

# Contribution of posterior corneal astigmatism to total corneal astigmatism

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**PURPOSE:** To determine the contribution of posterior corneal astigmatism to total corneal astigmatism and the error in estimating total corneal astigmatism from anterior corneal measurements only using a dual-Scheimpflug analyzer.

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

**DESIGN:** Case series.

**METHODS:** Total corneal astigmatism was calculated using ray tracing, corneal astigmatism from simulated keratometry, anterior corneal astigmatism, and posterior corneal astigmatism, and the changes with age were analyzed. Vector analysis was used to assess the error produced by estimating total corneal astigmatism from anterior corneal measurements only.

**RESULTS:** The study analyzed 715 corneas of 435 consecutive patients. The mean magnitude of posterior corneal astigmatism was  $-0.30$  diopter (D). The steep corneal meridian was aligned vertically (60 to 120 degrees) in 51.9% of eyes for the anterior surface and in 86.6% for the posterior surface. With increasing age, the steep anterior corneal meridian tended to change from vertical to horizontal, while the steep posterior corneal meridian did not change. The magnitudes of anterior and posterior corneal astigmatism were correlated when the steeper anterior meridian was aligned vertically but not when it was aligned horizontally. Anterior corneal measurements underestimated total corneal astigmatism by  $0.22 \pm 0.18$  D and exceeded  $0.50$  D in 5% of eyes.

**CONCLUSIONS:** Ignoring posterior corneal astigmatism may yield incorrect estimation of total corneal astigmatism. Selecting toric intraocular lenses based on anterior corneal measurements could lead to overcorrection in eyes that have with-the-rule astigmatism and undercorrection in eyes that have against-the-rule astigmatism.

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Accurate measurement of total corneal astigmatism is a critical element in correcting astigmatism during cataract surgery. The anterior and posterior corneal surfaces contribute to total corneal astigmatism. Traditionally, however, corneal power and astigmatism have been calculated based on anterior corneal measurements only, assuming a fixed posterior:anterior curvature ratio to estimate the contribution of posterior corneal power. In these devices, which include manual and automated keratometers and Placido disk corneal topographers, a standardized corneal refractive index (1.3375 for most devices) is used to convert anterior measurements into total corneal power and astigmatism. Newer technologies, such as slit-scanning technology, Scheimpflug devices, and optical coherence

tomography, are now used in the clinical setting for measuring the posterior corneal surface.

Posterior corneal surface toricity has been evaluated by a variety of approaches, including Purkinje images, Scheimpflug photography in 6 or fewer fixed meridians,<sup>1–6</sup> scanning-slit imaging, and rotating Scheimpflug imaging.<sup>7–10</sup> In these studies, total corneal astigmatism was calculated by vector summation of anterior and posterior corneal astigmatism, assuming parallel rays approaching the posterior corneal surface and ignoring the contribution of corneal thickness.

The Galilei dual Scheimpflug analyzer (Ziemer Group) uses a dual-channel Scheimpflug camera and a Placido disk to measure anterior and posterior corneal surfaces. To date, it is the only device on the

market that uses ray tracing to calculate total corneal power and total corneal astigmatism. Ray tracing propagates incoming parallel rays and uses Snell's law to refract these rays through the anterior and posterior corneal surfaces. In this way, the refracted rays, instead of parallel rays, approach the posterior corneal surface. In our recent study,<sup>11</sup> we found that calculating posterior corneal power using the Gaussian formula and its paraxial assumptions introduces errors in the calculation of total corneal power.

The purpose of this study was to determine, using the dual Scheimpflug analyzer, (1) the contribution of posterior corneal astigmatism to overall corneal astigmatism and (2) the error introduced by estimating total corneal astigmatism from only anterior corneal measurements.

## PATIENTS AND METHODS

Institutional review board approval was obtained for this study. Retrospectively, this study reviewed consecutive patients who visited the clinic for cataract surgery and refractive surgery assessment and had corneal power measurements with the dual Scheimpflug analyzer from January 2008 to March 2011. Inclusion criteria were patients with (1) good-quality dual Scheimpflug analyzer scans (green check mark displayed on the map), (2) no previous ocular trauma or surgery, (3) no corneal or other ocular diseases, and (4) no contact lens use within 2 weeks of the dual Scheimpflug analyzer measurements.

## Corneal Astigmatism Measurements

The dual Scheimpflug analyzer was used to obtain the corneal measurements. The dual Scheimpflug analyzer calculates anterior corneal curvature values by a proprietary method of merging the Placido and Scheimpflug data. The posterior corneal surface is constructed using the Scheimpflug data. A previous study<sup>12</sup> assessed the repeatability and comparability of the anterior corneal power values obtained from the dual Scheimpflug analyzer, the Atlas device (Carl Zeiss Meditec), the IOLMaster device (Carl Zeiss Meditec), and a manual keratometer and found that the corneal power measurements from these 4 devices were highly reproducible and comparable. For posterior corneal

astigmatism measurements, the within-subject standard deviation (SD) values were 0.05 diopter (D) for astigmatism magnitude and 0.03 D for J0 (posterior corneal astigmatism along the 0-degree meridian) and J45 (posterior corneal astigmatism along the 45-degree meridian).<sup>13</sup> This device was calibrated by the company.

Four categories of corneal astigmatic values (CA) were obtained as follows:

1.  $CA_{TCP}$ : Corneal astigmatism from total corneal power (TCP) displayed on the device. The  $CA_{TCP}$  is calculated by ray tracing through the anterior and posterior corneal surfaces using the Snell law over the central 1.0 to 4.0 mm zone. This calculation of total corneal astigmatism combines the contributions of the anterior and posterior corneal surfaces and accounts for the effect of corneal thickness.
2.  $CA_{SimK}$ : Corneal astigmatism from simulated keratometry (K) over the 1.0 to 4.0 mm zone as displayed on the device. The magnitude of  $CA_{SimK}$  is the difference between steep simulated K and flat simulated K, and the meridian is the steep simulated K meridian. This value is calculated based on the anterior corneal measurement only.
3.  $CA_{ant}$ : Corneal astigmatism from the anterior corneal surface, which is calculated from  $CA_{SimK}$  by multiplying by  $(1.376 - 1.0)/(1.3375 - 1.0)$ , assuming that the refractive index of the air is 1.0, the refractive index of the cornea is 1.376, and the standardized corneal refractive index is 1.3375. The  $CA_{ant}$  meridian is the steep simulated K meridian.
4.  $CA_{post}$ : Corneal astigmatism from the posterior corneal surface over the 1.0 to 4.0 mm zone as displayed on the device, which is calculated with the indices of refraction of the cornea (1.376) and the aqueous humor (1.336) using the paraxial approximation with the assumption of parallel rays approaching the posterior corneal surface.

## Data Analysis

**Corneal Astigmatism** The mean magnitude, SD, and range of corneal astigmatism estimated by each of the 4 methods described above was calculated. For each method, the distribution (% eyes) of corneal astigmatism magnitudes up to 0.25 D, 0.50 D, 0.75 D, and 1.00 D was calculated.

**Correlation of Corneal Astigmatism of Anterior and Posterior Corneal Surfaces:  $CA_{ant}$  Versus  $CA_{post}$**  The correlation of magnitude and alignment of astigmatism on the anterior and posterior corneal surfaces was evaluated.

**Age-Related Changes in Astigmatism on Anterior and Posterior Corneal Surfaces** Eyes were further divided into subgroups depending on their age at the time of dual Scheimpflug analyzer measurement. To assess the changes in location of the steep meridian over time, the percentages of eyes with the steep meridian aligned vertically (60 to 120 degrees), obliquely (30 to 60 degrees or 120 to 150 degrees), and horizontally (0 to 30 degrees or 150 to 180 degrees) on the anterior and posterior corneal surfaces were calculated for each group. Aggregate corneal astigmatism was calculated using vector analysis.<sup>14</sup>

**Simulated Keratometry Corneal Astigmatism Estimation Error:  $CA_{TCP}$  Versus  $CA_{SimK}$**  Using  $CA_{TCP}$  as the gold standard, the  $CA_{SimK}$  estimation error was assessed by

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comparing the  $CA_{SimK}$  and the  $CA_{TCP}$ . Using vector analysis,<sup>14</sup> double-angle plots were generated and the vector difference in astigmatism ( $CA_{TCP} - CA_{SimK}$ ) was calculated. To assess the magnitude of astigmatism estimation error by the  $CA_{SimK}$ , the differences in magnitude of astigmatism between  $CA_{TCP}$  and  $CA_{SimK}$  and the percentages of eyes with differences up to 0.25 D and 0.50 D were calculated. To assess intraocular lens (IOL) misalignment error or steep meridian estimation error by the  $CA_{SimK}$ , the differences in location of steep meridian and percentages of eyes within 5 degrees and 10 degrees were evaluated.

**Case Sample** A sample case was introduced to show corneal astigmatism measurements before cataract surgery and the results after IOL implantation.

### Statistical Analysis

Correlation analysis was used to assess the relationship between (1) the magnitude of astigmatism on the anterior and posterior corneal surfaces and (2) the differences in the steep meridian on anterior and posterior surfaces and the differences in magnitude between  $CA_{TCP}$  and  $CA_{SimK}$ . A chi-square test was used to compare the proportion data between groups, and a Bonferroni correction was used for multiple comparisons. SPSS for Windows software (version 15.0, SPSS, Inc.) was used for statistical analysis. A  $P$  value less than 0.05 was considered statistically significant.

### RESULTS

The study comprised 715 eyes of 435 patients. The mean age of the patients was 55 years  $\pm$  20 (SD) (range 20 to 89 years). The subgroups of eyes based on age at the time of dual Scheimpflug analyzer measurement were as follows: (1) 101 eyes of 56 patients from 20 to 29 years, (2) 104 eyes of 60 patients from 30 to 39 years, (3) 101 eyes of 57 patients from 40 to 49 years, (4) 101 eyes of 64 patients from 50 to 59 years, (5) 101 eyes of 63 patients from 60 to 69 years, (6) 105 eyes of 66 patients from 70 to 79 years, and (7) 102 eyes of 69 patients from 80 to 89 years.

### Corneal Astigmatism

Table 1 shows the magnitudes of the 4 calculations of corneal astigmatism. The mean magnitude of posterior corneal astigmatism was  $-0.30 \pm 0.15$  D (range  $-0.01$  to  $-1.10$  D). Posterior corneal astigmatism was

0.25 D or less in 43.1% (308 eyes) and exceeded 0.50 D in 9.0% (64 eyes) of eyes (Table 1).

### Correlation of Corneal Astigmatism on Anterior and Posterior Corneal Surfaces: $CA_{ant}$ Versus $CA_{post}$

Vertical alignment of the steep corneal meridian was seen in 50.9% (364 eyes) for the anterior cornea and in 86.8% (619 eyes) for the posterior cornea (Figure 1). Following were the correlations between the magnitudes of corneal astigmatism on the anterior and posterior corneal surfaces: (1) moderate when the steep anterior meridian was aligned vertically (correlation coefficient  $r = 0.56$ ,  $P < .001$ ) (Figure 2, top), (2) weak when the steep anterior meridian was oriented obliquely ( $r = 0.37$ ,  $P < .001$ ) (Figure 2, middle), and (3) no correlation when the steep meridian on the anterior corneal surface was aligned horizontally ( $r = -0.08$ ,  $P = .26$ ) (Figure 2, bottom).

### Age-Related Changes in Astigmatism on Anterior and Posterior Corneal Surfaces

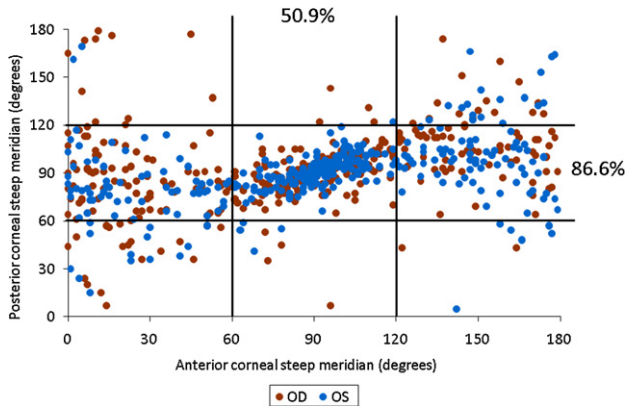
On the anterior corneal surface, with increasing age, the percentage of eyes with vertical alignment of the steep meridian decreased significantly from 78.2% (79 eyes) in patients in their 20s to 16.7% (17 eyes) of patients in their 80s, and the percentage of eyes with a horizontal steep meridian increased significantly from 6.9% (7 eyes) to 60.8% (62 eyes) (both  $P < .05$ ) (Figure 3, top). On the posterior corneal surface, there was a slight decrease in percentage of eyes with a vertically aligned meridian and a slight increase in the percentage with a horizontally aligned steep meridian; these changes were not statistically significant (both  $P > .05$ ) (Figure 3, bottom).

On the anterior corneal surface, with increasing age, the aggregate mean astigmatism shifted from with-the-rule (WTR) astigmatism (vertical steep meridian) to against-the-rule (ATR) astigmatism (horizontal steep meridian). In contrast, on the posterior corneal surface, the aggregate mean astigmatism changed minimally (Table 2).

**Table 1.** Corneal astigmatism magnitude (N = 715).

Parameter	Magnitude (D)		Percentage of Eyes			
	Mean $\pm$ SD	Range	$\leq 0.25$ D	$\leq 0.50$ D	$\leq 0.75$ D	$\leq 1.00$ D
$CA_{TCP}$	$1.07 \pm 0.71$	0.03, 4.26	7.0	22.0	38.5	54.4
$CA_{SimK}$	$1.08 \pm 0.71$	0.02, 4.40	5.3	21.8	37.1	54.4
$CA_{ant}$	$1.20 \pm 0.79$	0.02, 4.90	4.3	18.2	31.6	46.9
$CA_{post}$	$-0.30 \pm 0.15$	$-0.01, -1.10$	43.1	91.0	99.3	99.9

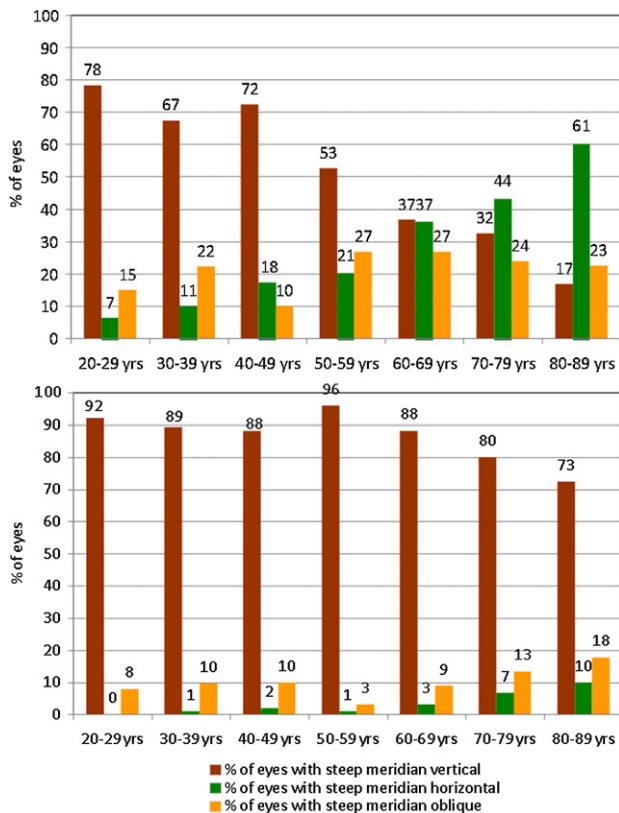
$CA_{ant}$  = corneal astigmatism from the anterior corneal surface;  $CA_{post}$  = corneal astigmatism from the posterior corneal surface;  $CA_{SimK}$  = corneal astigmatism from simulated keratometry;  $CA_{TCP}$  = corneal astigmatism from total corneal power



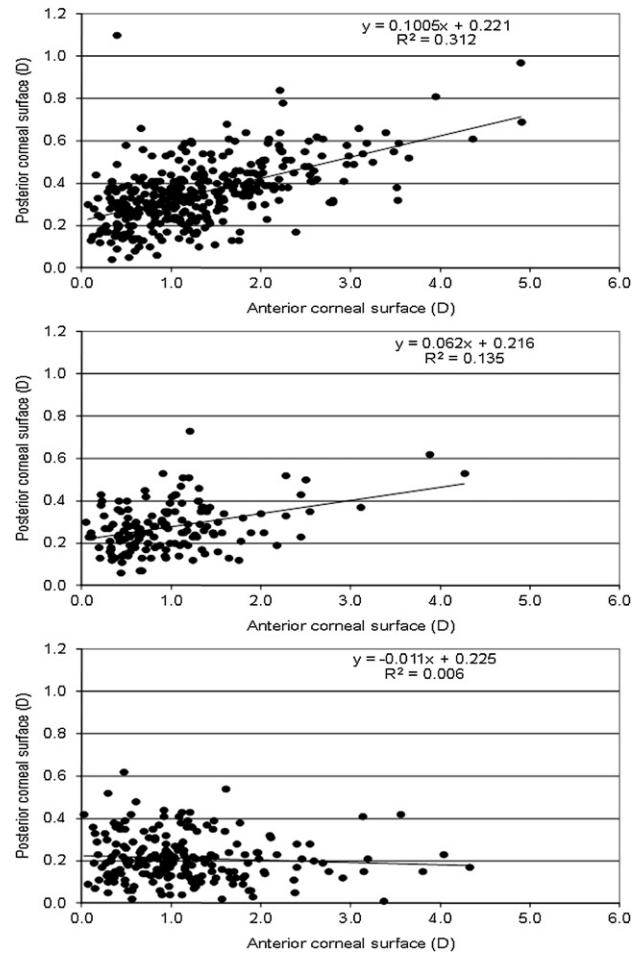
**Figure 1.** Location of steep meridian on anterior and posterior corneal surfaces.

### Simulated Keratometry Corneal Astigmatism Estimation Error: CA<sub>TCP</sub> Versus CA<sub>SimK</sub>

The aggregate mean astigmatism was  $+0.09 \pm 0.87$  @ 105 for CA<sub>TCP</sub>, and  $+0.30 \pm 0.85$  @ 95 for CA<sub>SimK</sub> (Figure 4). The mean vector difference between CA<sub>TCP</sub> and CA<sub>SimK</sub> was  $0.22 \pm 0.14$  @ 180 (Figure 5); 53.0% (379 eyes), 95.1% (680 eyes), and 99.8% (714 eyes) had vector differences of within  $\pm 0.25$  D,  $\pm 0.50$  D, and  $\pm 1.00$  D, respectively. The differences in



**Figure 3.** Percentage of eyes with vertical, horizontal, and oblique steep meridian in each decade on anterior corneal surface (top) and posterior corneal surface (bottom).



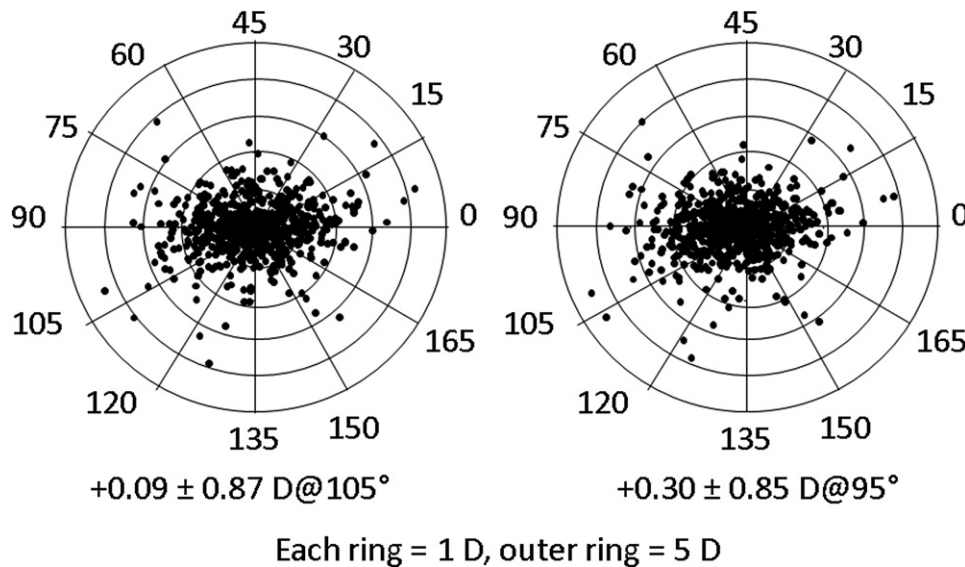
**Figure 2.** Magnitude of astigmatism on the anterior corneal surface and posterior corneal surface grouped according to the orientation of the steep meridian on the anterior cornea. Top: Vertical ( $r = 0.56$ ,  $P < .001$ ). Middle: Oblique ( $r = 0.37$ ,  $P < .001$ ). Bottom: horizontal ( $r = -0.08$ ,  $P = .26$ ).

magnitude between CA<sub>TCP</sub> and CA<sub>SimK</sub> significantly increased with increasing differences in the steep meridian location between anterior and posterior corneal astigmatism ( $r = 0.85$ ,  $P < .01$ ) (Figure 6).

The arithmetic differences in the magnitude of astigmatism between CA<sub>TCP</sub> and CA<sub>SimK</sub> ranged from  $-0.62$  to  $+1.22$  D, with an arithmetic mean of  $-0.01$

**Table 2.** Aggregate anterior and posterior corneal astigmatism.

Age (Y)	Mean $\pm$ SD (D) @ Degree	
	Anterior Cornea	Posterior Cornea
20-29	$0.85 \pm 0.72$ @ 92.72	$-0.28 \pm 0.13$ @ 91.76
30-39	$1.01 \pm 1.00$ @ 93.79	$-0.28 \pm 0.17$ @ 91.40
40-49	$0.78 \pm 0.99$ @ 93.13	$-0.28 \pm 0.16$ @ 90.96
50-59	$0.39 \pm 0.81$ @ 91.73	$-0.26 \pm 0.14$ @ 91.59
60-69	$0.05 \pm 0.79$ @ 118.93	$-0.24 \pm 0.15$ @ 90.84
70-79	$0.18 \pm 0.85$ @ 172.96	$-0.20 \pm 0.16$ @ 91.79
80-89	$0.60 \pm 1.02$ @ 3.96	$-0.17 \pm 0.17$ @ 91.40



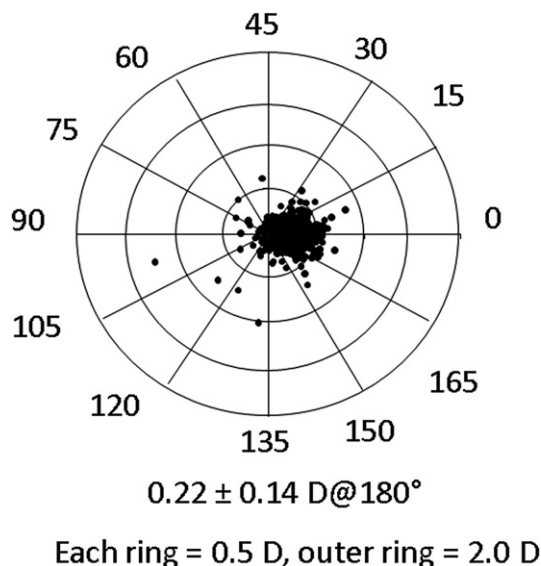
**Figure 4.** Double-angle plots of corneal astigmatism from total corneal power (*left*) and corneal astigmatism from simulated K (*right*).

± 0.23 D and absolute mean of  $0.19 \pm 0.13$  D; 71.3% (510 eyes) and 97.9% (700 eyes) had differences within ± 0.25 D and ± 0.50 D, respectively. The differences in the location of the steep meridian between  $CA_{TCP}$  and  $CA_{SimK}$  ranged from 0 to 89 degrees, with a mean of  $7 \pm 11$  degrees; 64.1% (458 eyes) and 82.8% (592 eyes) had differences within ± 5 degrees and ± 10 degrees, respectively.

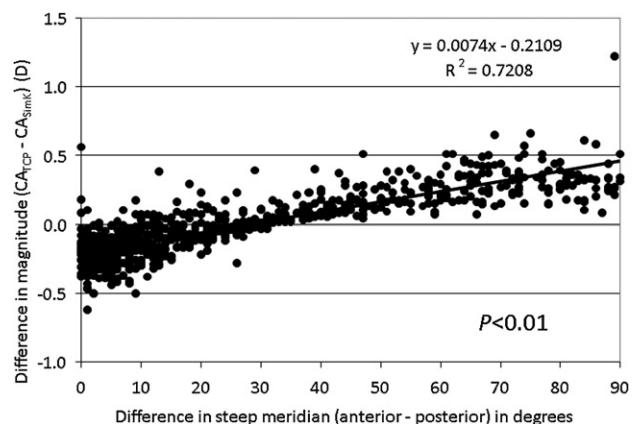
### Case Sample

A 41-year-old woman presented for preoperative evaluation for cataract surgery. In the right eye, the

uncorrected distance visual acuity (UDVA) was 20/40, the manifest refraction was  $+0.25 + 1.50 \times 165$  with a corrected distance visual acuity of 20/40, and retinoscopic refraction was  $+0.50 + 1.50 \times 160$ . The measured corneal astigmatism was 1.52 @ 79 with Atlas corneal topography, 1.40 @ 86 with the IOLMaster device, and 1.45 @ 82 with the Lenstar device. Using the dual Scheimpflug analyzer,  $CA_{post}$  was  $-0.40 @ 95$  and  $CA_{TCP}$  was  $0.63 @ 159$ . Because of the uncertainty produced by the disparity between refractive and anterior corneal astigmatism, a monofocal IOL was implanted. Three weeks postoperatively, the UDVA was



**Figure 5.** Double-angle plot of vector difference between corneal astigmatism from total corneal power and simulated K.



**Figure 6.** Differences between anterior corneal steep meridian and posterior corneal steep meridian as a function of the differences in magnitude between  $CA_{TCP}$  and  $CA_{SimK}$  ( $r = 0.85$ ,  $P < .01$ ) ( $CA_{SimK}$  = corneal astigmatism from simulated keratometry;  $CA_{TCP}$  = corneal astigmatism from total corneal power).

**Table 3.** Published values of mean posterior astigmatism.

Study*	Imaging Modality Used	Eyes/Patients (n)	Mean Age (Y) $\pm$ SD	Posterior Astigmatism (D)	
				Mean $\pm$ SD	Range
Royston <sup>1</sup>	Purkinje images (Polaroid camera)	5/5	—	0.38 <sup>†</sup>	0.17, 0.78
Dunne <sup>3</sup>	Purkinje images (Polaroid camera)	60/60	22.0 $\pm$ 3.3	0.26 <sup>†</sup>	
Prisant <sup>7</sup>	Scanning-slit topography (Bausch & Lomb Orbscan)	40/31	—	0.66 $\pm$ 0.23	0.32, 1.38
Módis <sup>8</sup>	Scanning-slit topography (Bausch & Lomb Orbscan)	44/44	61.4 $\pm$ 16.4	0.78 $\pm$ 0.61	0.16, 3.30
Dubbelman <sup>6</sup>	Scheimpflug photography in 6 fixed meridians (Topcon SL-45 camera)	114/114	39 $\pm$ 14	0.31	—
Ho <sup>10</sup>	Rotating Scheimpflug imaging (Oculus Pentacam)	493/493	41.1 $\pm$ 21.9	0.33	0.00, 0.94
Current	Rotating Scheimpflug imaging (Ziemer Galilei DSA)	715/435	55 $\pm$ 20	0.30	0.01, 1.10

\*First author

<sup>†</sup>Values for posterior corneal astigmatism were published in radii of curvature (mm) and were converted to diopters for purpose of comparison.

20/25 and the manifest refraction was  $-0.25$  D sphere. The IOL was well centered and without discernible tilt.

## DISCUSSION

Because of the smaller difference in refractive indices between the cornea and aqueous, it has been thought that the magnitude of posterior corneal astigmatism is clinically negligible.<sup>15</sup> However, the posterior surface has greater toricity than the anterior surface.<sup>3,6</sup> Using various methodologies, including Purkinje images, Scheimpflug photography in 6 or fewer meridians, rotating Scheimpflug imaging, and scanning-slit topography, studies<sup>1,3,6-8,10</sup> have reported mean values for posterior corneal astigmatism that range from  $-0.26$  to  $-0.78$  D (Table 3). In our case series, the mean posterior corneal astigmatism was  $-0.30$  D, and 9% of eyes had astigmatism of more than 0.50 D. This value is similar to those reported previously. Remarkably, the existence of clinically important posterior corneal astigmatism was first postulated by Javal,<sup>16</sup> who in his 1890 publication in *Memoires d'Ophthalmometrie* described the eponymous Javal rule, which mathematically characterizes the relationship between refractive astigmatism and keratometric astigmatism.

The ray-tracing method implemented in the dual Scheimpflug analyzer uses the Snell law to calculate total corneal power and total corneal astigmatism. This approach, instead of assuming that parallel rays reach the posterior corneal surface, accounts for the refraction of rays by the anterior corneal surface and thereby more accurately calculates total corneal power and total corneal astigmatism.<sup>11</sup> To our knowledge, this is the first study to (1) evaluate the estimation error of total corneal astigmatism obtained from anterior corneal measurements only using the total corneal astigmatism calculated from ray tracing as the gold standard, (2) describe the correlation of anterior and

posterior corneal astigmatism as a function of the steep anterior corneal meridian, and (3) propose a theory to explain unanticipated outcomes in eyes with toric IOL implantation by ignoring the posterior corneal astigmatism.

Using vector analysis with CA<sub>TCP</sub> as the reference standard, the estimation error for CA<sub>SimK</sub> was 0.22 @ 180 on average, and 5% of eyes had an error greater than 0.50 D. Because the posterior corneal surface has negative power, steeper curvature in the vertical meridian creates ATR astigmatism; therefore, most TCP measurements (which incorporate posterior corneal astigmatism) showed more power at 180 degrees than the CA<sub>SimK</sub> measurements. As an estimation of total corneal astigmatism, simulated K produced IOL toricity selection error or magnitude of astigmatism estimation error of more than 0.50 D in 2.1% of eyes and IOL misalignment error or location of steep meridian estimation error of more than 10 degrees in 17.2% of eyes.

In our study, there was a moderate positive correlation between the magnitude of corneal astigmatism on the anterior and posterior corneal surfaces when the steep meridian on the anterior cornea was oriented vertically. However, the strength of this correlation decreased in eyes with the steep anterior corneal meridian aligned obliquely, and no correlation was found in eyes whose steep anterior corneal meridian was aligned horizontally. However, in all groups, there was clinically important variability in the magnitude of posterior corneal astigmatism. For example, in corneas having approximately 1.00 D of WTR astigmatism, posterior corneal astigmatism ranged from less than 0.10 D to more than 0.50 D. These data indicate that the only way to accurately assess the magnitude or optical impact of posterior corneal astigmatism is to measure it directly (as with the dual Scheimpflug analyzer) or indirectly (as with intraoperative aberrometry).

We also found that with increasing age, the anterior corneal steep meridian shifted from vertical to horizontal, whereas the posterior corneal steep meridian did not change. This indicates that posterior corneal astigmatism often partially compensates for anterior corneal astigmatism in young adults (ie, those with the steep corneal meridian aligned vertically) and is often additive to anterior corneal astigmatism in older individuals (ie, those with the steep meridian aligned horizontally).

Using the Pentacam to measure anterior and posterior corneal curvature, Ho et al.<sup>9</sup> evaluated the accuracy of corneal astigmatic values when posterior corneal measurements are not performed. They found the mean error vector with the keratometric corneal astigmatism was 0.28 @ 177.2, similar to our finding. They also found that the steep meridian was aligned vertically in 71.8% of eyes on the anterior cornea and in 96.1% of eyes on the posterior cornea, values that are higher than our findings (50.9% and 86.6%, respectively). In a subsequent study,<sup>10</sup> the same group studied the effects of aging on anterior and posterior corneal astigmatism. Using polar values, they found that with increasing age, the posterior cornea became less steep vertically and more steep horizontally on the posterior cornea. Although statistically significant, the association between age and the change on the posterior cornea was weak, with an  $r^2$  value of 0.12. On the posterior cornea, the percentage of eyes with WTR astigmatism or with the steep meridian aligned horizontally increased from 0% in the 21 to 30 year age group to 9.1% in the 71 and older age group. In our study, on the posterior cornea, the percentage of eyes with steep meridian aligned horizontally increased from 0% in the 20s to 7% in the 70s and 10% in the 80s. The similarity in findings is striking, despite the following methodology differences: (1) Different devices were used (Pentacam rotating Scheimpflug versus Galilei dual Scheimpflug analyzer). (2) Different methods were used to calculate the gold standard of total corneal astigmatism (vector summation of anterior and posterior corneal astigmatism in their study versus ray tracing in ours). (3) Younger patients were included in their first study (6 to 85 years versus 20 to 89 years). (4) The radius of curvature in the 3.0 mm ring was used in their study, whereas astigmatism over the 1.0 to 4.0 mm zone was used in our study.

We believe that there are 2 key implications of our study. First, one cannot confidently predict the amount of posterior corneal astigmatism from anterior measurements only. Second, posterior corneal astigmatism may affect the outcome of astigmatic surgical interventions that are based on anterior corneal

measurements only. For example, failure to account for a vertically steep posterior corneal curvature (and the ATR ocular astigmatism it produces) will cause overcorrection of eyes having WTR anterior corneal astigmatism and undercorrection of eyes having ATR anterior corneal astigmatism. In our case sample, a typical approach might have been to implant a toric IOL to correct the more than 1.00 D of anterior corneal astigmatism; however, this would have overcorrected the astigmatism by approximately 1.00 D (in addition to increasing the costs to the patient).

Limitations of this study were that (1) both eyes of some patients were included; however, we analyzed the subgroup of right eyes from each patient and found similar results (not shown), so we included all eyes in this study to have a sample size of more than 100 eyes in each age group; (2) we have no way to validate the accuracy of posterior corneal measurements because no test object or other calibration method is available; (3) we used 1 sample case to support our theory. A study evaluating the astigmatic outcome in eyes implanted with toric IOLs is underway, and the preliminary results support our theory.<sup>A</sup>

In summary, our study showed that 9% of eyes had posterior corneal astigmatism in excess of 0.50 D and that posterior corneal astigmatism tends to partially compensate for anterior corneal astigmatism in young adults and to increase total corneal astigmatism in older individuals. In patients having cataract surgery, the incorrect estimation of total corneal astigmatism that can occur by ignoring the posterior corneal astigmatism could lead to errors in astigmatic correction. Because in most eyes posterior corneal astigmatism is aligned vertically, this error for toric IOL implantation would be overcorrection in eyes with WTR anterior corneal astigmatism and undercorrection in eyes with ATR astigmatism. Validation of this theory in patients having toric IOL implantation is underway.

#### WHAT WAS KNOWN

- As determined by a range of methodologies, the magnitude of posterior corneal astigmatism is approximately 0.30 D.

#### WHAT THIS PAPER ADDS

- Correlations between anterior and posterior corneal astigmatism varied according to the alignment of the steep corneal meridian; however, the magnitude and alignment of total corneal astigmatism could not be accurately predicted from anterior corneal measurements.
- Ignoring posterior corneal astigmatism could cause unanticipated outcomes in eyes having toric IOL implantation.

## REFERENCES

1. Royston JM, Dunne MCM, Barnes DA. Measurement of posterior corneal surface toricity. *Optom Vis Sci* 1990; 67:757–763. Available at: [http://journals.lww.com/optvissci/Abstract/1990/10000/Measurement\\_of\\_Posterior\\_Corneal\\_Surface\\_Toricity.2.aspx](http://journals.lww.com/optvissci/Abstract/1990/10000/Measurement_of_Posterior_Corneal_Surface_Toricity.2.aspx). Accessed August 7, 2012
2. Royston JM, Dunne MCM, Barnes DA. Measurement of the posterior corneal radius using slit lamp and Purkinje image techniques. *Ophthalmic Physiol Opt* 1990; 10:385–388
3. Dunne MCM, Royston JM, Barnes DA. Posterior corneal surface toricity and total corneal astigmatism. *Optom Vis Sci* 1991; 68:708–710. Available at: [http://journals.lww.com/optvissci/Abstract/1991/09000/Posterior\\_Corneal\\_Surface\\_Toricity\\_and\\_Total.6.aspx](http://journals.lww.com/optvissci/Abstract/1991/09000/Posterior_Corneal_Surface_Toricity_and_Total.6.aspx). Accessed August 7, 2012
4. Dunne MCM, Royston JM, Barnes DA. Normal variations of the posterior corneal surface. *Acta Ophthalmol (Copenh)* 1992; 70:255–261
5. Dubbelman M, Weeber HA, van der Heijde RGL, Völker-Dieben HJ. Radius and asphericity of the posterior corneal surface determined by corrected Scheimpflug photography. *Acta Ophthalmol Scand* 2002; 80:379–383. Available at: <http://onlinelibrary.wiley.com/doi/10.1034/j.1600-0420.2002.800406.x/pdf>. Accessed August 7, 2012
6. Dubbelman M, Sicam VADP, van der Hijde GL. The shape of anterior and posterior surface of the aging human cornea. *Vision Res* 2006; 46:993–1001
7. Prisant O, Hoang-Xuan T, Proano C, Hernandez E, Awwad ST, Azar DT. Vector summation of anterior and posterior corneal topographical astigmatism. *J Cataract Refract Surg* 2002; 28:1636–1643
8. Módis L Jr, Langenbucher A, Seitz B. Evaluation of normal corneas using the scanning-slit topography/pachymetry system. *Cornea* 2004; 23:689–694
9. Ho J-D, Tsai C-Y, Tsai RJ-F, Kuo L-L, Tsai I-L, Liou S-W. Validity of the keratometric index: evaluation by the Pentacam rotating Scheimpflug camera. *J Cataract Refract Surg* 2008; 34:137–145
10. Ho J-D, Tsai C-Y, Liou S-W. Accuracy of corneal astigmatism estimation by neglecting the posterior corneal surface measurement. *Am J Ophthalmol* 2009; 147:788–795
11. Wang L, Mahmoud AM, Anderson BL, Koch DD, Roberts CJ. Total corneal power estimation: Ray tracing method versus Gaussian optics formula. *Invest Ophthalmol Vis Sci* 2011; 52:1716–1722. Available at: <http://www.iovs.org/content/52/3/1716.full.pdf>. Accessed August 7, 2012
12. Shirayama M, Wang L, Weikert MP, Koch DD. Comparison of corneal powers obtained from 4 different devices. *Am J Ophthalmol* 2009; 148:528–535
13. Wang L, Shirayama M, Koch DD. Repeatability of corneal power and wavefront aberration measurements with a dual-Scheimpflug Placido corneal topographer. *J Cataract Refract Surg* 2010; 36:425–430
14. Holladay JT, Moran JR, Kezirian GM. Analysis of aggregate surgically induced refractive change, prediction error, and intraocular astigmatism. *J Cataract Refract Surg* 2001; 27:61–79
15. Cheng L-S, Tsai C-Y, Tsai RJ-F, Liou S-W, Ho J-D. Estimation accuracy of surgically induced astigmatism on the cornea when neglecting the posterior corneal surface measurement. *Acta Ophthalmol* 2011; 89:417–422. Available at: <http://onlinelibrary.wiley.com/doi/10.1111/j.1755-3768.2009.01732.x/pdf>. Accessed August 7, 2012
16. Javal É. *Mémoires d'Ophtalmométrie: Annotés et Précédés d'une Introduction*. Paris, France, G. Masson, 1890; 131

## OTHER CITED MATERIAL

- A. Koch DD, “The Charles D. Kelman Innovator’s Lecture. Corneal Optics for IOL Selection: Cracking the Code,” presented at the ASCRS Symposium on Cataract, IOL and Refractive Surgery, Chicago, Illinois, USA, April 2012