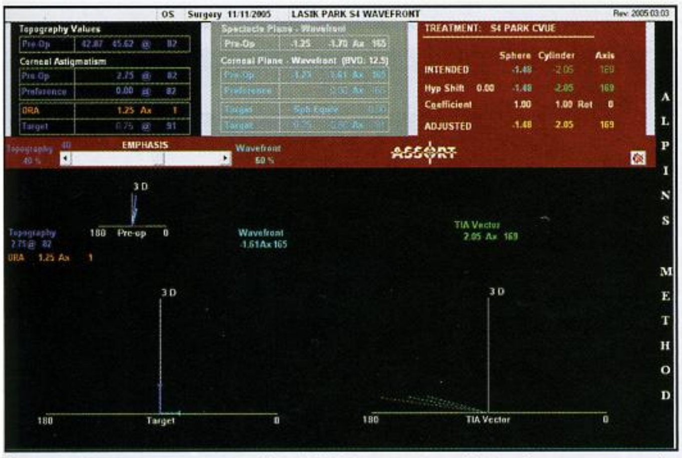

Figure 2. The treatment screen of the ASSORT outcomes analysis software program displays the wavefront refraction in the middle (gray) column and the simulated keratometry from topography on the left column. The emphasis bar determines what proportion of the ORA will be left on the cornea compared with the refraction.

Astigmatic Treatments and Correction

REFRACTIVE LASER SURGERY

Treatment of astigmatism using excimer laser surgery optimally incorporates both corneal and refractive parameters and leaves the minimum amount of astigmatism in the eye. Including the topography data reduces the amount of astigmatism remaining on the cornea. This has the potential for improving best-corrected visual acuity (BCVA) and reducing higher-order aberrations. Vector planning is used for the optimized astigmatism treatment.

Figure 2 displays a wavefront refraction of −1.25 DS/−1.70 DC × 165 at the spectacle plane and a simulated keratometry of 42.87/45.62 at 82 from topography. The ORA has been calculated as 1.25 D × 1. The best that can be done for this patient is to leave 1.25 D entirely on the (1) cornea, (2) spectacle refraction, or (3) apportioned between the two in varying amounts ranging from 1% topography/99% refraction to 99% topography/1% refraction, as indicated by the emphasis bar. It is important to note that the corneal target is 90 degrees away from the ORA axis to neutralize the vectorally calculated amount of astigmatism within the eye's optical system. In this example, the emphasis to correct the residual astigmatism (ORA) was set at 40% topography/60% refraction. Instead of treating −1.23 DS/−1.61 DC × 165 by using refractive parameters alone, the laser treatment (ie, −1.48 DS/−2.05 DC × 169) was derived from the combined refractive and corneal parameters.

The maximum correction of astigmatism is achieved with this method of treatment, and the corneal plus refractive astigmatism values remaining are at the minimum, whatever the emphasis value is between 0% and 100%. However, the most desirable result should be achieved by optimizing the emphasis to reduce corneal astigmatism to a minimum in this way.

CATARACT SURGERY AND REFRACTIVE LENS EXCHANGE

Employing incisions to minimize postoperative astigmatism is effective in cataract surgery. Application of the incision at varying points around the limbus will reduce the amount of remaining astigmatism, provided that an accurate keratometry measurement determining the steepest meridian is performed. Patients with previous corneal surgery require a more detailed topography measurement to accurately calculate the IOL power. The use of astigmatism data from manifest refraction is limited here, apart from gauging the BCVA, as it represents a combination of lenticular and corneal astigmatism as well as other components of the optical pathway and nonoptical psychophysical components of subjective astigmatism. If these measurements do not match up, then the first parameter to be removed from consideration is the refraction. The steepest meridian becomes the most effective site for the incision. This is measured by keratometry and topography and leaves the smallest amount of resultant astigmatism and rotates the target astigmatism meridian to the most favorable orientation toward 90 degrees (ie, with-the-rule).

INCISIONAL SURGERY

AK and LRIs are also effective at reducing the preoperative astigmatism. In the postoperative cataract eye, it is important to know what astigmatic effect the major incision and paracentesis had on the corneal astigmatism and to plan the corrective incisional surgery on the resultant shifted magnitude and axis. When planning the treatment, consideration of the keratometry, topography, and refraction is invaluable in these cases. This is particularly important for surgeons who perform LRIs simultaneous to cataract surgery. Accurate postoperative astigmatism measurements using manifest refraction, keratometry, and topography will give reliable outcome analysis, ie, the amount of flattening and torque produced by the incisions[6] (Figure 3) with rotation and reduction of the existing astigmatism. These analyses can then be used to refine future incision nomograms for further enhanced satisfaction.

Having measured the astigmatism of these 3 modalities using pre- and postoperative values, a more accurate analysis and parallel comparison of astigmatism changes by refraction, keratometry, and topography is enabled. This can be done using the target induced astigmatism vector (TIA), which quantifies the intended astigmatism treatment at the corneal plane and is the key to enabling an integrated analysis to be performed by any modality of astigmatism measurement—corneal or refractive. It is important to note that the preoperatively calculated TIA can be based on refractive, corneal, or a combination of both parameters as determined by the surgeon.

Over- or undercorrection of the incision effect (AK or LRI) can be calculated using the correction index (CI), which is the ratio of the surgically induced astigmatism vector (SIA) to the TIA. The CI is preferably 1.0. It is greater than 1.0 if an overcorrection occurs, and less than 1.0 if there is an undercorrection.

Determining whether the incision was on- or off-axis is calculated using the angle of error (AE), which is the angle

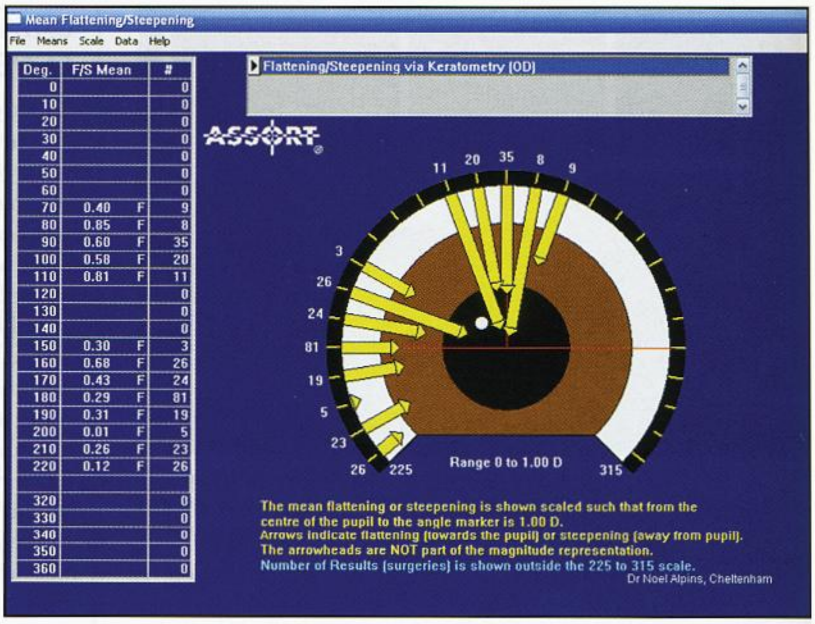

Figure 3. Mean flattening via keratometry of cornea by incisions at various meridia (OD). The numerics located at each meridian indicate the number of eyes and the amount of flattening in diopters is shown in the table on the left.

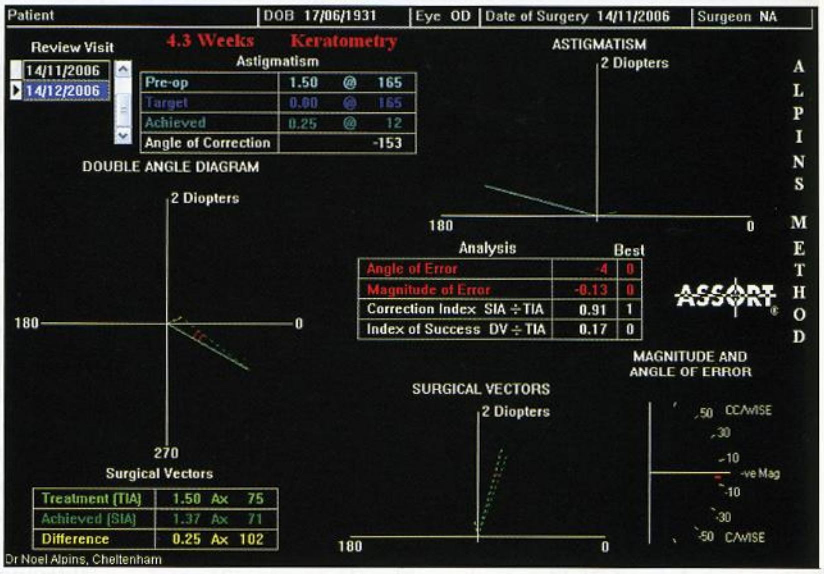

Figure 4. Astigmatic analysis showing correction index (CI) of 0.91 and angle of error (AE) of 4 degrees in CW direction.

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

Using an example, Figure 4 shows a case with preoperative corneal astigmatism as measured by keratometry of 1.50 D at 165. LRIs were performed at meridian 165/345 degrees to reduce the astigmatism and 1-month postoperative keratometry readings showed 0.25 D at 12. The SIA, calculated using the vectorial difference between the post- and preoperative values, was 1.37 D × 71 (Figure 4, "Double Angle Diagram"). The CI determined by the SIA to TIA ratio = 1.37/1.50 = 0.91, showing an undercorrection of 9%. The AE can also be calculated using basic trigonometry as −4 degrees, which is in a CW direction from the TIA (Figure 4, "Analysis"). These calculations can be performed to obtain means on multiple cases of the CI and AE to further refine outcomes.

POSTKERATOPLASTY ASTIGMATISM

Keratometry, corneal topography, and manifest refraction are used to determine the steep meridian for postoperative suture removal. Agreement in these measurements indicates a good visual prognosis, whereas disagreement may result in a greater chance of a decrease in visual acuity.[7,8] Refraction and keratometry are inaccurate in keratoplasty patients who have irregular astigmatism (ie, nonorthogonal and asymmetrical), because they only evaluate the astigmatism as one steep and one flat meridian. Topography allows for more information about the corneal shape in separate parts of the cornea and assists in selective suture removal. Corneal topography can also quantify the amount of nonorthogonal asymmetrical irregularity using the vector parameter of TD.[4]

When planning an excimer laser retreatment, it is useful to compare the outcomes of the first treatment by all 3 modalities—refraction, keratometry, and topography. This enables quantification of over- or undercorrection of astigmatism and adjusting the amount of the second treatment according to the effect achieved by the first surgery.

These 3 measures, keratometry, topography, and refraction, all provide useful information regarding the astigmatic status of patients. When the astigmatism measured by these tools is not in agreement in (1) magnitude, (2) orientation, or (3) both, then the surgeon needs to decide where to place more emphasis—either on the corneal or refractive astigmatism, depending on what procedure is being planned.

Accurate interpretation of astigmatism change is dependant on the type of surgical procedure being investigated. Systematic or surgical technique errors can be revealed by aggregate analysis using the CI and AE. The TIA is the key to enabling an integrated and more precise analysis to be performed by all refractive or corneal astigmatism measurement modes.

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