Adjustment of Anterior Corneal Astigmatism Values to Incorporate the Likely Effect of Posterior Corneal Curvature for Toric Intraocular Lens Calculation

Michael Goggin, FRCSI; Katherine Zamora-Alejo, MD; Adrian Esterman, PhD; Lourens van Zyl, FCPhth

ABSTRACT

PURPOSE: To establish if average refractive overcorrection or undercorrection of corneal astigmatism based on the “rule” of the astigmatism occurs if toric intraocular lenses (IOLs) are calculated on the basis of anterior corneal measurements, and to calculate an adjustment for individual eyes to avoid this systematic error.

METHODS: One hundred forty-three consecutive eyes of 115 patients underwent phacoemulsification with IOL powers calculated using anterior corneal curvature data alone. Eyes were grouped as either “with-the-rule” or “against-the-rule” on the basis of the steep anterior corneal meridian. Targeted versus achieved astigmatic outcomes were compared. Main outcome measure was residual refractive astigmatism following the insertion of a toric IOL due to the likely effect of posterior corneal astigmatism.

RESULTS: Significant prediction errors in astigmatic outcome occurred only with IOL cylinders of 2 diopters or less. Overcorrection occurred by a factor of 1.38 in with-the-rule eyes and undercorrection occurred by a factor of 0.65 in against-the-rule eyes.

CONCLUSIONS: A coefficient of adjustment of 0.75 for with-the-rule eyes and 1.41 for against-the-rule eyes can be applied to the corneal astigmatism power value to calculate a more appropriate IOL cylinder power than that calculated by using unadjusted anterior corneal curvature measurements. These adjustment coefficients apply only to those eyes that would have received IOLs with 2 diopters or less and calculated with such unadjusted measurements. Greater IOL cylinder powers are sufficiently accurately calculated using unadjusted values.

eyes to avoid this systematic error for toric IOLs subsequently implanted, which is a new approach to this problem.

**PATIENTS AND METHODS**

Institutional Human Research Ethics Committee approval was obtained for this study.

Retrospectively, data were collected for 143 consecutive eyes of 115 patients who underwent cataract surgery or refractive lens exchange between November 2009 and October 2013 and had received AT TORBI 709M or 709MP toric IOLs (Carl Zeiss Meditec, Jena, Germany). Exclusion criteria were oblique keratometric astigmatism (7 eyes, this number being too few for analysis) and postoperative corrected visual acuity less than 6/9.5 (1 eye). Two eyes of 2 patients who had developed dementia between the decision to intervene surgically and postoperative examination were also excluded, leaving a study population of 133 eyes. Preoperative IOL calculations were performed on the basis of IOLMaster (Carl Zeiss Meditec) keratometry and biometry in 118 eyes, and Nidek automated keratometry (Nidek Co., Ltd., Tokyo, Japan) and ultrasound biometry using the Ocuscan RxP Ophthalmic Ultrasound System (Alcon Laboratories, Inc., Fort Worth, TX) in 15 eyes with cataract too dense for partial coherence interferometry. IOL powers (ie, sphere and cylinder) were calculated using the Carl Zeiss Meditec online calculator (https://zcalc.meditec.zeiss.com/zcalc/) that provides expected postoperative refraction values. Errors in toric IOL calculations are minimized by this calculator by incorporating anterior chamber depth and axial length measurements and the index of refraction used by the keratometric device.3

All eyes underwent micro-incision phacoemulsification using a 1.9-mm temporal clear corneal incision on the horizontal meridian performed by three surgeons (MG, KZ-A, LVZ) using identical techniques. The technique is astigmatically neutral, allowing the use of preoperatively measured keratometric values in the IOL calculations and obviating the necessity to predict postoperative keratometric astigmatism using previously established surgically induced corneal astigmatism.4 The summated vector mean (or centroid) of the corneal incisions was 0.19 diopters (D) and mean flattening at the incision was 0.18 D. These values are less than that measurable by clinical refraction. The mean surgically induced corneal astigmatism axis was 89° with a wide standard deviation of 44° (range: 1° to 174°), indicating the random distribution of the surgically induced astigmatism value consistent with the test-to-test variability of keratometric values.4 As a consequence, the calculated surgically induced corneal astigmatism was not subtracted from the overall astigmatic change of the procedure (incision and toric IOL insertion), eye by eye, because it would introduce an error when examining population averages.

The vertical corneal meridian was marked preoperatively using a technique previously described.5 The incision and IOL meridian were established from this mark using a Mendez ring preoperatively. Postoperative review was performed at 6 weeks by one of three surgeons (MG, KZ-A, LVZ) and included manifest refraction, keratometry, and observation of the meridian of the IOL cylinder.

Eyes were grouped according to “rule” (with-the-rule: anterior keratometric steep meridian between 60° and 120°; against-the-rule: anterior keratometric steep meridian between 0° and 30° or 150° and 180°; all others [oblique]: anterior keratometric steep meridian between 31° and 59° or 121° and 149°). Vector analysis was used to compare preoperative anterior keratometric astigmatism with postoperative targeted refractive astigmatism provided by the online toric IOL calculator and the achieved postoperative refractive astigmatism, the latter two values being corrected to the corneal plane.6 Targeted-induced and surgically induced astigmatism vector values for IOL insertion were thus derived for each eye. Overcorrection or undercorrection was established for each eye by the arithmetic difference between the two values (ie, magnitude of error), subtracting the targeted-induced astigmatism from the surgically induced astigmatism. Therefore, positive values represent overcorrection and negative values represent undercorrection.

The ratio of these two values can express the proportion of corrected astigmatism (surgically induced astigmatism/targeted-induced astigmatism, astigmatism correction index) and the inverse of this ratio (targeted-induced astigmatism/surgically induced astigmatism) can be used as a coefficient of adjustment for subsequent treatments. In this study, a coefficient of adjustment was derived for each eye and geometric means of these coefficients were calculated.

With-the-rule eyes were compared with against-the-rule eyes. To establish if any differences detected were present throughout the dioptic range of IOL cylinders used, a comparison of two subgroups of eyes with IOL cylinder powers of 2 D or less and 2.5 D or more were made within both groups. Stratification into smaller subgroups within these ranges yielded group data with insufficient statistical power for valid intergroup analysis.

To establish if the magnitude of error for with-the-rule and against-the-rule eyes represented real prediction error, one-sample t tests were used to demonstrate if the values differed significantly from zero. Two-sample t tests with equal variances were used to compare means between the groups.
A probability of less than 5% or a $P$ value of less than .05 was considered statistically significant.

**RESULTS**

In 133 eyes, the mean ± standard deviation of preoperative keratometric astigmatism was 2.34 ± 1.24 D (range: 1.22 to 7.97 D). The mean ± standard deviation of implanted IOL cylinder power was 2.60 ± 1.68 D (range: 1 to 10.5 D). The mean ± standard deviation of postoperative refractive astigmatism corrected to the corneal plane and targeted corneal plane refractive astigmatism was 0.77 ± 0.60 D (range: 0 to 3.59 D) and 0.20 ± 0.11 D (range: 0 to 0.48 D), respectively. The mean ± standard deviation of the magnitude of the error (signed value) for all eyes was 0.02 ± 0.68 D (range: -2.30 to 2.65 D) and the absolute value was 0.51 ± 0.44 D (range: 0.001 to 2.65 D). For all 133 eyes, the geometric mean astigmatism correction index was 0.98 and the coefficient of adjustment was 1.02 (the ideal for both being 1.00).

Of the 133 eyes, 67 had with-the-rule astigmatism and 66 had against-the-rule astigmatism. The two groups were further subdivided into eyes that received IOLs with cylinder powers of 2.5 D or more or 2 D or less. Table 1 shows the comparison of the magnitude of the error between with-the-rule and against-the-rule eyes.

Table 2 shows the magnitude of the error in with-the-rule and against-the-rule eyes that was analyzed using a one-sample $t$ test to examine if the values differed significantly from zero (ie, if there were significant errors in outcome prediction).

Because there were significant errors only in eyes (with-the-rule and against-the-rule) receiving IOL cylinder powers of 2 D or less, estimation of astigmatism correction index and coefficient of adjustment was confined to these eyes. These are presented in Table 3 as geometric means.

---

### TABLE 1  
Magnitude of Error: Two-sample $t$ Test With Equal Variances

<table>
<thead>
<tr>
<th>Astigmatism Type</th>
<th>IOL Cylinder Power ≥ 2.5 D</th>
<th>IOL Cylinder Power ≤ 2 D</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean ± SD (D) (Range)</td>
<td>n</td>
</tr>
<tr>
<td>With-the-rule</td>
<td>0.06 ± 0.67 (-2.30 to +1.22)</td>
<td>33</td>
</tr>
<tr>
<td>Against-the-rule</td>
<td>-0.15 ± 0.52 (-1.23 to +1.25)</td>
<td>35</td>
</tr>
</tbody>
</table>

IOL = intraocular lens; D = diopters; SD = standard deviation  
*Magnitude of error is presented as a negative value for undercorrection and a positive value for overcorrection (surgically induced astigmatism – targeted-induced astigmatism).

### TABLE 2  
Magnitude of Error: One-sample $t$ Test Comparing Means to Zero

<table>
<thead>
<tr>
<th>Astigmatism Type</th>
<th>IOL Cylinder Power ≥ 2.5 D</th>
<th>IOL Cylinder Power ≤ 2 D</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean ± SD (D) (Range)</td>
<td>n</td>
</tr>
<tr>
<td>With-the-rule</td>
<td>0.06 ± 0.67 (-2.30 to +1.22)</td>
<td>33</td>
</tr>
<tr>
<td>Against-the-rule</td>
<td>-0.15 ± 0.52 (-1.23 to +1.25)</td>
<td>35</td>
</tr>
</tbody>
</table>

IOL = intraocular lens; D = diopters; SD = standard deviation

### TABLE 3  
Astigmatism Correction Index and Coefficient of Adjustment for Eyes With IOL Cylinder of 2 Diopters or Less

<table>
<thead>
<tr>
<th>Astigmatism Type</th>
<th>Astigmatism Correction Index*</th>
<th>Coefficient of Adjustment</th>
</tr>
</thead>
<tbody>
<tr>
<td>With-the-rule</td>
<td>1.38</td>
<td>0.73</td>
</tr>
<tr>
<td>Against-the-rule</td>
<td>0.65</td>
<td>1.53</td>
</tr>
</tbody>
</table>

IOL = intraocular lens  
*Values greater than 1 imply overcorrection.

### TABLE 4  
Astigmatism Correction Index and Coefficient of Adjustment for Eyes With IOL Cylinder of 2 Diopters or Less

<table>
<thead>
<tr>
<th>Astigmatism Type</th>
<th>Astigmatism Correction Index</th>
<th>Coefficient of Adjustment</th>
</tr>
</thead>
<tbody>
<tr>
<td>With-the-rule</td>
<td>1.34</td>
<td>0.75</td>
</tr>
<tr>
<td>Against-the-rule</td>
<td>0.71</td>
<td>1.41</td>
</tr>
</tbody>
</table>

IOL = intraocular lens  
*Excluding eyes with magnitude of error greater than 2 standard deviations from the mean.
To improve outcome prediction in subsequent eyes, the coefficient of adjustment can be applied to the corneal cylinder value using five steps (Appendix, available in the online version of this article) to calculate a more appropriate IOL cylinder power than that calculated by using unadjusted anterior corneal curvature measurements. For this purpose, to avoid the excessive effect of statistical outlying results on the mean coefficient of adjustment, data from eyes where the magnitude of the error was greater than two standard deviations from the mean for the relevant group were not used. This yielded astigmatism correction indices and coefficients of adjustment appropriate for use in nomogram adjustment, as shown in Table 4.

**Discussion**

The data presented show that average refractive astigmatism overcorrection occurs in eyes with with-the-rule corneal astigmatism that receive toric IOLs when the IOL cylinder power is calculated on the basis of anterior corneal astigmatism alone; undercorrection occurs in eyes with against-the-rule astigmatism.

For the total 133 eyes studied (both with-the-rule and against-the-rule), there was, on average, no clinically significant overcorrection or undercorrection (astigmatism correction index: 0.98). However, sub-group analysis demonstrated significant overcorrection confined to with-the-rule eyes receiving IOLs with cylinder powers of 2 D or less. Similarly, systematic undercorrection occurred in eyes with against-the-rule corneal astigmatism, but only in the same range of cylinder powers.

Overcorrection or undercorrection may be confined to those eyes requiring IOL cylinder powers of 2 D or less because the relatively small contribution of posterior corneal astigmatism is swamped in eyes with larger anterior corneal astigmatism. A systematic correction coefficient can be derived for these eyes, with lower astigmatism on the basis of the proportion of overcorrection or undercorrection. For eyes receiving the AT TORBI 709M(P) IOL of 2-D cylinder power or less, the coefficient of adjustment for with-the-rule and against-the-rule eyes was 0.75 and 1.41, respectively. Planning of toric IOL cylinder power using anterior keratometric astigmatism values adjusted by these coefficients is likely to reduce the average overcorrection or undercorrection related to the “rule” of corneal curvature. This overcorrection and undercorrection of astigmatism by IOLs related to “rule” is likely to be due to the finding that the steep meridian of the posterior cornea is vertically oriented in most eyes. However, this observation does not apply to all eyes and use of these coefficients would be inappropriate in them. A more generally applicable solution would be to measure the posterior cornea reliably in every eye with the assistance of a corneal tomographer. We have shown that one of these devices (Pentacam; Oculus Optikgeräte, Wetzlar, Germany) at least has demonstrable test-to-test variability that may make it unreliable for this purpose, meaning an adjustment of the keratometry on the basis of observed refractive results in a population of eyes is currently legitimate and likely to improve toric IOL refractive outcome in most eyes.

Koch et al. published a simple nomogram for adjusting IOL cylinder choice according to corneal astigmatism “rule.” Its purpose is to “take into account the mean values of posterior corneal astigmatism” and, when applied, “leave eyes with small amounts of with-the-rule refractive astigmatism.” This may allow for the “ongoing against-the-rule shift that occurs in most eyes.”

Our approach has not included an allowance for the against-the-rule shift on the principle that it is not universal and of varying degree, patient to patient. Our logic is that the fullest possible correction is preferable, particularly in patients with cataract (where long-term survival is not assured). Their published “Baylor nomogram” is based on observation of Alcon toric IOLs, which, of course, may differ from our data using Carl Zeiss Meditec IOLs. Alcon has been shown to underestimate effective corneal plane IOL cylinder power in their online calculator. Any IOL manufacturer’s online toric IOL calculator that does not include calculation of sphere or spherical equivalent power in conjunction with cylinder power may be prone to similar error. This error in calculation may reduce refractive astigmatic outcome for some eyes with a with-the-rule anterior corneal power value and increase it for against-the-rule anterior corneas. For optimal use of the coefficients of adjustment we described, a more accurate third party calculator that does include these calculations might be useful. Inherent differences in outcome due to lens design (as opposed to IOL cylinder power calculation) between manufacturers will not be addressed by the IOL cylinder power adjustment we suggest. However, the suggested adjustments are generic to the effect of anterior corneal “rule” and the likely effect of the posterior cornea.

In simplified terms, the Baylor nomogram suggests slightly less than 1 D of reduction in the implanted IOL cylinder powers versus the power calculated using anterior corneal power data alone in the cylinder power range of 1 to 4 D for with-the-rule eyes and an augmentation of just over 0.45 D for against-the-rule eyes. In principle, this will lead to greater proportional adjustment of lower powered cylinders similar to our suggested adjustment. However, it will also lead to a considerably
greater power adjustment in most IOLs with 2 D or less of cylinder power than our method. Furthermore, it adjusts implant power for eyes where we would suggest the IOL cylinder power is currently adequate to achieve full astigmatism correction (with IOL cylinder powers > 2 D). Notably, it does not allow for the alteration in corneal plane effective cylinder power induced by the variation of IOL sphere power. In contrast, our new approach has been to alter the anterior keratometric powers before final IOL calculation for the IOL cylinder and sphere power, specifically to avoid this source of error. The reason for limitation of overcorrection and undercorrection associated with “rule” to those eyes requiring an IOL cylinder power of 2 D or less requires further study.

We confirmed the average overcorrection and undercorrection of refractive astigmatism in eyes with with-the-rule and against-the-rule corneal astigmatism, respectively, requiring IOLs with up to 2 D of cylinder power as calculated using anterior corneal curvature data, but not for greater IOL cylinder powers. For eyes that would require 2 D or less of IOL cylinder power, we suggest alteration of the keratometric values used in toric IOL calculation by the coefficient of adjustment derived from separate populations of with-the-rule and against-the-rule eyes is the best currently available approach to improve the outcome. To our knowledge, this method has not previously been described. The data do not suggest a clinically or statistically significant problem in eyes receiving IOLs with 2.5 D or more of cylinder power. Continued use of good anterior corneal curvature data is reasonable in these eyes.

**AUTHOR CONTRIBUTIONS**

Study concept and design (LVZ, MG); data collection (LVZ, KZ-A, MG); analysis and interpretation of data (AE, MG); drafting of the manuscript (LVZ, KZ-A, AE, MG); critical revision of the manuscript (MG); statistical expertise (AE); supervision (MG)

**REFERENCES**

Step 1. Establish if the intraocular lens (IOL) required has a cylinder of 2 dipters (D) or less using routine anterior keratometric readings adjusted by the surgeon's previously established surgically induced corneal astigmatism value (it was a value of zero in this study because of the astigmatically neutral incision used). Make note of the keratometric spherical equivalent (KSEₘ) thus established. If the required IOL cylinder power is greater than 2 D, no adjustment is needed.

Example: Preoperative keratometric values, anterior cornea: 44.18/45.36 steep axis 96°. Sphere equivalent: 44.77 (KSEₘ). IOL cylinder, calculated on the basis of the anterior corneal data alone by the Carl Zeiss Meditec on-line calculator (Z Calc; Carl Zeiss Meditec, Jena, Germany [available at https://zcalc.meditec.zeiss.com/zcalc/]): 1.5D.

Step 2. For eyes that require IOL cylinder powers of 2 D or less on the basis of step 1, decide on the “rule” of the cornea based on the steep anterior corneal curvature meridian as above, and exclude eyes with “oblique” corneal astigmatism.

Example: Steep axis 96°: with-the-rule.

Step 3. In with-the-rule and against-the-rule eyes, calculate new corneal curvature data by applying the appropriate with-the-rule or against-the-rule coefficient of adjustment (CofA) to the surgeon’s routinely measured corneal cylinder power (Cₘ) to derive an adjusted cylinder power (Cₐ):

\[ Cₐ = Cₘ \times \text{CofA} \]

For with-the-rule eyes, the derived coefficient was 0.75; in against-the-rule eyes, it was 1.41 (Table 4).

Example: With-the-rule coefficient of adjustment: 0.75 (CofA). Anterior measures corneal cylinder power: 1.18 D (Cₘ); \[ 0.75 \times 1.18 = 0.88 \text{ D} \] (Cₐ)

Step 4. To avoid inducing sphere power error, new adjusted keratometric values should be calculated that do not change the keratometric spherical equivalent from that noted at the original keratometric measurement, as described above (KSEₘ). This can be achieved by subtracting half of the adjusted cylinder value (Cₐ/2) from the original KSEₘ value to derive an adjusted flat keratometric value (FKₐ). An adjusted steep keratometric value (SKₐ) can be derived by adding half of the adjusted cylinder value (Cₐ/2) to the original KSEₘ value:

\[ FKₐ = KSEₘ - Cₐ/2 \]
\[ SKₐ = KSEₘ + Cₐ/2 \]

Example: 0.88/2 = 0.44 (Cₐ); 44.77 - 0.44 = 44.33 D (FKₐ); 44.77 + 0.44 = 45.21D (SKₐ)

Step 5. These adjusted keratometric values (ie, FKₐ and SKₐ) can then be used to recalculate an adjusted toric IOL by using them in the online calculator instead of the original values. For this second calculation of IOL cylinder power, the surgeon’s usual surgically induced corneal astigmatism value should be used.

Example: IOL cylinder, calculated on the basis of these adjusted corneal data (FKₐ and SKₐ) and a corneal surgically induced astigmatism of zero by the Carl Zeiss Meditec on-line calculator (Z Calc): 1.0 D.