Correcting astigmatism with toric intraocular lenses: Effect of posterior corneal astigmatism

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PURPOSE: To evaluate the impact of posterior corneal astigmatism on outcomes with toric intraocular lenses (IOLs).

SETTING: Cullen Eye Institute, Baylor College of Medicine, Houston, Texas, USA.

DESIGN: Case series.

METHODS: Corneal astigmatism was measured using 5 devices before and 3 weeks after cataract surgery. Toric IOL alignment was recorded at surgery and at the slitlamp 3 weeks postoperatively. The actual corneal astigmatism was calculated based on refractive astigmatism 3 weeks postoperatively and the effective toric power calculated with the Holladay 2 formula. The prediction error was calculated as the difference between the astigmatism measured by each device and the actual corneal astigmatism. Vector analysis was used in all calculations.

RESULTS: With the IOLMaster, Lenstar, Atlas, manual keratometer, and Galilei (combined Placido–dual Scheimpflug analyzer), the mean prediction errors (D) were, respectively, 0.59 @ 89.7, 0.48 @ 91.2, 0.51 @ 78.7, 0.62 @ 97.2, and 0.57 @ 93.9 for with-the-rule (WTR) astigmatism (60 to 120 degrees), and 0.17 @ 86.2, 0.23 @ 77.7, 0.23 @ 91.4, 0.41 @ 58.4, and 0.12 @ 7.3 for against-the-rule (ATR) astigmatism (0 to 30 degrees and 150 to 180 degrees). In the WTR eyes, there were significant WTR prediction errors (0.5 to 0.6 diopters [D]) by all devices. In ATR eyes, WTR prediction errors were 0.2 to 0.3 D by all devices except the Placido–dual Scheimpflug analyzer (all P<.05 with Bonferroni correction).

CONCLUSIONS: Corneal astigmatism was overestimated in WTR by all devices and underestimated in ATR by all except the Placido–dual Scheimpflug analyzer. A new toric IOL nomogram is proposed.

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Accurate measurement of total corneal astigmatism in cataract patients is crucial for achieving optimum postoperative uncorrected visual acuity and patient satisfaction, especially with the implantation of toric intraocular lenses (IOLs). Traditionally, keratometers and Placido-disk corneal topographers have been used to measure the curvature of the anterior surface of the cornea and corneal power and astigmatism values have been calculated by assuming a fixed posterior:anterior curvature ratio. Since Jaffe and Clayman\(^1\) first analyzed the relationship between cataract surgical technique and refractive results in individual patients in 1975, ophthalmic surgeons have calculated surgically induced refractive change in an attempt to minimize postoperative corneal and ocular astigmatism. Unfortunately, several studies suggest that current methodology is inadequate for achieving optimum astigmatic outcomes. In 3 studies of results with toric IOLs,\(^2\)\(^\text{3–4}\) the mean postoperative refractive astigmatism after implantation of a toric IOL ranged from \(-0.72\) diopter (D) \pm 0.43 (SD) to \(-1.03 \pm 0.79\) D.

Traditionally, it has been assumed that the posterior cornea induces minimal refractive astigmatism and can therefore be ignored in astigmatic calculations. However, several studies using different methodologies\(^5\)\(^\text{–11}\) recently reported that the posterior cornea has astigmatism that ranges from 0.26 to 0.78 D. In our recent study,\(^11\) we found that in most eyes, the
posterior corneal steep meridian is aligned vertically and proposed a theory that for toric IOL implantation, ignoring the posterior corneal astigmatism would result in overcorrection in eyes having with-the-rule (WTR) anterior corneal astigmatism and undercorrection in eyes with against-the-rule (ATR) astigmatism. Validation of this theory in patients having toric IOL implantation is desirable.

The purposes of this study were (1) in eyes with toric IOLs, to evaluate the prediction errors of total corneal astigmatism with 5 devices, 1 of which uses Scheimpflug imaging and ray-tracing analysis to measure anterior and posterior corneal astigmatism and 4 of which measure the anterior surface only, and (2) to provide a nomogram for selecting the appropriate toric power for astigmatic correction that factors in posterior corneal astigmatism.

PATIENTS AND METHODS

Patients

Institutional review board approval was obtained for this study. Prospectively, patients who were willing to participate in this study and met the following inclusion criteria were enrolled from July 2011 to September 2012: (1) good quality scans with all 5 devices, (2) no previous ocular trauma or surgery, (3) no corneal or other ocular disease, (4) no contact lens wear within 2 weeks before the surgery, and proposed a theory that for toric IOL implantation, ignoring the posterior corneal astigmatism would result in overcorrection in eyes having with-the-rule (WTR) anterior corneal astigmatism and undercorrection in eyes with against-the-rule (ATR) astigmatism. Validation of this theory in patients having toric IOL implantation is desirable.

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Corneal Astigmatism Measurements

The following 5 devices were used for corneal astigmatism measurements in this study:

1. IOLMaster (Carl Zeiss Meditec AG). This PCI device measures corneal power by automated keratometry and uses data from a hexagonal array of 6 points reflected off the surface of the cornea at a diameter of approximately 2.5 mm, depending on the corneal curvature.
2. Lenstar (Haag-Streit AG). This optical low-coherence reflectometry (OLCR) device calculates keratometry (K) from an array of 32 light reflections projected off the anterior corneal surface. Sixteen measuring points on each eye are arranged in 2 rings at diameters of approximately 1.65 mm and 2.30 mm, respectively, again depending on the corneal curvature.
3. Atlas corneal topographer (Carl Zeiss Meditec AG). This Placido disk–based corneal topographer provides simulated K values along the steepest and flattest meridians at the 3.0 mm zone.
4. Manual kerometer (Bausch & Lomb). Manual keratometry is the conventional method for measuring corneal power at a diameter of approximately 3.0 mm, depending on the corneal curvature.
5. Galilei Placido–dual Scheimpflug analyzer (Ziemer Ophthalmic Systems AG). The anterior corneal measurements are made by a proprietary method of merging Placido and Scheimpflug data, and the posterior corneal surface is constructed using Scheimpflug data. The device calculates the total corneal power (TCP) using ray tracing, which propagates incoming parallel rays and uses Snell law to refract the rays through the anterior and posterior corneal surfaces.

Of the 5 devices, the first 4 systems measure anterior corneal curvature only and astigmatism values were calculated from the differences between the steep K and flat K values based on these anterior corneal data. For the Placido–dual Scheimpflug analyzer, the TCP astigmatism value, which is the difference between the steep TCP and flat TCP at the 1.0 to 4.0 mm central zone, was used. Corneal astigmatism was measured with all 5 devices at the preoperative and 3-week postoperative visits.

Biometry was performed using the PCI device and the OLCR device. The Holladay 1 formula was used for toric IOL power calculation. Selection of the toric IOL power and alignment was determined by the surgeons based on all data available and a previous study of posterior corneal astigmatism. Three surgeons (D.D.K., M.P.W., E.Y.) performed the surgeries through 2.4 mm clear corneal incision. The axis of the alignment of the toric IOL was recorded at the time of surgery and at the slitlamp during the 3-week postoperative visit. Manifest refraction was performed 3 weeks postoperatively.

Data Analysis

Eyes were divided into 2 groups depending on the anterior corneal steep meridian measured by the PCI device as follows: (1) WTR group with corneal steep meridian at 60 to 120 degrees and (2) ATR group with corneal steep meridian at 0 to 30 degrees or 150 to 180 degrees. Vector analysis was used in all calculations.12 To account for the impact of IOL power and anticipated effective lens position (ELP), the effective toric power of the IOL at the corneal plane was calculated using the Holladay 2 Consultant Program (Holladay Consulting). The assumed actual corneal astigmatism was calculated as the difference between the postoperative manifest refraction corrected to the corneal plane and the effective toric power. Then, for
each device, the corneal astigmatism prediction error, or the deviation from actual corneal astigmatism, was obtained by subtracting the actual corneal astigmatism from the corneal astigmatism measured by each device.

Analysis of aggregate corneal astigmatism prediction errors was performed. Using preoperative and postoperative corneal astigmatism measurements, preoperative and postoperative corneal astigmatism prediction errors were assessed for each device. The corneal astigmatism prediction errors were further analyzed as follows: (1) WTR/ATR prediction errors, which are displayed along the horizontal axis in the double-angle plot of the prediction errors, with negative values indicating WTR prediction errors (the device overestimates corneal WTR astigmatism compared with the actual amount) and positive values, ATR errors, and (2) oblique prediction errors, which are displayed along the vertical axis in the double-angle plot of the prediction errors, with positive values indicating oblique astigmatism prediction errors along 45 degrees and negative values, along 135 degrees.

**Statistical Analysis**

A sample-size calculation was performed to detect a corneal astigmatism prediction error of more than 0.2 D. The primary data showed that the standard deviation of corneal astigmatism prediction error was approximately 0.4 D. With a significance level of 5% and a test power of 80%, 32 eyes were required.

To assess whether the prediction errors were WTR/ATR or oblique, a 1-sample *t* test was performed to evaluate whether the mean vector component values were significantly different from zero. Bonferroni correction was used for multiple comparisons. Statistical analysis was performed using SPSS for Windows software (version 15.0, SPSS, Inc.). A probability of less than 5% (*P* < .05) was considered statistically significant.

**RESULTS**

Forty-one eyes of 41 patients were enrolled. The mean age of the 18 men and 23 women was 71 ± 9 years (range 46 to 91 years). The mean IOL power was 18.0 ± 6.0 D (range 6.0 to 28.0 D). *Table 1* shows the mean preoperative corneal astigmatism measured by each device. The mean postoperative refractive astigmatism was 0.08 × 11 and 0.12 × 148 in the WTR group and ATR group, respectively.

**Aggregate Corneal Astigmatism Prediction Errors**

With the 4 devices that measure anterior corneal curvature only, the mean preoperative and postoperative corneal astigmatism prediction errors in WTR eyes ranged from 0.27 to 0.62 D, all aligned along the vertical meridian (Figure 1, A to D) and in ATR eyes ranged from 0.17 to 0.37 D, also aligned along the vertical meridian (Figure 1, A to D). With the combined Placido–dual Scheimpflug analyzer TCP, the mean preoperative and postoperative corneal astigmatism prediction errors were 0.57 @ 93.9 and 0.26 @ 97.0, respectively, in the WTR eyes and 0.12 @ 7.3 and 0.18 @ 8.7, respectively, in the ATR eyes (Figure 1, E).

**With-the-Rule/Against-the-Rule and Oblique Corneal Astigmatism Prediction Errors**

In the WTR group, the WTR/ATR prediction errors ranged from −0.60 to −0.26 D and oblique prediction errors, from −0.26 to +0.20 D (Table 2). There were significant WTR prediction errors (0.5 to 0.6 D) by all devices except the Placido-disk corneal topographer and combined Placido–dual Scheimpflug analyzer postoperative measurements. There was a significant oblique prediction error of −0.26 D by the OLCR device for postoperative corneal astigmatism measurements (all *P* < .05 with Bonferroni correction). In the ATR group, the WTR/ATR prediction errors ranged from −0.29 to +0.17 D and oblique prediction errors, from −0.13 to +0.36 D. There were significant WTR prediction errors of 0.2 to 0.3 D by the PCI device, OLCR device, Placido-disk corneal topographer, and manual keratometer and oblique prediction errors of 0.3 to 0.4 D by manual keratometry corneal astigmatism (all *P* < .05 with Bonferroni correction). There was no significant WTR/ATR or oblique prediction error by the combined Placido–dual Scheimpflug analyzer.

**DISCUSSION**

Accurate correction of astigmatism requires accurate measurements. In this study, in eyes implanted with toric IOLs, we assessed the prediction errors of total corneal astigmatism using 4 devices that estimate total corneal astigmatism based on anterior surface measurements only and 1 device that measures both anterior and posterior corneal astigmatism.

To account for the ELP variations in different eyes, we used the Holladay 2 Consultant Program to calculate the effective toric power of the IOL at the corneal plane. Based on actual postoperative refractive
astigmatism, the actual total corneal astigmatism was determined; the corneal astigmatism prediction error for each device was then calculated.

With the 4 devices that had measurements from the anterior corneal surface only, the mean corneal astigmatism prediction errors were 0.5 to 0.6 D WTR in eyes with WTR corneal astigmatism and 0.2 to 0.3 D WTR in eyes with ATR corneal astigmatism for preoperative and postoperative corneal measurements. In a recent study, we found that (1) the posterior cornea is steeper along the vertical meridian in more than 85% of eyes and (2) the magnitude of posterior corneal astigmatism increased with increasing amounts of anterior corneal astigmatism in WTR.

**Figure 1.** Double-angle plots of preoperative and postoperative corneal astigmatism prediction errors in the WTR eyes (left) and ATR eyes (right) using the PCI device (A), OLCR device (B), Placido-disk corneal topographer (C), manual keratometry (D), and combined Placido-dual Scheimpflug analyzer TCP (E). (ATR = against the rule; PE = prediction error; WTR = with the rule).
Table 2. Mean corneal astigmatism prediction errors (D): WTR/ATR and oblique by each device.

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<tr>
<th>Parameter</th>
<th>WTR/ATR</th>
<th>WTR/ATR</th>
<th>Placido-Disk Topographer</th>
<th>Manual K</th>
<th>Placido-Dual Scheimpflug</th>
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<tr>
<td></td>
<td>Preop</td>
<td>Postop</td>
<td>Preop</td>
<td>Postop</td>
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<td>OLCR</td>
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In summary, our study found that using the devices that calculate total corneal astigmatism based on anterior corneal measurements only, WTR astigmatism exceeds the refractive astigmatism; however, when the axis is closer to ATR at 180 degrees, the refractive astigmatism has the greater value.

The difference between refractive and keratometric astigmatism has been attributed to an intracorneal astigmatic component, which is believed to be produced mainly by the lens (ie, lenticular astigmatism). However, 2 recent studies analyzed refractive and keratometric astigmatism in pseudophakic eyes and found that the relationship described by the simplified Javal rule holds true. Because the posterior cornea is a negative lens, refractive astigmatism with the steep meridian aligned vertically on the posterior surface produces net plus refractive power along the horizontal meridian. These findings point to posterior corneal astigmatism as the link between refractive and keratometric astigmatism and the explanation of the simplified Javal rule.

There are some limitations to this study. We of course did not actually measure the astigmatism induced by the toric IOL, so we cannot rule out effects from IOL tilt or variances in the actual toricity of the IOLs. We did not measure actual total corneal astigmatism but inferred it from other pertinent clinical data. We do not have a sound explanation for the greater-than-anticipated differences between the actual corneal astigmatism and the values calculated by the Galilei device. Possible explanations for this disparity are device inaccuracy, flaws in our methodology for calculating the actual corneal astigmatism, or some IOL tilt was present, creating an ATR refractive effect. However, it seems highly unlikely that tilt could be the source of the magnitude of prediction errors found in our patients because tilt was not detectable at the slitlamp examination.

In summary, our study found that using the devices that calculate total corneal astigmatism based on anterior corneal measurements only, WTR astigmatism
was overestimated by 0.5 to 0.6 D and ATR astigmatism was underestimated by 0.2 to 0.3 D. A toric IOL nomogram accounting for posterior corneal astigmatism is provided (Table 3). This nomogram takes into account the mean values of posterior corneal astigmatism that we found and aims to leave eyes into account the mean values of posterior corneal astigmatism. Examples: (1) If the cornea has 3.70 D WTR and surgically induced astigmatism is 0.20 D WTR, use the value of 1.70 D to select IOL toricity. (2) If the cornea has 3.70 D WTR and surgically induced astigmatism is 3.70 D WTR and surgically induced astigmatism, use the value of 3.9 D to select IOL toricity. (3) If the cornea has 1.90 D ATR and surgically induced astigmatism is 0.20 D WTR and surgically induced astigmatism is 0.20 D WTR, use the value of 1.70 D to select IOL toricity.

### Table 3. Baylor toric IOL nomogram (target range up to 0.40 D WTR). Values in the table are the vector sum of the anterior corneal and surgically induced astigmatism. Examples: (1) If the cornea has 3.70 D WTR and surgically induced astigmatism is 0.20 D WTR, use the value of 3.9 D to select IOL toricity. (2) If the cornea has 1.90 D ATR and surgically induced astigmatism is 0.20 D WTR, use the value of 1.70 D to select IOL toricity.

<table>
<thead>
<tr>
<th>Effective IOL Cylinder Power at Corneal Plane (D)</th>
<th>WTR (D)</th>
<th>ATR (D)</th>
</tr>
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<tr>
<td>0.00</td>
<td>≤1.69 (PCRI if &gt;1.00)</td>
<td>&lt;0.39</td>
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<tr>
<td>1.00</td>
<td>1.70–2.19</td>
<td>0.40–0.79</td>
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<tr>
<td>1.50</td>
<td>2.20–2.69</td>
<td>0.80–1.29</td>
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<tr>
<td>2.00</td>
<td>2.70–3.19</td>
<td>1.30–1.79</td>
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<tr>
<td>2.50</td>
<td>3.20–3.79</td>
<td>1.80–2.29</td>
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<td>3.00</td>
<td>3.80–4.39</td>
<td>2.30–2.79</td>
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<td>4.40–4.99</td>
<td>2.80–3.29</td>
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<td>4.00</td>
<td>5.00–</td>
<td>3.30–3.79</td>
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</table>


### WHAT WAS KNOWN

- Astigmatism is present on the posterior corneal surface, which is independent in magnitude and meridian from the astigmatism of the anterior surface.
- Residual postoperative astigmatism occurs often in eyes with toric IOL implantation.

### WHAT THIS PAPER ADDS

- In eyes with toric IOL implantation, corneal astigmatism prediction errors with devices that measure anterior corneal astigmatism only were 0.5 to 0.6 D WTR in WTR eyes and 0.2 to 0.3 D WTR in ATR eyes, showing the effect of posterior corneal astigmatism.
- A nomogram is proposed for toric IOL selection based on preoperative corneal astigmatism.

### REFERENCES


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