Refractive surprise after toric intraocular lens implantation: Graph analysis

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PURPOSE: To determine the refractive cylinder effect of rotating a toric intraocular lens (IOL) and identify the sources of refractive astigmatic surprise after toric IOL implantation.

SETTING: Private practice, Melbourne, Australia.

DESIGN: Experimental study.

METHODS: Vergence formulas using a standard reduced eye model were used to bring all lens powers to the corneal plane. Double-angle vector diagrams were then used to (1) determine the refractive cylinder effect of rotating a toric IOL and (2) show how the prevailing astigmatism and the various planning and surgical steps involved in implanting a toric IOL contribute to the postoperative manifest refractive cylinder.

RESULTS: An example calculation is given to illustrate the method.

CONCLUSIONS: Refractive cylinder surprises can occur after toric IOL implantation. Understanding the causes enables surgeons to address contributory factors and choose an appropriate surgical method for managing individual cases of refractive cylinder surprise.

Financial Disclosure: Dr. Alpins and Mr. Stamatelatos have a financial interest in the Assort software program used to support the planning and analysis of astigmatic correction. Dr. Ong is an employee of Assort.

J Cataract Refract Surg 2014; 40:283–294 © 2014 ASCRS and ESCRS

Cataract surgeons customarily select the power of an implanted intraocular lens (IOL) to reach a desired refractive outcome. In most cases, they aim for emmetropia. However, even when state-of-the-art measurement devices and planning software are used, postoperative refractive surprises inevitably occur. This is particularly challenging when a toric IOL has been implanted because the orientation of the IOL must be considered in addition to the cylinder power and the spherical power of the IOL. Sometimes, refractive surprises occur when a toric IOL is mistakenly implanted at a orientation different from what was intended or by rotation of a toric IOL after implantation.[1,2] However, even when a toric IOL has the correct power and orientation, an astigmatic refractive surprise is possible. For example, a phacoemulsification incision may cause unexpected surgically induced astigmatism (SIA)[3] or there may be longstanding ocular residual astigmatism (ORA) that could not be accurately calculated before surgery because of the presence of a cataract.[4,5]

Several surgical procedures can be used when excess manifest refractive cylinder leads to an unacceptable level of unaided vision in a patient after toric IOL implantation. These include a refractive laser procedure at the cornea, IOL replacement, and even IOL rotation. Intraocular lens rotation should be the preferred choice if (1) the surgeon expects the corrective rotation will reduce the manifest refractive cylinder to an acceptable level, (2) the surgeon knows how much and in which direction to rotate the IOL, and (3) the surgeon is capable of performing the desired rotation.

The challenges in rotating a toric IOL to reduce manifest refractive cylinder have been considered.[6,7] In this

Submitted: December 24, 2012.
Final revision submitted: May 8, 2013.
Accepted: June 11, 2013.

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0886-3350/$ - see front matter
http://dx.doi.org/10.1016/j.jcrs.2013.06.029

paper, we show how graph representations of vector calculations can be used to determine the refractive effect of corrective IOL rotation and to understand why a refractive surprise occurred before any secondary procedure. We consider graph representations to be important for 2 reasons. First, they can be generated quickly as a way to check the plausibility of calculations performed in software. Second, they allow the surgeon to quickly assess the astigmatic contributions of multiple surgical factors.

MATERIALS AND METHODS

Vergence calculations based on a standard reduced eye model were used to convert lens powers to their equivalent powers at the corneal plane. Using these equivalent powers, graph vector calculations were performed to (1) determine the refractive effect of rotating a toric IOL and (2) derive the corrective IOL rotation that is required to minimize the manifest refractive cylinder or optimize the axis of the remaining refractive cylinder to a favorable orientation. This graph analysis was also used to understand how the combined effects of the phacoemulsification incision, IOL implantation, and ORA contribute to refractive surprises.

Calculating Equivalent Lens Powers at the Corneal Plane Using Vergence Formulas

This section gives an overview of how to calculate equivalent lens powers at the corneal plane using the standard reduced eye model (Figure 1). This model is used when the IOL position is specified indirectly through the use of a lens constant.[8,9] The other components of the model are as follows:

1. Spectacle lens (power R_{spec}), which is represented by a thin lens in front of the cornea separated by the back vertex distance (BVD).
2. Cornea (power K), which is represented by single refracting surface separating air (refractive index n_{air} = 1.000) and aqueous (refractive index $n_{internal}$ = 1.336) positioned at the secondary principal plane of the cornea.
3. Intraocular lens (power P_{IOL}), represented by a thin lens in aqueous positioned at the effective lens position (ELP) behind the corneal surface.
4. Length of eye, given by the axial length (AL).

When the spectacle lens completely neutralizes any existing refractive error, paraxial collimated light entering through the spectacle lens ends up focused exactly at the retina. The manifest refraction is how the unaided visual success of the surgery is routinely measured in the clinical setting; the smaller the magnitude of the spherical and cylindrical components, the more successful the procedure. In this case, it is possible to trace the light through the whole model even though the power of the cornea is not explicitly known. The path of the collimated light is traced through the spectacle lens to the cornea, which gives the equivalent power of the spectacle lens at the corneal plane. The focused light from the retina toward the cornea is also traced to determine the equivalent power of the IOL at the corneal plane. Only in the case of a completely neutralizing manifest refraction is the equivalent power of the IOL at the corneal plane aligned with the cylinder axis of the implanted IOL at the IOL plane, independent of the corneal astigmatism. As a consequence, rotation of a toric IOL causes no change in the equivalent power of the IOL at the corneal plane as long as the spectacle lens in front of the eye always completely neutralizes the refractive error.

Vergence formulas are used for the case with a completely neutralizing manifest refraction that produces an exact focus on the retina to obtain the following (with all variables in SI units):

When light is traced through the spectacle lens to the cornea, the equivalent power of the manifest refraction at the corneal plane (power R_{corn}) is

$$R_{corn} = \frac{n_{air}}{\frac{n_{air}}{R_{spec}} - BVD}$$

This calculation is performed separately for the 2 principal meridia.

When tracing from the retina toward the cornea (Figure 2), the 3 vergences behind the IOL (V_{back}), in front of the IOL (V_{front}), and behind the cornea (V_{corn}) are

$$V_{back} = \frac{n_{internal}}{AL - ELP}$$

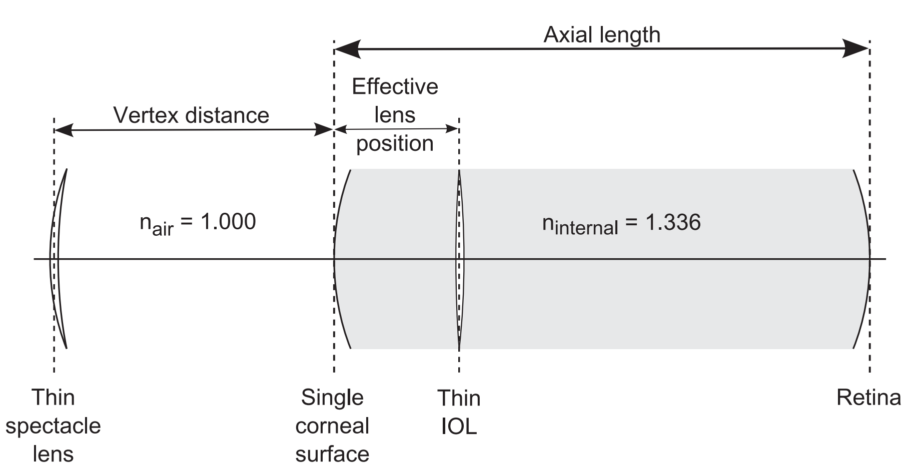

Figure 1. Standard reduced eye model (IOL = intraocular lens; n_{air} = 1.000; $n_{internal}$ = 1.336).

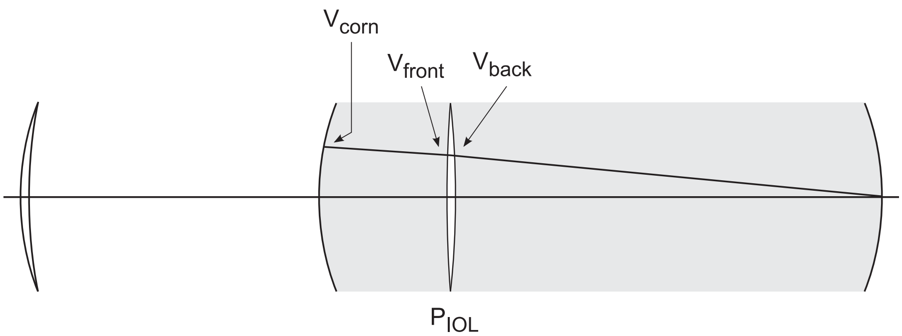

Figure 2. Ray tracing from the retina toward the cornea (P_{IOL} = intraocular lens power at the IOL plane; V_{back} = vergence behind the intraocular lens; V_{corn} = vergence behind the cornea; V_{front} = vergence in front of the intraocular lens).

$$V_{front} = \frac{n_{internal}}{AL - ELP} - P_{IOL}$$

$$V_{corn} = \frac{n_{internal}}{ELP + \frac{n_{internal}}{\frac{n_{internal}}{AL-ELP} - P_{IOL}}}$$

All calculations are performed separately for the 2 principal IOL meridia.

The equivalent power of the IOL at the corneal plane (P_{corn}) is the spherocylindrical difference between the total power necessary at the corneal plane for emmetropia and the vergence required behind the cornea to produce an exact focus on the retina as follows:

$$P_{corn} = \frac{n_{internal}}{AL} - V_{corn}$$

The equivalent powers resulting from these calculations are then used in the vector calculations described below to calculate the expected manifest refraction after IOL rotation.

Calculating the Expected Manifest Refraction after Rotating a Toric Intraocular Lens

This section shows how vector calculations at the corneal plane can be performed graphically to determine the expected manifest refractive cylinder after IOL rotation. The process is conceptually simple: To calculate the expected manifest refractive cylinder, the change in astigmatism caused by a specific rotation of a toric IOL (implanted after cataract surgery) is calculated, and this is added to the pre-rotation manifest refractive cylinder at the corneal plane. This is a hybrid corneal and refractive analysis that combines subjective (refractive) and objective (corneal) measurements. It avoids many of the problems associated with converting a corneal radius measurement into a suitable representation of corneal power; for example, the appropriate choice of corneal refractive index[8] or the contribution of the posterior corneal surface.[5] The analysis of toric IOL rotation is purely astigmatic: The spherical equivalent of the manifest refraction remains unchanged by IOL rotation (see Vergence Formulas section above).

Figure 3 shows the graph calculations that determine the refractive effect of rotating a toric IOL. The calculations start with polar representations of the post-implantation manifest refractive cylinder and the IOL toric power, both adjusted to the corneal plane. The cylindrical magnitude of the manifest refraction is aligned along the positive cylinder axis, which represents the total ocular astigmatism power that is being neutralized by the manifest refraction (Figure 3, *A*). The IOL toric power is aligned at right angles to the IOL positive axis because the positive axis (displayed by markings on the toric IOL) represents the direction along which the IOL has the least positive power (Figure 3, *B*). The cylindrical power of a rotated IOL remains unchanged at the corneal plane when there is a corresponding completely neutralizing manifest refraction in front of the eye (Figure 3, *C*; see also Vergence Formulas section). Next, double-angle vector diagrams (DAVDs) are used,[10,11] which allow astigmatisms to be combined using vector calculations. Each double-angle vector has the same magnitude as its corresponding astigmatism on a polar diagram but is oriented at double the axis. The target induced astigmatism vector (TIA) caused by the rotation of the IOL ($TIA_{rotation}$) is the vector difference between the pre-rotation and post-rotation IOL toric powers at the corneal plane (Figure 3, *D*). The $TIA_{rotation}$ increases in magnitude as the IOL is rotated until the rotation reaches 90 degrees. The $TIA_{rotation}$ is applied to the manifest cylinder after implantation to obtain the target refractive cylinder achieved after the IOL is rotated (Figure 3, *E*).

It is possible to choose $TIA_{rotation}$ to minimize the magnitude of the refractive cylinder target (Figure 3, *F*). The key element is that this choice is equivalent to rotating the IOL so that the rotated IOL toric power points toward the origin. This is the result of a simple geometric principle: The closest point to the origin on the circle of possible refractive targets will always be on the radial line that passes through the origin and the center of the circle. It is also possible to aim for a different, but preferred orientation if a larger target refractive cylinder magnitude is acceptable. Once a target refractive cylinder has been derived from a DAVD, it is converted back to polar coordinates by halving its axis (Figure 3, *G*). In this way, it is possible to determine the target refractive cylinder for all possible rotations of the IOL (Figure 3, *H*).

Discovering the Causes of Refractive Surprise

So far, this paper has described how to determine the refractive effect of rotating an implanted toric IOL. This allows a surgeon to determine whether surgical rotation of the IOL is likely to improve the astigmatic refractive surprise, and if so, by how much.

It is important to understand why refractive surprises occur. Two implantation scenarios illustrate how to identify the causes of refractive surprise. The first is a simple scenario

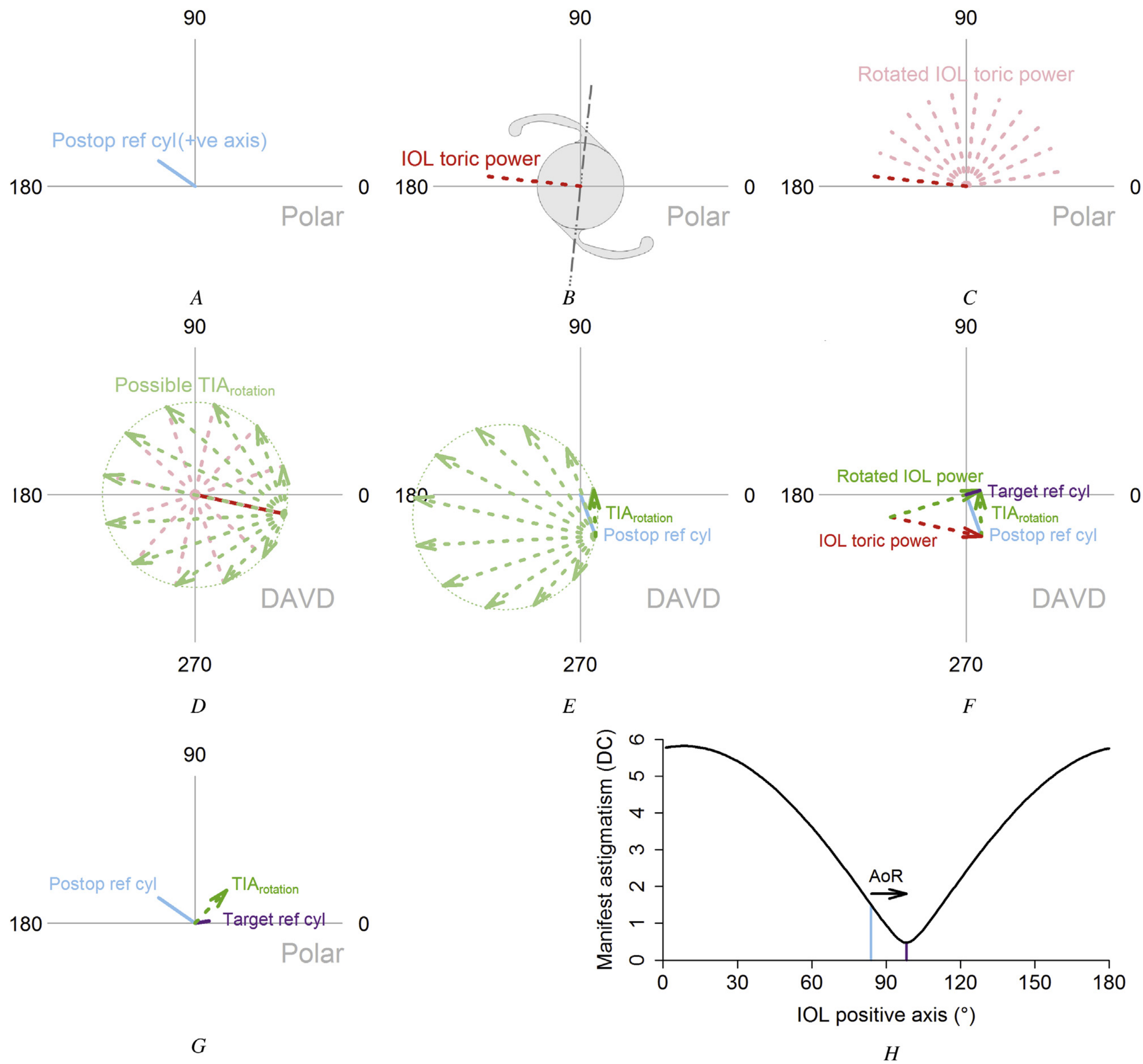

Figure 3. Corneal plane calculations of the effect of toric IOL rotation. All diagrams except the last are polar diagrams or DAVDs. *A*: Postoperative (pre-IOL rotation) manifest refractive cylinder at the corneal plane, displayed at the positive cylinder axis. *B*: Toric IOL orientation showing the markings that locate the flat axis of the optic (*gray line*) and the toric power of the IOL at the corneal plane (*red line*) 90 degrees away. *C*: Twelve possible toric powers of the IOL at the corneal plane after rotation in steps of 15 degrees, shown on a polar plot. All these powers assume the presence of a corresponding completely neutralizing manifest refractive lens before the eye. *D*: The 12 rotated IOL powers displayed on a DAVD (*pink lines*) at 30 degrees apart. The TIA vectors caused by IOL rotation ($TIA_{rotation}$, *green lines*) start from the original IOL power (*red line*) and go toward the rotated IOL powers (*pink lines*). *E*: Each possible $TIA_{rotation}$ changes the postoperative refractive cylinder into a possible target refractive cylinder, which lies on the dotted green circle. The highlighted $TIA_{rotation}$ shown here minimizes the post-rotation target refractive cylinder. *F*: The $TIA_{rotation}$ is the vector difference between the postoperative IOL toric power and the rotated IOL toric power. *G*: Comparison of the postoperative (pre-rotation) and target (post-rotation) refractive cylinders. The $TIA_{rotation}$ to achieve the target refractive cylinder is shown on a polar diagram. *H*: Relationship between IOL target orientation and the magnitude of the target refractive cylinder. The angle of rotation required to achieve the minimum refractive cylinder target is also shown (+ve axis = positive refractive cylinder axis; AoR = angle of rotation; DAVD = double-angle vector diagram; IOL = intraocular lens; ref cyl = refractive cylinder).

in which the phacoemulsification incision has the desired astigmatic effect (Figure 4). The second is a complex scenario in which the phacoemulsification incision does not have the desired astigmatic effect (Figure 5).

In both scenarios, the surgeon measures the preoperative keratometry and decides on a location for the phacoemulsification incision (figures 4, *A*, and 5, *A*). The incision is expected to induce a certain amount of change in

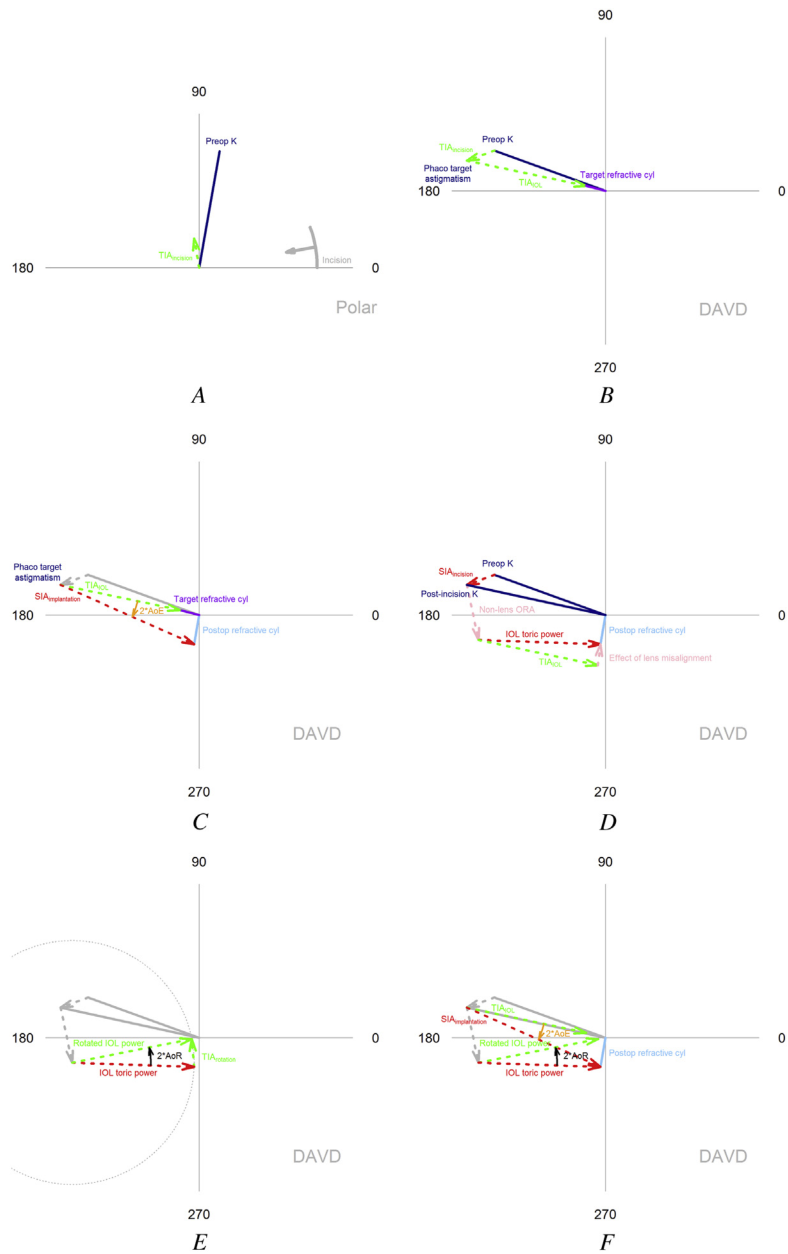

Figure 4. Derivation of the relationship between angle of error and the IOL angle of rotation when the phacoemulsification incision behaves as expected. *A*: Before IOL implantation is performed, the keratometry of the eye (Preop K) and the expected effect of the phacoemulsification incision ($TIA_{incision}$) are known. *B*: The phacoemulsification-adjusted corneal astigmatism (phaco target astigmatism) is used to select the toric power and orientation of the IOL (TIA_{IOL}). The expected amount of refractive cylinder remaining (target refractive cylinder) is the endpoint of the TIA_{IOL} vector. *C*: After the IOL has been implanted, the postoperative manifest refraction shows some unexpected remaining refractive cylinder (postoperative refractive cylinder). The change in astigmatism caused by the IOL implantation procedure ($SIA_{implantation}$) differs from the expected toric power of the IOL. The angle of error describes the mismatch in directions between the $SIA_{implantation}$ and the TIA_{IOL}. *D*: The actual effect of the phacoemulsification incision is given by the $SIA_{incision}$. In this case, the incision has exactly the expected effect, so the post-incision keratometry matches the phaco target astigmatism. The IOL toric power matches the TIA_{IOL} in magnitude (see Vergence Formulas section); however, the orientation may not be as intended. The unexpected remaining refractive cylinder can be attributed to a combination of IOL misalignment (measured under slitlamp) and the non-lens ORA. *E*: Rotation of the IOL alters the refractive status of the eye in a well-defined way. The possible refraction cylinder targets are shown as a dotted circle. To minimize the amount of refractive cylinder after surgical rotation, the surgeon must choose the point on this circle that is closest to the origin as the post-rotation refractive target. The angle of rotation is the angle by which the IOL needs to be rotated. *F*: The derivations for the angle of error and the angle of rotation are shown on the same diagram. Double angles are shown on the DAVDs (AoE = angle of error; AoR = angle of rotation; cyl = cylinder; DAVD = double-angle vector diagram; IOL = intraocular lens; K = keratometry; ORA = ocular residual astigmatism; $TIA_{rotation}$ = astigmatic change induced by rotation of toric IOL).

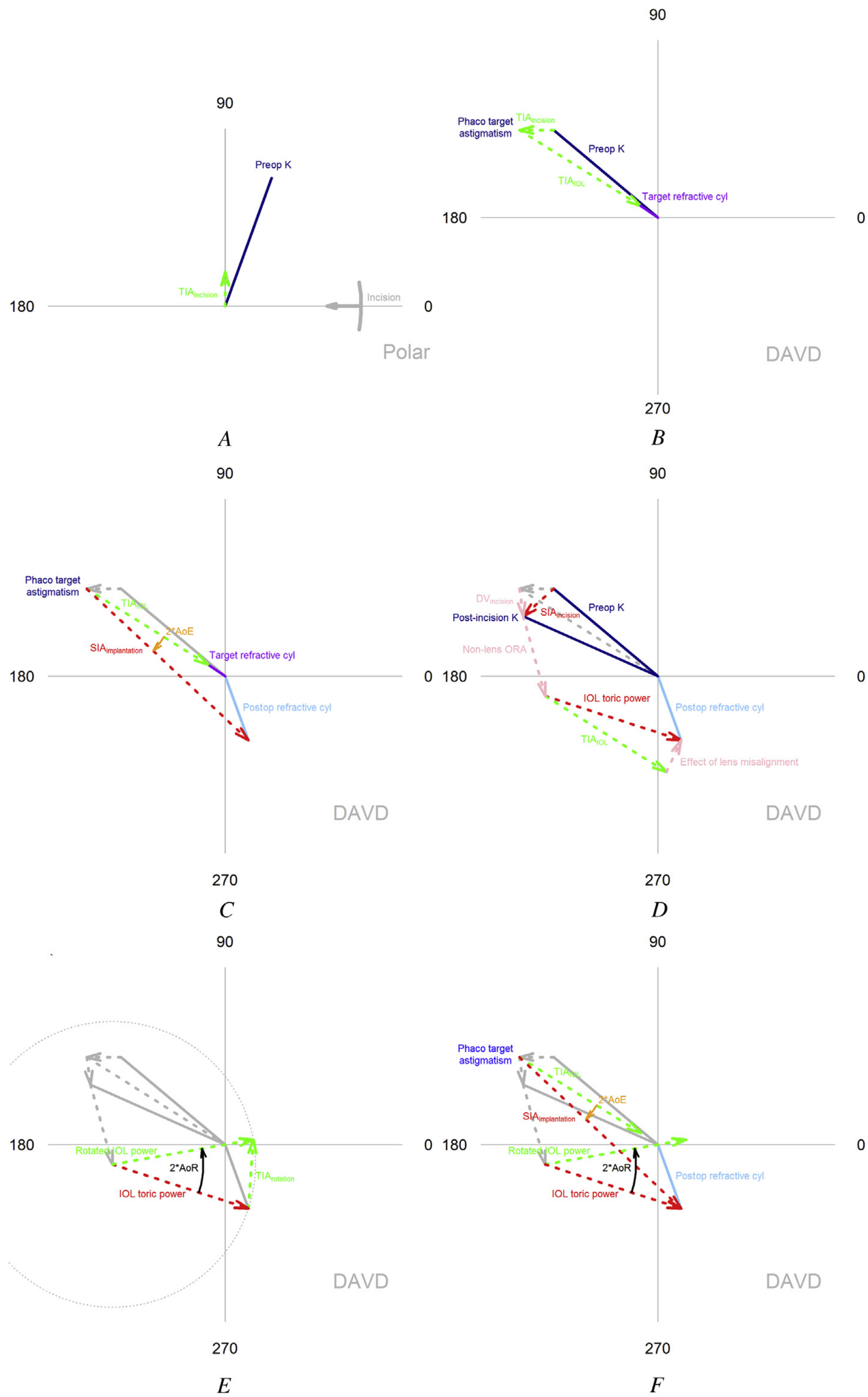

Figure 5. Derivation of the relationship between angle of error and the IOL rotation angle when the phacoemulsification incision does not behave as expected. For graphs *A*, *B*, *C*, *E*, and *F*, the descriptions are the same as in Figure 4. In Figure 5, *D*, the actual effect of the incision is given by the $SIA_{incision}$. In this case, the incision differs from the expected effect; thus, the post-incision keratometry does not match the phaco target astigmatism. The difference vector for the incision ($DV_{incision}$) quantifies the mismatch. The IOL toric power matches the TIA_{IOL} exactly in magnitude (see Vergence Formulas section); however, the orientation is not as intended (again measured under slitlamp). The unexpected remaining refractive cylinder (postop refractive cyl) can be attributed to a combination of effects from the phacoemulsification incision, IOL misalignment, and the non-lens ORA (AoE = angle of error; AoR = angle of rotation; cyl = cylinder; DAVD = double-angle vector diagram; IOL = intraocular lens; K = keratometry; ORA = ocular residual astigmatism; $TIA_{rotation}$ = astigmatic change induced by rotation of toric IOL).

astigmatism ($TIA_{incision}$). The expected post-incision corneal astigmatism (which in this paper is called the phaco target astigmatism) can be calculated as the vector sum of the preoperative keratometry and the $TIA_{incision}$ on a DAVD. The surgeon should hence use the phaco target astigmatism and not the preoperative keratometry when choosing the toric power of the IOL. After choosing a particular IOL model and power, the toric power of the IOL at the corneal plane (TIA_{IOL}) is calculated (see Vergence Formula section above). The target manifest refractive cylinder (at the corneal plane) is then the vector sum of the phaco target astigmatism and the TIA_{IOL} (Figures 4, *B*, and 5, *B*). The target refractive cylinder will normally not be precisely zero because most toric IOL manufacturers offer toric powers in steps of 0.50 diopter cylinders (DC) or 0.75 DC at the IOL plane.

After IOL implantation, a postoperative manifest refraction may show unexpected cylinder. The SIA of the whole surgical process ($SIA_{implantation}$)—which is a hybrid vectorial difference composed of corneal and refractive measurements—has to be compared with the TIA_{IOL} to determine by how much the actual outcome of the surgery differs from the expected outcome. The angle of error[10] is the angle between the TIA_{IOL} and the $SIA_{implantation}$ (Figures 4, *C*, and 5, *C*; double the angle of error is shown in these DAVD figures).

The 2 scenarios diverge here in their parameter values. In the simple scenario (Figure 4), the phacoemulsification incision has the expected astigmatic effect; thus, the post-incision keratometry matches the phaco target astigmatism. The IOL toric power will have the same magnitude as the TIA_{IOL}, with an orientation at the actual orientation of the IOL as observed under the slitlamp. In this case, the astigmatic difference between the target refractive cylinder and the post-implantation refractive cylinder cannot be attributed to the incision. Removing the effect of IOL misalignment from the refractive surprise leaves the non-lens ORA (Figure 4, *D*). The non-lens ORA represents the astigmatism in the eye that is not caused by the cornea or the lens, whether the lens be crystalline or implanted. To minimize the magnitude of the post-rotation refractive cylinder, it is necessary to rotate the IOL so that the rotated IOL power counters the contribution of the post-incision cornea and the non-lens ORA (Figure 4, *E*). We refer to this rotation angle as the angle of rotation and can be defined as the amount of IOL rotation required, in degrees, from the postoperative implanted position measured at the slitlamp to the targeted refractive cylinder. All vectors required for the definition of the angle of error and the angle of rotation are shown in Figure 4, *F*.

In the complex scenario (Figure 5), the astigmatic effect of the phacoemulsification incision does not match the surgeon's expectations. (The surgery has followed the $SIA_{incision}$ path instead of $TIA_{incision}$ path.) The post-incision keratometry differs from the phaco target astigmatism. In this scenario, the refractive surprise is caused by a combination of the unexpected effect of the incision, the effect of any IOL misalignment, and the non-lens ORA (Figure 5, *D*). To achieve the minimum post-rotation refractive target, the IOL again has to counter the contribution of the post-incision cornea and the non-lens ORA (Figure 5, *E*). All vectors needed to define the angle of error and the angle of rotation for the complex scenario are shown in Figure 5, *F*.

Possible contributors to the postoperative non-lens ORA are addressed in the Discussion.

Relationship between Angle of Error and Angle of Rotation

This section explores the relationship between the angle of error and the angle of rotation. To illustrate the situation, simplified versions of Figures 4, *F*, and 5, *F*, are shown in Figure 6.

In the simple scenario, in which the phacoemulsification incision has the expected astigmatic effect (Figure 6, *A*) and hence the postoperative keratometry is the same or very similar to the phaco target astigmatism, if there is no non-lens ORA, the magnitudes of the angle of error and the angle of rotation will be identical. Here, the IOL should simply be rotated back to the original intended orientation. If the non-lens ORA is small, the magnitudes of the angle of error and angle of rotation will be similar. The larger the non-lens ORA, the more the angle of error and the angle of rotation will differ from each other in magnitude. The cyclical directions of the angle of error and the angle of rotation will always be opposite to each other because the angle of error is the error and the angle of rotation is the correction required to eliminate that error.

In the complex scenario, in which the astigmatic effect of the phacoemulsification incision is different from what was expected (Figure 6, *B*) together with non-lens ORA, there is no well-defined relationship between the angle of error and the angle of rotation. The concept of angle of error relies on the assumption that the effect of the phaco incision is consistent and predictable. The angle of error quantifies the angular deviation from the targeted orientation, not the rotation required to achieve the minimum manifest refractive cylinder.

RESULTS

Example Calculation

Table 1 shows the numerical values corresponding to the complex example in Figure 5; the method is detailed in the Discussion. Table 2 shows the results of the vergence formulas. From these vergence calculations, it was determined that the TIA_{IOL} is 3.15 D Ax 164. Table 3 shows the values of the vectors in Figure 5.

DISCUSSION

Unexpected magnitudes of remaining refractive cylinder after toric IOL implantation are unavoidable in a proportion of cases, and they will continue to occur despite improvements in astigmatism measurements and surgical accuracy. Apart from errors in measurement and IOL selection,[12] there are a several reasons these refractive surprises occur as follows:

1. *Incision effect*. There is variation in the astigmatic effect of a phacoemulsification incision.[13]
2. *Incision position*. The incision may not have been placed accurately on the planned corneal meridian.
3. *Intraocular lens power*. The toric power of the IOL at the corneal plane may differ from the expected toric power. This may be caused by the use of a nonoptimized lens constant,[14] by the settling of the IOL at a

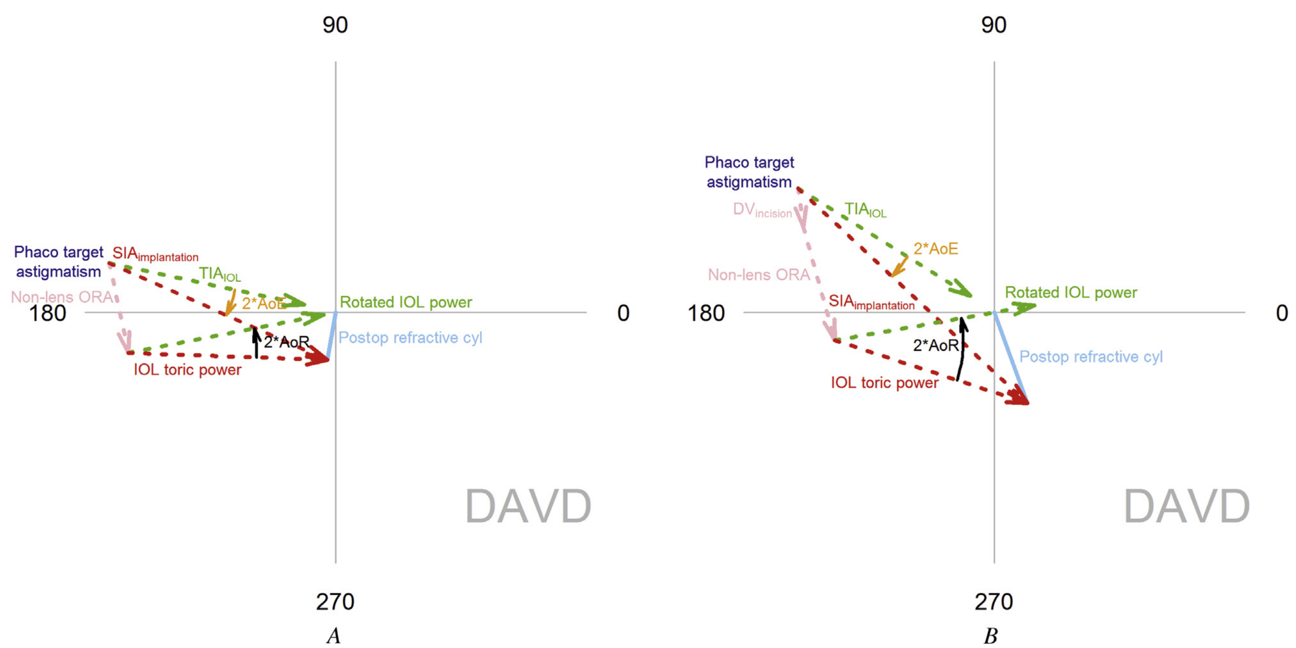

Figure 6. Summary of the relationship between the angle of error and the IOL angle of rotation for the 2 scenarios shown in Figures 4, *F*, and 5, *F*. *A*: In the simple scenario, the phacoemulsification incision has the expected effect. If there is no non-lens ORA, the angle of error and the angle of rotation have exactly the same magnitude and opposite signs. In general, the larger the amount of non-lens ORA, the more difference there could be between the angle of error and the angle of rotation. *B*: In the complex scenario, the incisional effect is different than expected. There is now no well-defined relationship between the angle of error and the angle of rotation (AoE = angle of error; AoR = angle of rotation; cyl = cylinder; DAVD = double-angle vector diagram; IOL = intraocular lens; ORA = ocular residual astigmatism; $SIA_{implantation}$ = change in total astigmatism at the corneal plane caused by IOL implantation; TIA_{IOL} = astigmatic change adjusted to the corneal plane induced by rotation of toric IOL).

position different from the expected anterior–posterior location,[15] or because the IOL power differs from the labeled power by an allowable manufacturing tolerance.[16]

4. *Intraocular lens orientation*. The orientation of the IOL may differ from the intended orientation. This may be caused by incorrect positioning of the IOL during implantation or by IOL rotation after implantation.[1,2]
5. *Non-lens ORA*. There may be postoperative astigmatism that remains unexplained after the postoperative keratometry or the toric effect of the IOL has been accounted for. We refer to this astigmatism as non-lens ORA. Some possible causes of postoperative non-lens ORA are longstanding pre-cataract non-lens ORA[4,5] astigmatism caused by substantial tilt of the implanted IOL[17] and changes in the patient's subjective perception of astigmatic neutralization.[18,19]

Table 1. Numerical values corresponding to the parameters in Figure 5.

Input Parameter	Value
Preoperative keratometry (D)	42.00/45.00, steep meridian @ 70
Intended phacoemulsification incision flattening (D)	0.75 @ 0
Implanted IOL power (D)	+21.00 +4.50 × 74
Back vertex distance (mm)	12.5
Effective lens position (mm)	5.1
Axial length (mm)	23.0
Postoperative keratometry (D)	41.85/45.10, steep meridian @ 78
Postoperative (pre-rotation) refraction (D)	−0.50 +1.50 × 145

IOL = intraocular lens

To understand how these terms apply in practice and how to address a refractive cylinder surprise, consider the example given in the Results section. A preoperative keratometry of 3.00 diopters (D) at 70 degrees together with a phacoemulsification incision of 0.75 D at 0 degree are shown in Figure 5, *A*. The expected steepening from the phacoemulsification incision ($TIA_{incision}$) is 0.75 D at 90 degrees away from its placement meridian (0 degree for a left eye).

The resulting corneal astigmatism, termed the phaco target astigmatism, is calculated by vectorially adding the effect of the incision ($TIA_{incision}$) to the preoperative keratometry (Figure 5, *B*). The amount of corneal astigmatism to be corrected by the IOL (TIA_{IOL}) originates at the phaco target astigmatism

Table 2. Vergence parameters for the example in Figure 5.

Parameter	Value (D)
Equivalent power of manifest refraction at the corneal plane	−0.50 +1.49 × 145
Power behind IOL	+74.64
Power in front of IOL	+49.14 +4.50 × 164
Power behind cornea	+41.38 +3.15 × 164
Equivalent power of IOL at corneal plane*	+13.57 +3.15 × 74

IOL = intraocular lens
*In the presence of a completely neutralizing manifest refraction so the light is focused exactly on the retina

on a DAVD (Figure 5, *B*) and aims as close as possible to achieving zero astigmatism (the origin on the DAVD); this is calculated to be 3.61 D Ax 328 (or 164 degrees on a polar diagram). Complete neutralization of the corneal astigmatism cannot be achieved because the toric power of the IOL selected is 4.50 D Ax 164 at the IOL plane, which converts to 3.15 D Ax 164 at the corneal plane using vergence calculations. Hence, there is a non-zero target refractive cylinder of 0.46 D × 164 (on a polar diagram).

Table 3. Values for astigmatisms and vectors in Figure 5.

Vector Analysis Parameter	Polar Representation
Preop K (D)	3.00 @ 70
$TIA_{incision}$ (D)	0.75 Ax 90
TIA_{IOL} (D)	3.15 Ax 164
Target refractive cyl (DC)	0.46 × 74
Postop refractive cyl (DC)	1.50 × 145
$SIA_{implantation}$ (D)	4.88 Ax 158
AoE (degrees)	−6
Post-incision K (D)	3.25 @ 78
$SIA_{incision}$ (D)	0.90 Ax 111
$DV_{incision}$ (D)	0.61 Ax 139
IOL toric power (DC)	3.15 Ax 171
Effect of lens misalignment (D)	0.77 Ax 33
Non-lens ORA (D)	1.82 Ax 143
Rotated IOL power (DC)	3.15 Ax 5
$TIA_{rotation}$ (D)	1.52 Ax 43
AoR (degrees)	+14

AoE = angle of error; AoR = angle of rotation; Ax = direction of the vector; cyl = cylinder; $DV_{incision}$ = difference vector of phaco incision; IOL = intraocular lens; K = keratometry; ORA = ocular residual astigmatism; $SIA_{implantation}$ = surgically induced astigmatism vector of implantation procedure; $SIA_{incision}$ = surgically induced astigmatism vector of phaco incision; $TIA_{incision}$ = target induced astigmatism vector of phaco incision; TIA_{IOL} = target induced astigmatism vector of IOL at corneal plane; $TIA_{rotation}$ = target induced astigmatism vector of IOL rotation

The SIA from the implantation procedure ($SIA_{implantation}$ excluding the phacoemulsification) can be calculated as the path taken from the phaco target astigmatism to the postoperative refractive cylinder on a DAVD (Figure 5, *C*), which is calculated and shown as 4.88 D Ax 316.

The angle of error in Figure 5, *C*, is calculated as the axis difference between the toric axis of the IOL (328 degrees) and the $SIA_{implantation}$ (316 degrees), which is −12 degrees on a DAVD and −6 degrees on a polar diagram. The negative sign indicates clockwise rotation from the intended axis (TIA) to the achieved axis (SIA). Figure 5, *D*, shows a situation in which the phacoemulsification incision has not gone according to plan, resulting in a postoperative keratometry of 3.25 D @ 78 instead of the planned 3.61 D @ 74.

The $SIA_{incision}$ can be calculated in the clinical setting by measuring the postoperative keratometry and comparing it vectorially with the preoperative keratometry. In cases in which the $SIA_{incision}$ is minimal (<0.75 D) and a refractive surprise has occurred, this can be attributed to non-lens ORA, toric IOL misalignment, or both.

In this example, in which the $SIA_{incision}$ is 0.90 D, the 1.50 D postoperative refractive surprise can be attributed to the $SIA_{incision}$ not going according to plan, IOL misalignment, and the non-lens ORA. The physical IOL misalignment can be measured under a slitlamp by noting the toric marks placed on the positive axis of the IOL.

In the majority of cases, the surgeon will target the minimum refractive cylinder magnitude. Selecting to target the minimum refractive cylinder from Figure 3, *F*, the angle of rotation is the angle subtending the axis of the toric IOL as it appears postoperatively (on a DAVD) and the axis of the rotated IOL after adding the $TIA_{rotation}$ to the IOL toric power. This results in the IOL (toric power of 3.15 D Ax 171 [displayed at 342 degrees on a DAVD]) requiring rotation to the calculated rotated IOL power of 3.15 D Ax 5. This is a 14-degree angular separation on a polar diagram.

It is important that in some cases, IOL rotation will not result in a significant reduction in the refractive cylinder, in which case it is likely that non-lens ORA is present unless there has been an incorrect selection of the toric IOL. In this case, the only option may be to perform laser in situ keratomileusis to target plano and correct for the refractive surprise. Postoperative toric IOL analysis, including the expected refractive cylinder after IOL rotation, is freely available.[A]

Why is it useful to understand the causes of refractive surprise? At first glance, it might seem that a surgeon need only manage cases of refractive surprise as they arise. In this case, the simple analysis of the refractive effect of toric IOL rotation suffices to allow the surgeon to assess whether IOL rotation can achieve an acceptable refractive target. However, if refractive surprises occur more often than expected, there is a problem with the planning and/or execution of the IOL implantation or the expectations for the surgical outcome are unrealistic. In the former case, it is important to identify and address the sources of systematic error that are causing the refractive surprises. In the latter case, the surgeon should identify the amount of random error that occurs at each stage of planning and execution and then consider the potential combined effect on the final refractive outcome. The effects of random error can be understood using diagrams such as those presented in this paper. The patient consent process should take into account realistic expectations regarding the outcome of surgery, and it should allow for the possibility of a follow-up procedure for the inevitable occurrences when the surgical parameters fall outside these expectations.

We have considered the analytical term *angle of error* in this paper because it represents a measure of the surgical outcome of what was targeted preoperatively. The angle of rotation is the rotation required from the postoperative orientation to achieve the modified target due to $SIA_{incision}$ and non-lens ORA. The angle of error can be referred to when the phacoemulsification incision has gone according to plan and there is no possible source of astigmatism apart from the cornea and the IOL. If the planning of the toric IOL implantation has been correct, the IOL must be misaligned. The IOL then has to be rotated back to the intended orientation. In this case, the angle of rotation has exactly the same magnitude as the angle of error and the opposite cyclical direction.

If the incision does not have the expected astigmatic effect, or if there is unexpected postoperative astigmatism (ie, the non-lens ORA is significantly different from zero), there will be no well-defined relationship between the angle of error and the angle of rotation. In such a case, the angle of rotation must be calculated directly from the expected power of the IOL (at the orientation of the IOL when viewed at a slitlamp) and from the postoperative manifest refraction. The angle of error here is still an outcome measure of how well the procedure went to plan.

Although it is widely accepted and published that each degree of toric IOL misalignment yields a reduction in astigmatism correction of 3.3%,[21,22] and hence at 30 degrees of misalignment there is no correction to the astigmatism, the loss of effect (ie, neutralization of the corneal astigmatism at the treatment meridian) of a misaligned IOL is the vectorial method of considering IOL misalignment. This can be interpreted and measured as the postoperative astigmatism at the intended meridian of treatment. The loss of effect can be calculated using the formula $M \cos 2\theta$, where M is the magnitude of the astigmatism and θ is the angle of misalignment. This results in a 2% loss for a misalignment of 5 degrees and a 6% loss at a 10-degree misalignment.[20,B] However, at 15 degrees of misalignment, the loss of effect disproportionately increases to 13.6% as the steep slope of the sigmoid curve of the formula is reached. Thus, for IOLs with small to medium amounts of toricity, rotations of less than 10 degrees are likely to be of limited benefit. It has been frequently stated at the podium and in previous studies that the loss of effect of a misaligned toric IOL is much greater than noted here; however, these calculations are scalar comparisons between the postoperative refractive astigmatism and the preoperative corneal astigmatism by magnitude values alone. The loss of the astigmatic effect requires a vectorial calculation and is determined by measuring the reduction of astigmatism at the intended axis and not the outcome of the refractive cylinder magnitude.

If a surgeon wishes to choose a refractive target that is not the minimum refractive target, the calculations will be more complex and the patient's uncorrected visual acuity becomes the overriding factor of success. We have assumed there is always a completely neutralizing manifest refraction present in front of the eye in our calculations, focusing the light perfectly on the retina. In practice, surgeons will often aim for a spectacle-free outcome, meaning that the patient can perform many activities without wearing any sort of refractive correction. However, in the absence of a completely neutralizing manifest refraction, the effective power magnitude of the toric IOL at the corneal plane can change substantially as the IOL rotates. Also, the effective power axis of the toric IOL at the corneal plane does not necessarily agree with the axis of the IOL as seen under the slitlamp at the IOL plane. Thus, if the postoperative manifest refraction is targeted to be at the polar axis of 90 degrees or 180 degrees, it is unlikely that the primary focal lines for the uncorrected eye are precisely horizontal and vertical. This misalignment is likely to have a negative impact on visual performance after surgery.[23] If the surgeon wishes to aim for the best unaided visual performance, it is necessary to use the method of vergences we have outlined. This will allow the surgeon to calculate the expected total power of the eye (not only the expected manifest refraction) for each possible orientation of the toric IOL.

In conclusion, there are several causes of astigmatic refractive surprise after toric IOL implantation. Some are surgeon dependent and can be improved on, while others are due to intereye differences. These surprises will occur regardless of how well the implantation of the toric IOL was performed; the possibility that a second procedure may be required should thus be conveyed to the patient ahead of time. Calculating the minimum refractive cylinder that can be achieved by rotating the existing toric IOL and understanding the underlying causes of remaining postoperative refractive cylinder allow the surgeon to decide on the best treatment option available to achieve an optimum visual outcome.

WHAT WAS KNOWN

- How to calculate the toric IOL rotation to minimize the amount of manifest refractive cylinder in an average eye has been described. This assumes that the toric IOL has the toric power at the corneal plane specified by the manufacturer.

WHAT THIS PAPER ADDS

- How to calculate the angle of rotation, which is the toric IOL rotation, to minimize the amount of manifest refractive cylinder in any eye using optimized lens constants to account for eye-specific and surgeon-specific factors that affect the equivalent power of the toric IOL at the corneal plane.
- Graph representations of astigmatism and cylinder using Cartesian coordinates on DAVDs can identify the causes of astigmatic refractive surprises after toric IOL implantation.
- The role of the angle of error as an outcome tool and why it should not be used for therapeutic adjustment.
- The differences between angle of rotation and angle of error.
- The term *non-lens ORA* is used to quantify the unpredictable nature of refractive cylinder outcomes.

REFERENCES

1. Shah GD, Praveen MR, Vasavada AR, Vasavada VA, Rampal G, Shastry LR. Rotational stability of a toric intraocular lens: influence of axial length and alignment in the capsular bag. J Cataract Refract Surg 2012; 38:54–59
2. Patel CK, Ormonde S, Rosen PH, Bron AJ. Postoperative intraocular lens rotation: a randomized comparison of plate and loop haptic implants. Ophthalmology 1999; 106:2190–2195; discussion by DJ Apple, 2196
3. Tejedor J, Pérez-Rodríguez JA. Astigmatic change induced by 2.8-mm corneal incisions for cataract surgery. Invest Ophthalmol Vis Sci 2009; 50:989–994. Available at: http://www.iovs.org/content/50/3/989.full.pdf. Accessed September 5, 2013
4. Alpins NA. New method of targeting vectors to treat astigmatism. J Cataract Refract Surg 1997; 23:65–75
5. Koch DD, Ali SF, Weikert MP, Shirayama M, Jenkins R, Wang L. Contribution of the posterior corneal astigmatism to total corneal astigmatism. J Cataract Refract Surg 2012; 38:2080–2087
6. Tseng SS, Ma JJ. Calculating the optimal rotation of a misaligned toric intraocular lens. J Cataract Refract Surg 2008; 34:1767–1772
7. Felipe A, Artigas JM, Díez-Ajenjo A, García-Domene C, Alcocer P. Residual astigmatism produced by toric intraocular lens rotation. J Cataract Refract Surg 2011; 37:1895–1901
8. Holladay JT. Standardizing constants for ultrasonic biometry, keratometry, and intraocular lens power calculations. J Cataract Refract Surg 1997; 23:1356–1370
9. Haigis W. The Haigis formula. In: Shammas HJ, ed, Intraocular Lens Power Calculations. Thorofare, NJ, Slack, 2004; 41–57
10. Alpins NA. A new method of analyzing vectors for changes in astigmatism. J Cataract Refract Surg 1993; 19:524–533
11. Jaffe NS, Clayman HM. The pathophysiology of corneal astigmatism after cataract extraction. Trans Am Acad Ophthalmol Otolaryngol 1975; 79:OP615–OP630
12. Jin GJ, Crandall AS, Jones JJ. Intraocular lens exchange due to incorrect lens power. Ophthalmology 2007; 114:417–424
13. Borasio E, Mehta JS, Maurino V. Surgically induced astigmatism after phacoemulsification in eyes with mild to moderate corneal astigmatism; temporal versus on-axis clear corneal incisions. J Cataract Refract Surg 2006; 32:565–572
14. Aristodemou P, Knox Cartwright NE, Sparrow JM, Johnston RL. Intraocular lens formula constant optimization and partial coherence interferometry biometry: refractive outcomes in 8108 eyes after cataract surgery. J Cataract Refract Surg 2011; 37:50–62
15. Preussner PR, Wahl J, Weitzel D, Berthold S, Kriechbaum K, Findl O. Predicting postoperative intraocular lens position and refraction. J Cataract Refract Surg 2004; 30:2077–2083
16. International Organization for Standardization. Ophthalmic Implants – Intraocular Lenses – Part 2: Optical Properties and Test Methods. Geneva, Switzerland, ISO, 2003; 1999 (ISO 11979–2); technical corrigendum 1
17. Marcos S. Special circumstances: effect of IOL tilt on astigmatism. In: Hoffer KJ, ed, IOL Power. Thorofare, NJ, Slack, 2011; 223–230
18. Vinas M, Sawides L, de Gracia P, Marcos S. Perceptual adaptation to the correction of natural astigmatism. PLoS One 2012; 7:e46361. Available at: http://www.plosone.org/article/fetchObject.action?uri=info%3Adoi%2F10.1371%2Fjournal.pone.0046361&representation=PDF. Accessed September 5, 2013
19. Alpins NA. Wavefront technology: a new advance that fails to answer old questions on corneal vs. refractive astigmatism correction [editorial]. J Refract Surg 2002; 18:737–739
20. Alpins NA. Vector analysis of astigmatism changes by flattening, steepening, and torque. J Cataract Refract Surg 1997; 23:1503–1514
21. Bauer NJ, De Vries NE, Webers CA, Hendrikse F, Nuijts RM. Astigmatism management in cataract surgery with the AcrySof toric intraocular lens. J Cataract Refract Surg 2008; 34:1483–1488
22. Chang DF. Comparative rotational stability of single-piece open-loop acrylic and plate-haptic silicone toric intraocular lenses. J Cataract Refract Surg 2008; 34:1842–1847

23. Kobashi H, Kamiya K, Shimizu K, Kawamorita T, Uozato H. Effect of axis orientation on visual performance in astigmatic eyes. J Cataract Refract Surg 2012; 38:1352–1359

OTHER CITED MATERIAL

A. ASSORT Toric IOL Calculator. Available at: http://www.assort.com/ASSORT-toric-calculator-intro.asp. Accessed September 5, 2013

B. Black DA, "Key Steps Ensure Success With Toric IOL Implantation," Ocular Surgery News, USA edition October 25, 2011. Available at: http://www.healio.com/ophthalmology/cataract-surgery/news/print/ocular-surgery-news/%7B7B4E727A-8D7F-4D01-AC24-93C915B10FEF%7D/Key-steps-ensure-success-with-toric-IOL-implantation?Filter=&page=1. Accessed September 3, 2013

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