Influence of posterior corneal astigmatism on total corneal astigmatism in eyes with moderate to high astigmatism

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PURPOSE: To evaluate the influence of posterior corneal astigmatism on total corneal astigmatism in patients with 1.00 diopter (D) or more of corneal astigmatism.

SETTING: Private practice, Bologna, Italy.

DESIGN: Prospective case series.

METHODS: Corneal astigmatism was measured using a Scheimpflug camera combined with a corneal topographer (Sirius). Keratometric astigmatism, anterior corneal astigmatism, posterior corneal astigmatism, and total corneal astigmatism were evaluated. Vector analysis was performed according to the Næser method.

RESULTS: One hundred fifty-seven eyes were enrolled. Keratometric astigmatism was with the rule (WTR), against the rule (ATR), and oblique in 84.0%, 11.5%, and 4.5% of eyes, respectively. Posterior corneal astigmatism exceeded 0.50 D and 1.00 D in 55.4% of eyes and 5.7% of eyes, respectively. The mean posterior corneal astigmatism was 0.54 D, inclined 91 degrees in relation to the steeper anterior corneal meridian. The steepest meridian was vertically aligned in 93.0% of cases. Compared with total corneal astigmatism, keratometric astigmatism overestimated WTR astigmatism by a mean of 0.22 D $\pm$ 0.32 (SD), underestimated ATR astigmatism by 0.21 $\pm$ 0.26 D, and overestimated oblique astigmatism by 0.13 $\pm$ 0.37 D. In the whole sample, a difference in astigmatism magnitude of 0.50 D or more was detected between keratometric astigmatism and total corneal astigmatism in 16.6% of cases and the difference in the location of the steep meridian was greater than 10 degrees in 3.8% of cases.

CONCLUSION: In patients who are candidates for surgical correction of astigmatism, measuring only the anterior corneal curvature can lead to inaccurate evaluation of the total corneal astigmatism.

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Uncorrected astigmatism, even when as low as 1.00 diopter (D), can significantly affect distance and near visual acuity and lead to patient dissatisfaction after cataract surgery.[1,2] Today, the most common solution for treating preexisting corneal astigmatism during phacoemulsification is the implantation of toric intraocular lenses (IOLs). The amount of corneal astigmatism to be corrected by these IOLs is assessed by subtracting the power of the flattest corneal meridian from the steepest corneal meridian. In these cases, the corneal power is calculated using the keratometric refractive index (so-called keratometric astigmatism). The keratometric refractive index, which is usually 1.3375, aims to calculate the power of a fictitious single refractive surface (meant to represent both the anterior and posterior corneal surfaces) without knowing the curvature of the posterior corneal surface. This simplification was necessary until a few years ago because instruments to measure posterior corneal astigmatism were not commercially available. However, since slit-scanning topography and Scheimpflug imaging gained wide popularity, several investigators have addressed the influence of posterior corneal astigmatism on total corneal astigmatism and found that because the dioptric

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power of the anterior surface is positive and that of the posterior surface is negative, the astigmatism of the anterior corneal surface is partially compensated for by that of the posterior corneal surface. The compensation has been reported to range between 13.4% and 31.0%[3,4] and the vector difference between total corneal astigmatism and keratometric astigmatism to range between 0.22 @ 180 and 0.28 @ 177.2.[4,5]

The vector difference between the magnitude of keratometric astigmatism and total corneal astigmatism is higher than 0.50 D in up to 23.7% of eyes.[4] The difference between the location of the steep meridian in keratometric astigmatism versus the total corneal astigmatism is higher than 10 degrees in 17.2% to 23.7% of eyes.[4,5]

Contradicting results, however, have been reported. Srivannaboon et al.,[6] for example, did not observe a compensatory effect of posterior corneal astigmatism but rather found that the total corneal astigmatism overestimated the keratometric astigmatism. Moreover, all previous studies included patients with minimal to low astigmatism (<1.00 D), whereas our attention should be focused on eyes with more than 1.00 D of corneal astigmatism; that is, the minimum amount of preoperative astigmatism that is usually corrected when a toric IOL is implanted.

In the present study, we enrolled only patients who had more than 1.00 D of corneal astigmatism. We aimed to measure the magnitude and axis of posterior corneal astigmatism in the whole sample and in eyes that have with-the-rule (WTR), oblique, or against-the-rule (ATR) astigmatism; assess the influence of posterior corneal astigmatism by analyzing the relationship between keratometric astigmatism and total corneal astigmatism in eyes with WTR, oblique, or ATR astigmatism; and determine whether simulated keratometry (K) overestimates the cylinder in all eyes with WTR astigmatism and underestimates it in all eyes with ATR astigmatism.

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PATIENTS AND METHODS

The study was performed in accordance with the ethical standards stated in the 1964 Declaration of Helsinki and approved by the local clinical research ethics committee. All patients provided informed consent. The G.B. Bietti Foundation Institutional Review Board also approved the study.

Between January 2012 and December 2012, this study enrolled all patients who had an ophthalmologic examination for cataract surgery, refractive surgery assessment, or simple spectacle prescription and had more than 1.00 D of astigmatism based on simulated K values as defined below. Inclusion criteria were good-quality Scheimpflug–Placido scans (confirmed by internal software), no previous ocular trauma or surgery, no corneal or other ocular disease, and no contact lens use for at least 2 weeks before the measurements.

Corneal Astigmatism Measurements

Corneal curvature measurements were obtained using a Scheimpflug camera combined with Placido corneal topography (Sirius, software version 2.5, Costruzione Strumenti Oftalmici). The scanning process acquires a series of 25 Scheimpflug images (meridians) and 1 Placido top-view image. The ring edges are detected on the Placido image so that height, slope, and curvature data are calculated using the arc-step method with conic curves. From the Scheimpflug images, profiles of the anterior cornea, posterior cornea, anterior lens, and iris are derived. Anterior surface data from the Placido images and Scheimpflug images are merged using a proprietary method. All the other measurements for internal structures (posterior corneal curvature, anterior lens surface, and iris) are derived solely from Scheimpflug data. Previous studies report that the system's pachymetric and shape measurements (curvature, eccentricity, elevation) have good repeatability.[7–10]

The same experienced examiner performed all measurements according to the manufacturer's guidelines. The device was brought into focus, and the patient's eye was aligned along the visual axis using a central fixation light. One scan was obtained for each patient. Every examination was critically reviewed to assess the quality of the topographic and tomographic images, alignment, and anterior and posterior coverage; in cases of poor quality, a new scan was performed or the patient's data were excluded.

Four categories of corneal astigmatism values were obtained as follows:

1. Keratometric astigmatism was defined as the difference between the power of the steepest and flattest corneal meridians measured by simulated K (ie, simulation of the measurements obtained using a keratometer).[11] For this purpose, the combined Placido–Scheimpflug device uses the axial curvature of the anterior corneal surface. Because a keratometer cannot measure curvatures across the corneal vertex, an annular zone centered on the corneal vertex from the fourth to the eighth Placido ring is extracted (Figure 1). The zone considered, therefore, has a variable radius depending on the curvature of the cornea; in the average eye, it ranges from 1.0 to 1.8 mm. The mean values of the curvatures along each meridian are calculated. The principal meridians are selected by choosing the pair of orthogonal meridians that maximizes the ratio of their corresponding average curvatures. The corneal

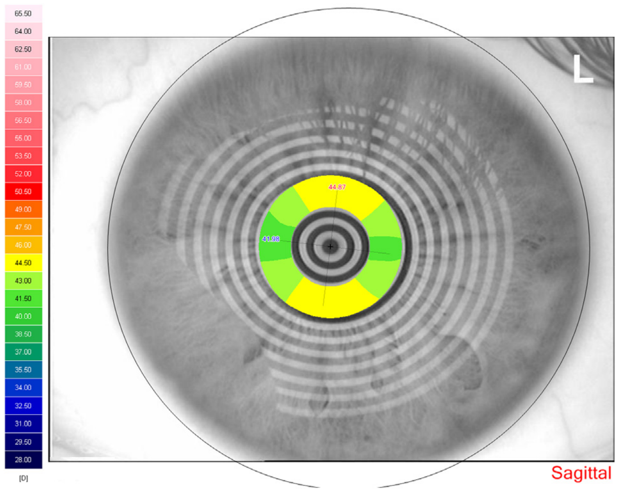

Figure 1. Area used to calculate keratometric astigmatism and anterior corneal astigmatism.

radii (r), measured in millimeters, are converted into dioptric power (P) using the formula $P=(n-1)/r$, where n is the keratometric index of refraction (1.3375).

2. Anterior corneal astigmatism was measured in the same manner as keratometric astigmatism except the radii were converted into power using the corneal refractive index (1.376) instead of the keratometric index of refraction.
3. Posterior corneal astigmatism was defined as the difference between the posterior corneal surface power of the steepest and flattest meridians. For the purpose of this calculation, the axial curvature of the posterior corneal surface inside a 3.0 mm circular zone centered on the vertex is considered. The measured corneal radii (r) are converted into power (P) using the formula $P=(1.336-1.376)/r$.
4. Total corneal astigmatism was defined as the total corneal astigmatism measured through ray tracing and wavefront error estimation. To make this measurement, a bundle of rays parallel to the instrumental axis and passing into the entrance pupil of the eye are traced through the anterior and posterior corneal surfaces using Snell's law. For each incoming ray, its intersection with the anterior corneal surface and its angle of incidence relative to the anterior surface normal are calculated. The ray refracted by the anterior surface is obtained using Snell's law with $n_{air} = 1.0$ and $n_{stroma} = 1.376$. This ray is then considered an incoming ray for the posterior corneal surface, and the same procedure as above is applied to calculate the ray refracted by this surface using Snell's law with $n_{stroma} = 1.376$ and $n_{aqueous} = 1.336$. All the traced rays are used to calculate the wavefront error; that is, the difference between the measured wavefront and an ideal spherical wavefront. The wavefront error is then fitted using Zernike polynomials as follows:

$$\mathrm{WFE}(\rho,\theta)=\sum_{n-0}^{N-1}\sum_{m=-n}^{n}c_n^m Z_n^m(\rho,\theta)$$

where

$$Z_n^m(\rho,\theta)$$

is the polar Zernike polynomial with the nth radial order and mth frequency and

$$c_n^m$$

is the corresponding coefficient. Thus, the magnitude (cyl) and the orientation (ax) of the cylindrical defect are calculated as

$$\mathrm{cyl}=\frac{4\sqrt{6}}{R_{mm}^2}\sqrt{\left(c_2^{-2}\right)^2+\left(c_2^{+2}\right)^2}$$

$$\mathrm{ax}=\frac{1}{2}\tan^{-1}\left(\frac{c_2^{-2}}{c_2^{+2}}\right)$$

where R_{mm} is the pupil radius in millimeters and c_2^{-2} and c_2^{+2} are expressed in microns. A pupil diameter of 3.0 mm was chosen, although the device offers the option of selecting a diameter ranging between 2.0 mm and 7.0 mm.

For better data consistency, total corneal astigmatism values were calculated with reference to the corneal vertex because keratometric astigmatism and posterior corneal astigmatism are both calculated with reference to it. (Usually, the device's software calculates total corneal astigmatism with reference to the pupil center.)

The steep meridian was considered vertical (ie, WTR astigmatism) when its axis ranged between 61 degrees and 119 degrees, horizontal (ie, ATR astigmatism) when its axis ranged between 0 degree and 30 degrees and between 150 degrees and 180 degrees, and oblique when its axis ranged between 31 degrees and 60 degrees and between 120 degrees and 149 degrees.

Analysis of Posterior Corneal Astigmatism in Relation to Steeper Anterior Meridian

Net astigmatism is given as (M @ α), where M is the astigmatic magnitude in diopters and α is the astigmatic direction in degrees.[12] This format can be used to characterize a single astigmatism but cannot be used for calculations that require transformation to components, as in the case of the polar value system.

Any net astigmatism is fully characterized by the curvital and torsional powers, where the former is the power acting along a given reference meridian Φ and the latter is the power twisting the astigmatic direction out of that plane. Simplifying and reducing equations from Næser,[12]

$$\begin{aligned}\text{Curvital power} &= \text{polar value along the meridian } \Phi = \mathrm{KP}(\Phi)\\ &= \mathrm{M}\times\cos[2\times(\alpha-\Phi)]\end{aligned}\tag{1}$$

$$\begin{aligned}\text{Torsional power} &= \text{polar value along the meridian } (\Phi+45)\\ &= \mathrm{KP}(\Phi+45)=\mathrm{M}\times\sin[2\times(\alpha-\Phi)]\end{aligned}\tag{2}$$

The reference plane Φ was the direction of the steeper anterior corneal meridian in the calculations of posterior corneal astigmatism.

For Φ = 0 degrees = 180 degrees, the polar values reduce to

$$\mathrm{KP}(0)=\mathrm{C}\times\cos 2\alpha\tag{3}$$

$$\mathrm{KP}(45)=\mathrm{C}\times\sin 2\alpha\tag{4}$$

Equations 3 and 4, with fixed references to the 0/180 and 45/135 degree meridians, were used to calculate the mean values shown in Table 1.

Table 1. Mean astigmatism values. Polar values along fixed meridians of 0/45 degrees (equations 3 and 4) were used to calculate the various mean net astigmatisms.

Parameter	Eyes (n)	KA (D)	CA_{Ant} (D)	CA_{Post} (D)	TCA (D)
Total	157	1.80 @ 93	1.99 @ 93	0.52 @ 3	1.57 @ 93
WTR	132	2.35 @ 92	2.61 @ 92	0.60 @ 3	2.13 @ 92
ATR	18	1.84 @ 1	2.05 @ 1	0.01 @ 168	2.00 @ 1
Oblique	7	1.39 @ 127	1.54 @ 125	0.40 @ 19	1.27 @ 131

ATR = against the rule; CA_{Ant} = anterior corneal astigmatism; CA_{Pos} = posterior corneal astigmatism; KA = keratometric astigmatism; TCA = total corneal astigmatism; WTR = with the rule

Any single set of polar values and the result of any compilation of polar values may be reconverted to the usual net cylinder notation by means of the following general equations[12]:

$$M = \sqrt{KP(\phi)^2 + KP(\phi + 45^2)} \qquad (5)$$

$$\alpha = \arctan\left|\frac{M - KP(\phi)}{KP(\phi + 45)}\right| + \phi \qquad (6)$$

Statistical Analysis

Statistics were performed using Graphpad Instat for Macintosh software (version 3a, Graphpad Software, Inc.) and Excel software (version 2010, Microsoft Corp.). The Gaussian distribution of data was assessed with the Kolmogorov-Smirnov method. A *P* value less than 0.05 was considered statistically significant. Measurements were compared using paired and unpaired *t* tests. Linear regression was used to quantify how well the measurements varied together.

RESULTS

One hundred fifty-seven eyes of 87 patients were analyzed. The mean age was 44.43 years ± 15.99 (SD) (range 13 to 84 years). On the anterior corneal surface, the steeper meridian was vertical in 132 eyes (84.0%), horizontal in 18 eyes (11.5%), and oblique in 7 eyes (4.5%).

Table 1 shows the mean keratometric astigmatism, anterior corneal astigmatism, posterior corneal astigmatism, and total corneal astigmatism values. The posterior corneal astigmatism was 0.25 D or lower in 14 eyes (8.9%), exceeded 0.50 D in 87 eyes (55.4%), and exceeded and 1.00 D in 9 eyes (5.7%). The steepest posterior corneal meridian was vertically aligned in 146 eyes (93.0%).

Correlation of Corneal Astigmatism of Anterior and Posterior Corneal Surfaces: Keratometric Astigmatism Versus Posterior Corneal Astigmatism

Across the whole sample, a significant correlation was found between the magnitude of keratometric

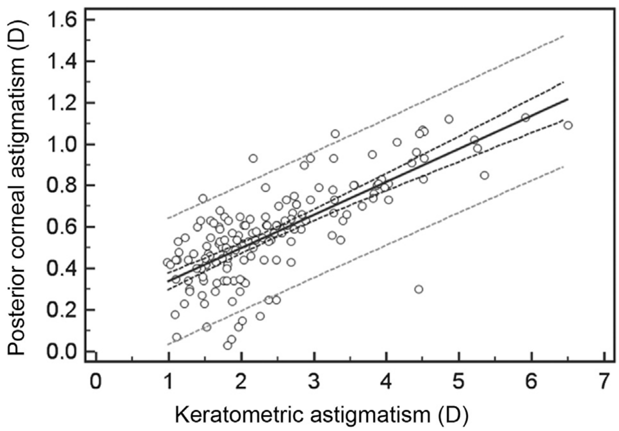

Figure 2. Correlation between the magnitude of posterior corneal astigmatism and keratometric astigmatism across the whole sample. The outer dotted lines represent the 95% prediction. The inner dotted lines represent the 95% confidence interval.

astigmatism and posterior corneal astigmatism ($P < .0001$, $r = 0.7538$, $r^2 = 0.5683$) (Figure 2). The equation that best fit the data was posterior corneal astigmatism = 0.1819 + 0.1594 × keratometric astigmatism. A similar correlation was found when posterior corneal astigmatism and keratometric astigmatism curvital powers were analyzed in relation to the steeper anterior meridian according to equation 1 ($P < .0001$, $r = 0.5772$, $r^2 = 0.3331$). The equation that best fit these data was posterior corneal astigmatism = 0.1649 + 0.1593 × keratometric astigmatism.

In eyes with the steepest anterior vertical meridian, the steepest posterior meridian was always vertical (thus generating an ATR astigmatism on the posterior corneal surface). The magnitude of the posterior corneal astigmatism ranged between 0.23 D and 1.13 D. In these eyes, a significant correlation was found between the magnitude of keratometric astigmatism and posterior corneal astigmatism ($P < .0001$, $r = 0.7969$) as well as between their axes ($P < .0001$, $r = 0.8453$).

In eyes with the steepest anterior horizontal meridian, the steepest meridian on the posterior corneal surface was vertical in 10 cases (55.6%), horizontal in 5 cases (27.8%), and oblique in 3 cases (16.7%). The magnitude of posterior corneal astigmatism ranged between 0.03 D and 0.44 D. No correlation was found between the magnitude and axis of keratometric astigmatism and posterior corneal astigmatism.

In eyes with the steepest anterior oblique meridian, the steepest meridian on the posterior corneal surface was vertical in 5 cases (71.4%) and oblique in 2 cases (28.6%). The magnitude of posterior corneal astigmatism ranged between 0.18 D and

Table 2. Posterior corneal astigmatism with the steeper anterior corneal meridian as the reference plane. All measurements are reported as polar values. The net astigmatism in the right column was calculated with equations 5 and 6 from the mean torsional and curvital powers. Statistical assessment was performed only for the total group because the number of eyes in the ATR group and oblique group was too small for meaningful analysis. The unpaired *t* test showed that the mean curvital power was significantly different from zero, while the mean torsional power did not show such a difference. For the total group, the mean posterior corneal astigmatism was 0.54 D inclined 91 degrees relative to the steeper anterior corneal meridian.

Group	Curvital Power (D) KP(Φ)	Torsional Power (D) KP(Φ + 45)	Net Astigmatism (D @ º)
WTR (132 eyes)			
Mean ± SD	−0.61 ± 0.20	−0.02 ± 0.11	0.61 @ 91
Range	−1.13, −0.20	−0.35, 0.31	—
ATR (18 eyes)			
Mean ± SD	−0.05 ± 0.19	0.01 ± 0.16	0.05 @ 86
Range	−0.37, 0.34	−0.33, 0.29	—
Oblique (7 eyes)			
Mean ± SD	−0.40 ± 0.17	0.13 ± 0.25	0.42 @ 81
Range	−0.71, −0.17	−0.43, 0.39	—
Total (157 eyes)			
Mean ± SD	−0.54 ± 0.27	−0.01 ± 0.13	0.54 @ 91
Range	−1.13, 0.34	−0.43, 0.39	—
P value*	<.0001	.27	—

Φ = reference plane; ATR = against the rule; KP(Φ) = curvital power; KP(Φ + 45) = torsional power; WTR = with the rule
*Unpaired *t* test

0.73 D. In these eyes, a significant correlation was found between the magnitude of keratometric astigmatism and posterior corneal astigmatism ($P<.0035$, $r = .9186$) as well as between their axes ($P<.0028$, $r = 0.9643$).

Table 2 shows the results of posterior corneal astigmatism analysis using the steeper anterior corneal meridian as the reference plane. The posterior corneal curvital power averaged −0.54 D while the mean torsional power was close to zero. The average net astigmatism was 0.54 D inclined 91 degrees relative to the steeper anterior corneal meridian. This means that the posterior corneal astigmatism exerted a power of −0.54 D along the direction of the steeper anterior corneal meridian. On average, the flatter posterior corneal meridian was therefore orthogonal to the steeper anterior corneal meridian, and the 2 steeper meridians coincided; however, large variations were observed. Some curvital powers were positive. In such cases, the steeper anterior and the flatter posterior meridians were aligned. Subgroup analyses showed a mean posterior corneal astigmatism of 0.61 @ 91 and 0.42 @ 81 for the vertical and oblique steeper anterior corneal meridians, respectively. In eyes with ATR astigmatism, the mean posterior corneal astigmatism was essentially zero and positive curvital powers were observed in this subgroup only.

Comparison of Keratometric Astigmatism Estimation and Total Corneal Astigmatism: Total Corneal Astigmatism Versus Keratometric Astigmatism

The analysis of the total corneal astigmatism with reference to the steeper meridian of keratometric astigmatism showed that compared with total corneal astigmatism, keratometric astigmatism overestimated astigmatism by 0.16 @ 91 in the whole group. The mean torsional power of total corneal astigmatism compared with keratometric astigmatism was 0.01 ± 0.27 D (range −0.86 to 1.33 D) ($P=.69$), meaning a low difference in axis orientation. Regarding the astigmatism subgroups, keratometric astigmatism overestimated WTR astigmatism by a mean of 0.22 ± 0.32 D, underestimated ATR astigmatism by a mean of 0.21 ± 0.26 D, and overestimated oblique astigmatism by a mean of 0.13 ± 0.37 D.

Table 3 shows the percentage of eyes with overestimation or underestimation greater than 0.50 and 1.00 D. In most cases, keratometric astigmatism overestimated WTR astigmatism and underestimated ATR astigmatism. However, in approximately 20% of eyes, the opposite was true (ie, keratometric astigmatism underestimated WTR astigmatism and overestimated ATR astigmatism). In the sample as a whole, a difference in astigmatism magnitude of 0.50 D or greater was detected in 26 eyes (16.6%); this rate increases to 18.2% if only eyes with keratometric astigmatism of 2.00 D or more were considered and to 21.6% if only eyes with keratometric astigmatism of 3.00 D or more were considered.

Overall, the difference in the location of the steep meridian as determined by keratometric astigmatism versus total corneal astigmatism was higher than 10 degrees in 6 eyes (3.8%). Of eyes with WTR astigmatism, 4 (3.0%) had an axis disagreement of more than 10 degrees. Such disagreement was observed in 1 (5.5%) of 18 eyes with ATR astigmatism and 1 (14.3%) of 7 eyes with oblique astigmatism.

Equations 1 and 2 were used to compare anterior corneal astigmatism and total corneal astigmatism (with the steeper anterior corneal meridian as the reference plane) because the difference between these 2 values better reflects the influence of posterior corneal astigmatism and can be compared with direct measurements of posterior corneal astigmatism. Table 4 shows the results of this comparison and

Table 3. Comparison between keratometric astigmatism and total corneal astigmatism in measuring astigmatism.

	Underestimation by KA		No Diff	Overestimation by KA		
Astigmatism	0.50–1.00 D	0.01–0.49 D	0.00 D	0.01–0.49 D	0.50–1.00 D	>1.00 D
WTR (%)	2.2	17.9	2.2	63.4	12.7	2.2
ATR (%)	11.1	66.7	—	22.2	—	—
Oblique (%)	—	42.9	—	42.9	14.3	—

ATR = against the rule; Diff = difference; KA = keratometric astigmatism; TCA = total corneal astigmatism; WTR = with the rule

the net astigmatism, which was calculated using equations 5 and 6. In the whole group, the mean total corneal astigmatism and anterior corneal astigmatism curvital powers averaged 2.28 D and 2.72 D, with practically no torsional component. This means that total corneal astigmatism and anterior corneal astigmatism were coincident; that is, the magnitude and direction of the total astigmatism were predominantly determined by anterior corneal astigmatism. The paired differences in net astigmatism (total corneal astigmatism − anterior corneal astigmatism) were very close to the direct calculation of posterior corneal astigmatism, the results of which are shown in Table 2.

DISCUSSION

Total corneal astigmatism has been traditionally calculated on the basis of anterior corneal curvature without information about the posterior corneal surface. To take into account the effect of the latter, the keratometric index (in most cases 1.3375) has been usually adopted when converting the anterior corneal curvature into the power of a fictitious thin lens representing the power of both corneal surfaces. This approach can generate inaccurate calculations. The availability of technologies such as Scheimpflug imaging and optical coherence tomography, which are able to image the posterior corneal curvature, has enabled us to measure the curvature and calculate the power of both corneal surfaces. Moreover, a few studies[4,5] have shown that posterior corneal astigmatism can have a significant influence on total corneal astigmatism; thus, traditional readings (based on the anterior corneal curvature only) may not be quite accurate.

Our study primarily aimed to measure the magnitude and axis of posterior corneal astigmatism and assess its influence on total corneal astigmatism in patients who may be considered surgical candidates (ie, with corneal astigmatism more than 1.00 D). We intentionally excluded eyes with lower astigmatism for several reasons. First, they do not usually have surgical correction of astigmatism; second, their data may generate noise; and third, they have been evaluated in previous studies.[4,5]

We used 2 types of vector analysis in the calculations. First, polar values along fixed meridians of zero/45 degrees were used to calculate the mean net astigmatisms. This method, which is similar to Thibos and Horner's J0 and J45 values,[13] works well to describe populations. Second, for a unique description of posterior corneal astigmatic direction and magnitude in preparation for refractive surgery, we thought that a reference meridian should be individualized. We chose the steeper anterior corneal meridian in each eye as our reference. (See pages 13 and 14 of the paper by Næser[12] for a comprehensive description of these methods.) The advantage of using the steeper anterior corneal meridian as a reference for vector calculations is that surgical procedures such as implantation of toric IOLs and limbal relaxing incisions are placed according to this meridian and surgeons have to know the influence of posterior astigmatism along the steeper anterior corneal meridian. If direct measurement of total astigmatism is not possible and only anterior corneal astigmatism can be determined, the presently described statistical evaluations of posterior corneal astigmatism should be considered. For example, Tables 2 and 4 suggest that in an eye with WTR astigmatism of 1.5 @ 90 (calculated with the 1.376 refractive index), only 1.00 D of astigmatism should be removed. The 0.5 D residual WTR anterior corneal astigmatism will be canceled by the negative posterior corneal astigmatism in the vertical meridian. In contrast, in an eye with 1.5 @ 0 ATR astigmatism, all astigmatism should be removed.

In the whole sample, the mean posterior corneal astigmatism was 0.52 @ 3; however, large variations were observed because more than 55% of eyes had posterior corneal astigmatism of more than 0.50 D and in some cases, of more than 1.00 D. Important differences were observed between eyes with WTR, ATR, or oblique astigmatism because the mean value

Table 4. Total corneal astigmatism measured by ray tracing with the steeper anterior corneal meridian as the reference plane. The values for anterior corneal astigmatism and the difference between total corneal astigmatism and anterior corneal astigmatism are also shown. Statistical assessment was only performed for the group as a whole because the number of eyes in the ATR and oblique subgroups was too small for meaningful analysis. The paired *t* test showed a statistically significant difference between anterior corneal astigmatism and total corneal astigmatism curvital power but no difference between torsional powers. Equations 5 and 6 were used to calculate the net astigmatism in the right column from the mean torsional and curvital powers. All measurements are shown as polar values.

Group	Curvital Power (D) KP(Φ)	Torsional Power (D) KP(Φ + 45)	Net Astigmatism (D @ º)
WTR (132 eyes)			
TCA			
Mean ± SD	2.31 ± 1.17	0.00 ± 0.24	2.31 @ 0
Range	0.49, 6.83	−0.67, 1.33	—
CA_{Ant}			
Mean ± SD	2.82 ± 1.26	0.00 ± 0.00	2.82 @ 0
Range	1.09, 7.24	—	—
TCA − CA_{Ant}			
Mean ± SD	−0.50 ± 0.35	0.00 ± 0.24	0.50 @ 90
Range	−1.61, 0.49	−0.67, 1.33	—
ATR (18 eyes)			
TCA			
Mean ± SD	2.22 ± 0.66	−0.09 ± 0.32	1.87 @ 0
Range	1.13, 4.14	−0.69, 0.77	—
CA_{Ant}			
Mean ± SD	2.24 ± 0.78	0.00 ± 0.00	2.24 @ 0
Range	1.24, 4.94	—	—
TCA − CA_{Ant}			
Mean ± SD	−0.02 ± 0.30	−0.09 ± 0.32	0.09 @ 129
Range	−0.80, 0.45	−0.86, 0.33	—
Oblique (7 eyes)			
TCA			
Mean ± SD	1.87 ± 0.58	−0.03 ± 0.50	2.22 @ 179
Range	1.06, 2,95	−0.86, 0.33	—
CA_{Ant}			
Mean ± SD	2.23 ± 0.63	0.00 ± 0.00	2.00 @ 0
Range	1.21, 2,98	—	—
TCA − CA_{Ant}			
Mean ± SD	−0.36 ± 0.40	−0.03 ± 0.50	0.36 @ 92
Range	−1.24, 0.01	−0.69, 0.77	—
Total (157 eyes)			
TCA			
Mean ± SD	2.28 ± 1.10	−0.01 ± 0.27	2.28 @ 0
Range	0.49, 6.83	−0.86, 1.33	—
CA_{Ant}			
Mean ± SD	2.72 ± 1.21	0.00 ± 0.00	2.72 @ 0
Range	1.10, 7.24	—	—
TCA − CA_{Ant}			
Mean ± SD	−0.44 ± 0.38	−0.01 ± 0.27	0.44 @ 91
Range	−1.61,0,49	0.86, 1.33	—
P value*	<.0001	.69	

Φ = reference plane; ATR = against the rule; CA_{Ant} = anterior corneal astigmatism; KP(Φ) = curvital power; KP(Φ + 45) = torsional power; TCA = total corneal astigmatism; WTR = with the rule
*Paired *t* test

of posterior corneal astigmatism was, respectively, 0.60 @ 3, 0.01 @ 168, and 0.40 @ 19. Our results on the magnitude of the posterior corneal astigmatism differ from those in previous studies. In our sample, the percentage of eyes in which posterior corneal astigmatism exceeded 0.50 D and 1.00 D was 55.4% and 5.7%, respectively. In a study by Koch et al.,[5] only 9.0% of eyes had posterior astigmatism with a magnitude of more than 0.50 D. This difference can be explained by the fact that we enrolled only patients with keratometric astigmatism over 1.00 D, whereas the sample of Koch et al. also included a large number of eyes with lower astigmatism. Differences in the measuring device may also have contributed to this discrepancy.

Regarding the axis of posterior corneal astigmatism, our results are in good agreement with those in previous studies.[3–5] We found that the steepest posterior meridian was almost always vertically aligned; the proportion of eyes with a vertically aligned steepest meridian on the posterior corneal surface was 93.0% in our sample and had been reported to range between 86.8% and 96.1% in previous studies.[3–5] The few cases with horizontally aligned posterior corneal astigmatism were eyes with ATR keratometric astigmatism.

Overall, the meridian of posterior corneal astigmatism was aligned with that of the anterior astigmatism, as shown by the fact that the mean torsional power of posterior corneal astigmatism was close to zero. In the group as a whole, the mean power of posterior corneal astigmatism was 0.54 D inclined 91 degrees relative to the steeper anterior corneal meridian (ie, a negative power of approximately 0.5 D along the meridian of the steeper anterior corneal meridian). Subgroup analyses showed a mean orthogonally inclined posterior corneal astigmatism of 0.61 D and 0.42 D for the vertical and oblique steeper anterior corneal meridians, respectively. In eyes with ATR astigmatism, the mean posterior corneal astigmatism was essentially zero.

The influence of the posterior corneal surface on total astigmatism could also be observed when looking at the difference between anterior corneal astigmatism (with a refractive index of 1.376) and total corneal astigmatism. In good agreement with direct measurements of posterior corneal astigmatism, we found that in the sample as a whole, anterior corneal astigmatism overestimated total corneal astigmatism by 0.44 @ 91. The difference was zero for ATR astigmatism, 0.50 D for WTR, and 0.36 D for oblique astigmatism. Keratometric astigmatism overestimated total astigmatism by a lower amount (0.16 @ 91). This can be easily explained by the fact that the 1.3375 keratometric index used to calculate keratometric astigmatism was developed to offset the negative power of the posterior corneal surface, while the 1.376 index used for anterior corneal astigmatism is the real refractive index of the cornea and allows us to calculate the power of the anterior corneal surface only.

Similar differences between keratometric astigmatism and total corneal astigmatism have been reported by other authors who observed that, on average, the posterior corneal surface adds a slight amount of ATR astigmatism to keratometric astigmatism. Koch et al.[5] found that total corneal astigmatism overestimated keratometric astigmatism by 0.22 @ 180. Similarly, Ho et al.[4] found that posterior corneal astigmatism resulted in an average reduction of 0.21 D in the magnitude of anterior corneal astigmatism. In good agreement, Bae et al.[14] found that pseudophakic residual astigmatism (ie, the difference between refractive astigmatism and keratometric astigmatism) was approximately 0.47 @ 176. These studies, however, did not separately report the results for WTR, ATR, and oblique astigmatism. Our study adds some information because the analysis of the total corneal astigmatism with reference to the steeper meridian of keratometric astigmatism showed that the mean keratometric astigmatism overestimated total corneal astigmatism in eyes with WTR astigmatism (by 0.22 D), underestimated total corneal astigmatism in eyes with ATR astigmatism (by 0.21 D), and overestimated total oblique astigmatism (by 0.13 D). However, mean values do not fully depict the actual situation because in about 20% of eyes, there was an opposite relationship between keratometric astigmatism and total corneal astigmatism (ie, keratometric astigmatism underestimated total WTR astigmatism and overestimated total ATR astigmatism). For this reason, we believe that using the mean values for overestimation and underestimation may generate inaccurate results in at least 20% of eyes and that direct measurement of total corneal astigmatism in eyes having toric IOL implantation is mandatory to obtain the most reliable refractive outcomes. A study is being performed to confirm this hypothesis in a sample of patients who received the Acrysof toric IOL (Alcon Laboratories, Inc.). The need to measure total corneal astigmatism is also confirmed by the observation that in eyes with WTR astigmatism, which represent the majority of cases, the magnitude of posterior astigmatism was directly correlated to that of anterior astigmatism, as shown in Figure 2 and previously reported by Ho et al.[4] This means that the influence of posterior astigmatism increases in eyes with higher keratometric astigmatism.

The magnitude and axis differences between keratometric astigmatism and total corneal astigmatism were different from those previously reported. A magnitude vector difference of more than 0.50 D was detected in 16.6% of our sample, whereas Ho et al.[4] found it in 7.1% of eyes and Koch et al.[5] in 4.9% of eyes. These discrepancies may be related to the higher mean astigmatism of our sample (mean arithmetic keratometric astigmatism 1.80 D) than that of Ho et al.[4] (57.2% of eyes with keratometric astigmatism >1.s0 D) and Koch et al.[5] (mean arithmetic keratometric astigmatism 1.08 D). Given that the magnitudes of anterior and posterior astigmatism are correlated ($r = 0.9186$), a higher influence of posterior astigmatism is not surprising in samples with a mean higher keratometric astigmatism. Regarding the location of the steepest meridian, an axis difference of more than 10 degrees was detected in 3.8% of our sample, a rate very similar to that reported by Ho et al.[4] (3.9%) in eyes with keratometric astigmatism more than 1.00 D but considerably lower than that reported by Koch et al.[5] (17.2%). The discrepancy between our results and those of Koch et al. may also be related to the different inclusion criteria in the 2 studies. Koch et al. enrolled eyes with any magnitude of astigmatism, whereas we enrolled eyes with keratometric astigmatism of more than 1.00 D. In a study by Dubbelman et al.,[3] the correlation between anterior and posterior astigmatism was higher after subjects with anterior astigmatism less than 0.50 D were excluded.

This study has limitations, and further studies are warranted. First, total corneal astigmatism was centered on the corneal vertex and not on the pupil center to maintain the same reference point as keratometric astigmatism and follow the approach adopted by Ho et al.[4] and Koch et al.[5] However, pupil-centered measurements may be more accurate and have to be assessed. Second, the number of patients with oblique astigmatism and ATR astigmatism was small. Third, clinical confirmation of the accuracy of different astigmatism measurement methods is still lacking. Thus, we have started a prospective study to assess which of the investigated methods allows the best refractive outcomes in patients having toric IOL implantation in cataract surgery.

In conclusion, our results suggest that in most eyes, posterior corneal astigmatism partially compensates for keratometric WTR astigmatism and increases ATR astigmatism; however, in approximately 20% of cases, the opposite effect may occur. Direct measurement of total corneal astigmatism by Scheimpflug imaging and ray tracing may be the best option to calculate the astigmatism to be surgically corrected.

WHAT WAS KNOWN

- Posterior corneal astigmatism, which has been found to exceed 0.50 D in 9% of eyes, partially compensates for keratometric astigmatism.

WHAT THIS PAPER ADDS

- In eyes with more than 1.00 D of keratometric astigmatism (ie, in candidates for surgical correction of corneal astigmatism), posterior corneal astigmatism exceeded 0.50 D in a considerably higher percentage of cases (55.4%).
- In the whole sample, the mean power of posterior corneal astigmatism was 0.54 D inclined 91 degrees relative to the steeper anterior corneal meridian. However, the effect of posterior corneal astigmatism on anterior corneal astigmatism was significantly higher in eyes with WTR astigmatism (0.61 D) than in those with ATR astigmatism (0.05 D).
- On average, posterior corneal astigmatism compensated for WTR keratometric astigmatism and increased ATR keratometric astigmatism; however, in approximately 20% of cases, the opposite effect may occur.

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