Accuracy of Corneal Astigmatism Estimation by Neglecting the Posterior Corneal Surface Measurement

JAU-DER HO, CHING-YAO TSAI, AND SHIOW-WEN LIOU

• PURPOSE: To evaluate the accuracy of corneal astigmatism estimation by neglecting the posterior corneal surface measurement.

• DESIGN: Prospective, observational study.

• METHODS: The right eyes of 493 subjects were measured with a rotating Scheimpflug camera (Pentacam; Oculus, Wetzlar, Germany). The keratometric corneal astigmatism (KA) was obtained by using the anterior corneal surface measurement and the keratometric index (1.3375) while neglecting the posterior corneal surface measurement. The Pentacam-derived total corneal astigmatism (PA) was derived by doubled-angle vector analysis of the astigmatisms on both corneal surfaces.

• RESULTS: The mean arithmetic and absolute estimation errors of the KA magnitude for the PA magnitude were −0.06 ± 0.28 diopters (D) (range, −0.59 to 0.91 D) and 0.24 ± 0.16 D (range, 0 to 0.91 D), respectively. The mean arithmetic and absolute estimation errors of the KA angle for the PA angle were −0.6 degrees ± 12.7 degrees (range, −69.9 degrees to 83.4 degrees) and 7.4 degrees ± 10.3 degrees (range, 0 degrees to 83.4 degrees), respectively. Among all eyes, 142 eyes (28.8%) had either a KA magnitude that differed by > 0.50 D from the PA magnitude or a KA angle that differed by > 10 degrees from the PA angle. For the 282 eyes with a KA magnitude exceeding 1.0 D (that are candidates for intraoperative correction of a preexisting astigmatism during cataract surgery), 29 eyes (10.3%) had either a KA magnitude that differed by > 0.50 D from the PA magnitude or a KA angle that differed by > 10 degrees from the PA angle.

• CONCLUSIONS: Neglecting the posterior corneal surface measurement may lead to significant deviation in the corneal astigmatism estimation in a proportion of eyes. (Am J Ophthalmol 2009;147:788–795. © 2009 by Elsevier Inc. All rights reserved.)

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Corneal astigmatism is a frequently encountered type of optical aberration of the cornea. It is important in determining the uncorrected visual acuity. It is also a significant factor in determining the axis and amount of intraoperative correction of astigmatism. Both the anterior and posterior corneal surfaces contribute to the total corneal astigmatism. However, the corneal astigmatism is conventionally solely derived clinically from the keratometer-measured anterior corneal curvature and the keratometric index (keratometric corneal astigmatism [KA]). The KA (or power) is not purported to be the net corneal astigmatism (or power) or the total corneal astigmatism (or power). This mathematical shortcut was employed attributable to difficulties in measuring the posterior corneal surface in clinical settings, especially in the past.[1–3] However, it has been shown that relying only on the anterior corneal surface measurement and neglecting the relationship between the anterior and posterior corneal surfaces can lead to unacceptable intraocular lens (IOL) power calculation results after corneal refractive surgery.[4–9]

Information on the astigmatism of the posterior corneal surface remains insufficient largely attributable to limitations of methodologies to evaluate the posterior surface of the cornea. Previous studies used techniques such as Purkuinje imagery, pachymetry, Scheimpflug photography, and slit-scan topography.[10–15] Many studies calculated the astigmatism of the posterior corneal surface on the basis of measurements in 3 or 6 fixed meridians.[10–16] Until recent years, only the Orbscan (Bausch & Lomb, Rochester, New York, USA) could measure a large number of data points (9,000 data points) over both the anterior and posterior surfaces of the entire cornea in a very short time (1.5 seconds).[17] Several studies used an Orbscan-measured corneal elevation map to summarize data from all meridians to calculate the astigmatism of the posterior corneal surface.[14–16] However, the accuracy of the Orbscan for posterior corneal elevation measurement has not been fully validated.[18,19] It has also been criticized as measuring the posterior corneal surface inaccurately in eyes after keratorefractive surgery.[19–21]

The Pentacam (Oculus, Wetzlar, Germany) is a device that uses a rotating Scheimpflug camera to image the anterior segment and provides the biometric measurements of the anterior segment.[22,23] It measures 25,000 data points over the cornea in less than 2 seconds.[24] In this study, we

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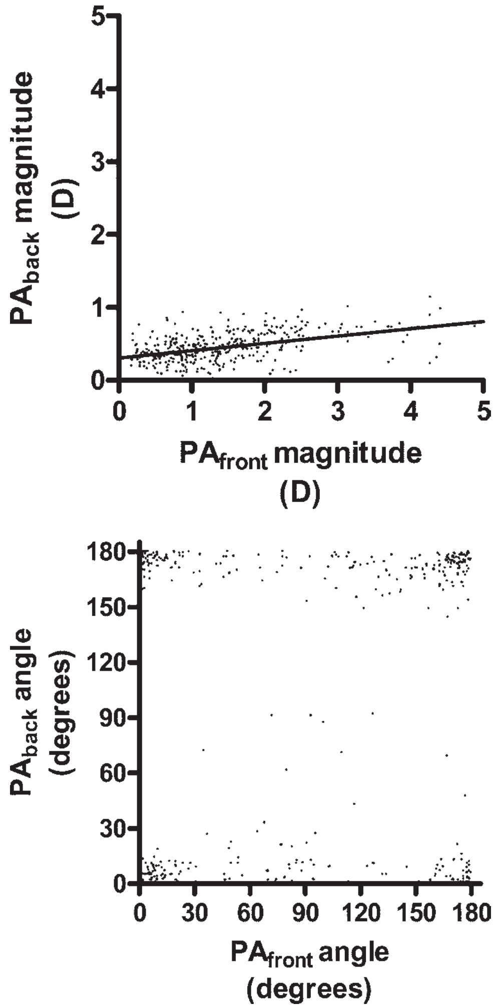

FIGURE 1. Scattergrams illustrating the relationship between the Pentacam-derived anterior and posterior corneal astigmatisms in all the 493 studied eyes. (Top) Scattergram of the Pentacam-derived posterior corneal astigmatism magnitude (PA_{back} magnitude) as a function of the Pentacam-derived anterior corneal astigmatism magnitude (PA_{front} magnitude). The regression formula was (PA_{back} magnitude) = 0.0998 × (PA_{front} magnitude) + 0.3073. (Bottom) Scattergram of the flat meridian orientation of the Pentacam-derived posterior corneal astigmatism (PA_{back} angle) as a function of that of the anterior cornea (PA_{front} angle). The flat meridian of the anterior cornea was distributed around the horizontal direction (0 degrees to 30 degrees or 150 degrees to 180 degrees; "with-the-rule" astigmatism) in 354 eyes (71.8%) and the flat meridian of the posterior cornea was distributed around the horizontal direction (0 degrees to 30 degrees or 150 degrees to 180 degrees) in nearly all eyes (474 eyes, 96.1%).

analyzed data obtained by the Pentacam of measurements of the anterior and posterior corneal surfaces. The accuracy of the total corneal astigmatism obtained using the conventional method (using the anterior corneal surface measurement only and neglecting the posterior corneal surface measurement) was evaluated.

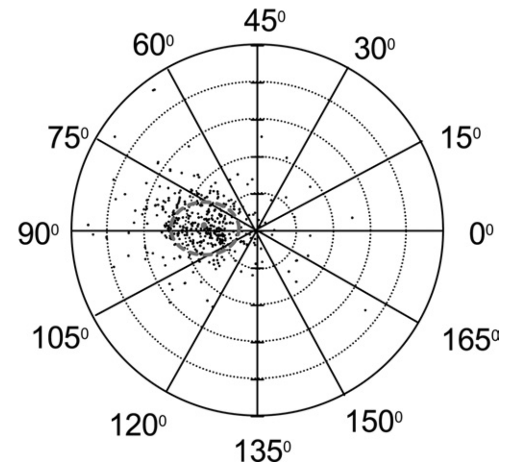

FIGURE 2. Doubled-angle plot for the error vectors ($\vec{EV}$, the difference between the vector representing the Pentacam-derived total corneal astigmatism [PA] and that representing the keratometric corneal astigmatism [KA]) of the studied eyes along with the centroid and standard deviation ellipse. The centroid (represented by the gray dot and ellipse) was 0.28 diopters (D) × 87.2 degrees ± 0.16 D. (The outermost circle represents 1.0 D and all vectors are presented in a positive cylinder form).

SUBJECTS AND METHODS

SUBJECTS WERE RANDOMLY SELECTED FROM THE OPHTHALmology clinic of Taipei City Hospital. Those who had corneal or retinal disease or had had previous ocular surgery were excluded. Subjects with a history of wearing contact lenses or who had poor quality Pentacam scans were also excluded. Data were collected from the right eyes of subjects. Curvatures of the flat central radius (Rf), steep central radius (Rs) in the 3-mm zone on the anterior and posterior corneal surfaces, the meridian of the Rf in the 3-mm zone on the anterior and posterior corneal surfaces, and the central corneal thickness were obtained. The measurement of the curvatures of the anterior and posterior corneal surfaces was done automatically. The anterior corneal surface powers in the flat and steep meridians ($P_{f,front}$ and $P_{s,front}$) were calculated by (n_c-1)/(Rf of posterior corneal surface) and (n_c-1)/(Rs of posterior corneal surface), respectively, where n_c is the refractive index of the cornea (= 1.376).[25] The spherical equivalent power of the anterior corneal surface (SE_{front}) was the average of the anterior corneal surface powers in the flat and steep meridians. Cylinder data were always presented in positive cylinder form throughout this study. The posterior corneal surface powers in the flat and steep meridians ($P_{f,back}$ and $P_{s,back}$) were calculated by (n_a-n_c)/(Rf of posterior corneal surface) and (n_a-n_c)/(Rs of posterior corneal surface), respectively, where n_a is the refractive index of the aqueous humor (= 1.336).[25] The spherical equivalent power of the posterior corneal surface (SE_{back}) was the average of the posterior corneal surface powers in the flat and steep

TABLE 1. Estimation Results for the Pentacam-derived Total Corneal Astigmatism Using the Conventional Keratometric Method (that Neglects the Posterior Corneal Surface Measurement) in all Studied Eyes (493 eyes)

Estimation Error for the Total Corneal Astigmatism Magnitude	
Mean arithmetic estimation error	−0.06 ± 0.28 D (−0.59 to 0.91)
Mean absolute estimation error	0.24 ± 0.16 D (0 to 0.91)
Within ± 0.25 D	58.2%
Within ± 0.50 D	94.1%
PA magnitude >1.0 D and KA magnitude <1.0 D	5.9%
PA magnitude <1.0 D and KA magnitude >1.0 D	5.7%
Estimation Error for the Total Corneal Astigmatism Angle	
Mean arithmetic estimation error	−0.6 degrees ± 12.7 degrees (−69.9 degrees to 83.4 degrees)
Mean absolute estimation error	7.4 degrees ± 10.3 degrees (0 degrees to 83.4 degrees)
Within ± 5 degrees	58.2%
Within ± 10 degrees	76.3%
Magnitude estimation error within ± 0.50 D and angle estimation error within ± 10 degrees (%)	71.2%
Magnitude estimation error > 0.50 D or angle estimation error > 10 degrees (%)	28.8%

D = diopters; KA = keratometric corneal astigmatism; PA = Pentacam-derived total corneal astigmatism.

meridians (Generally, the anterior corneal surface power is 8 times more important than the posterior corneal surface power. For example, in our study, the average spherical equivalent of the anterior and posterior corneal surface powers were 48.6 and −6.3 diopters [D], respectively).

We used the thick lens formula to calculate the Pentacam-derived spherical equivalent power of the total cornea:

$$SE_{total} = SE_{front} + SE_{back} - \frac{d}{n_c} \times SE_{front} \times SE_{back},$$

where d is the central corneal thickness.

To calculate the total corneal astigmatism, the algorithm of vergence tracing was applied. The vergence power (created by the anterior corneal surface) at the posterior corneal surface plane in the flat meridian of the anterior corneal surface (VP_{flat}) is $(n_c)/[(n_c/P_{f,front})-d]$. The vergence power (created by the anterior corneal surface) at the posterior corneal surface plane in the steep meridian of the anterior corneal surface (VP_{steep}) is $(n_c)/[(n_c/P_{s,front})-d]$. Therefore, the astigmatism at the posterior corneal surface plane caused by the anterior corneal surface is [$(VP_{steep}-VP_{flat})$ × flat meridian of the anterior corneal surface]. The Pentacam-derived total corneal astigmatism (PA) was then obtained by vector summation of the astigmatism at the posterior corneal surface plane created by the anterior corneal surface and the astigmatism from the posterior corneal surface.

We also calculated the keratometric corneal power, which neglects the posterior corneal surface measurement. The keratometric corneal powers in the flat and steep meridians were calculated by (1.3375−1)/(Rf of anterior corneal surface) and (1.3375−1)/(Rs of anterior corneal surface), respectively. The keratometric spherical equivalent power of the cornea was the average of the keratometric corneal powers in the flat and steep meridians.

We used the algorithm as recommended by the Astigmatism Project Group of the American National Standards Institute (ANSI)[26] to compare the corneal astigmatism estimations obtained when considering the posterior corneal measurement (PA) with that obtained when neglecting the posterior corneal measurement (KA). The vector representing the PA ($C_{PA} \times A_{PA,}$ where C_{PA} is the positive cylinder value and A_{PA} is the flat meridian) was assigned as $\vec{PA}$. The X and Y vector components of $\vec{PA}$ were as follows:

$$X_{PA} = C_{PA} \times \cos(2A_{PA})$$

and

$$Y_{PA} = C_{PA} \times \sin(2A_{PA}).$$

The vector representing the KA ($C_{KA} \times A_{KA}$, where C_{KA} is the positive cylinder value and A_{KA} is the flat meridian) was assigned as $\vec{KA}$. The X and Y vector components of $\vec{KA}$ were as follows:

$$X_{KA} = C_{KA} \times \cos(2A_{KA})$$

and

$$Y_{KA} = C_{KA} \times \sin(2A_{KA}).$$

Then the error vector ($\vec{EV}$) representing the vector difference between the vector of the PA and that of the KA was calculated by

$$\vec{EV} = \vec{PA} - \vec{KA}$$

The error of magnitude (EM) was the arithmetic difference of the magnitude between PA and KA, $|\vec{PA}| - |\vec{KA}|$. The error of angle (EA) measures the difference between the axis of the PA and that of the KA (Mathematically, it was half the angular difference between the $\vec{PA}$ and $\vec{KA}$ vectors. The EA was defined always to be an acute angle). As is conventional mathematically, the EA is negative if the $\vec{KA}$ is clockwise from the $\vec{PA}$ and positive if the $\vec{KA}$ is counterclockwise from the $\vec{PA}$.

We used the magnitude of $\vec{EV}(|\vec{EV}|)$ to evaluate the visual effects of the corneal astigmatism estimation error caused by neglecting the posterior corneal surface measurement (that was conceptually similar to the blurring strength of a power vector[27]),

$$\left|\vec{EV}\right| = \sqrt{(X_{PA} - X_{KA})^2 + (Y_{PA} - Y_{KA})^2}.$$

The estimation error for the PA using the keratometric method (ie, neglecting the posterior corneal surface measurement) was evaluated by the following criteria:[28]

1. Mean arithmetic and absolute estimation errors of magnitude (EM) of the KA for the PA.
2. Mean arithmetic and absolute estimation EA of the KA for the PA.
3. (a) The percentage of eyes that had a PA magnitude of > 1.0 D and a KA magnitude of < 1.0 D. Because the corneal astigmatism is most usually evaluated with keratometry in clinical settings, these eyes having a KA of less than 1.0 D would not be clinically considered for intraoperative astigmatism correction during cataract surgery. However, the corneal astigmatism of these eyes is more than 1.0 D when taking into consideration the posterior corneal surface measurement, therefore, these eyes really should be candidates for intraoperative astigmatism correction during cataract surgery if a corneal astigmatism of more than 1.0 D is used as the criterion for intraoperative correction of astigmatism. (b) The percentage of eyes that had a PA magnitude of < 1.0 D and a KA magnitude of > 1.0 D. These eyes with a KA of more than 1.0 D would clinically be candidates for intraoperative astigmatism correction during cataract surgery. However, the corneal astigmatism of these eyes is less than 1.0 D when taking into consideration the posterior corneal surface measurement and these eyes really should not be considered for intraoperative astigmatism correction during cataract surgery.
4. The percentage of eyes within a certain range of estimation errors of the KA magnitude for the PA magnitude (eg, within ± 0.5 D), and the KA angle for the PA angle (eg, within ± 10 degrees).

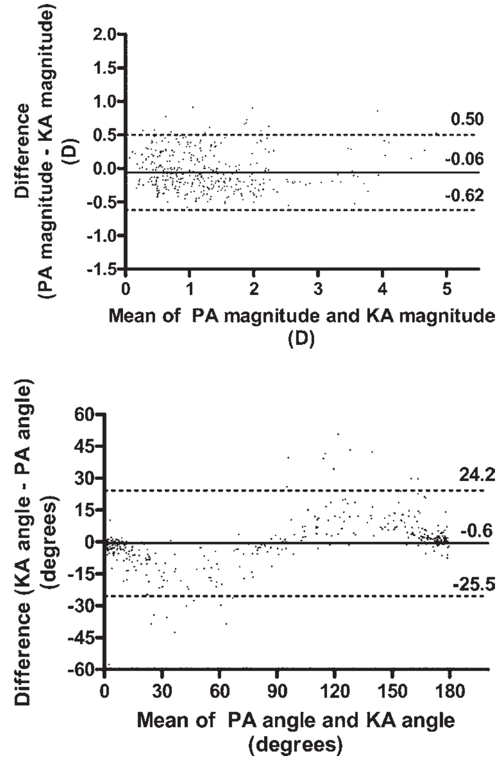

FIGURE 3. Bland-Altman plots comparing the PA with the KA (which neglects the posterior corneal surface measurement). (Top) Bland-Altman plot comparing the PA magnitude and the KA magnitude. The 95% limits of agreement (LoA) were −0.62 to 0.50 D. (Bottom) Bland-Altman plot comparing the PA angle and the KA angle. The 95% LoA were −25.5 degrees to 24.2 degrees. (Mean differences are represented by solid lines, and 95% LoA are represented by dotted lines.)

RESULTS

IN TOTAL, THE RIGHT EYES OF 275 MALES AND 218 FEMALES were included in this study. The mean age of these subjects was 41.1 ± 21.9 years (range, 6 to 85 years). The mean spherical equivalent of these eyes was −1.87 ± 3.25 D (range, −15.375 to 6.375 D). The mean spherical equivalent of the Pentacam-derived and keratometric corneal powers were 42.4 ± 1.5 D (range, 38.5 to 46.4 D) and

TABLE 2. Estimation Results for the Pentacam-derived Total Corneal Astigmatism Using the Conventional Keratometric Method (that Neglects the Posterior Corneal Surface Measurement) in Eyes with a Keratometric Corneal Astigmatism Exceeding 1.0 D (282 eyes)

Estimation Error for the Total Corneal Astigmatism Magnitude	
Mean arithmetic estimation error	0.12 ± 0.29 D (−0.59 to 0.89)
Mean absolute estimation error	0.26 ± 0.17 D (0 to 0.89)
Within ± 0.25 D	53.5%
Within ± 0.50 D	92.9%
Estimation Error for the Total Corneal Astigmatism Angle	
Mean arithmetic estimation error	−0.9 degrees ± 5.3 degrees (−57.8 degrees to 13.7 degrees)
Mean absolute estimation error	3.2 degrees ± 4.4 degrees (0 degrees to 57.8 degrees)
Within ± 5 degrees	78.0%
Within ± 10 degrees	96.1%
Magnitude estimation error within ± 0.50 D and angle estimation error within ± 10 degrees (%)	89.7%
Magnitude estimation error > 0.50 D or angle estimation error > 10 degrees (%)	10.3%

D = diopters.

43.6 ± 1.5 D (range, 39.6 to 47.8 D), respectively. The centroid for the PA and KA were 0.62 D × 1.6 degrees ± 0.91 D and 0.90 D × 0.3 degrees ± 0.84 D, respectively.

A scattergram of the Pentacam-derived posterior corneal astigmatism magnitude (PA_{back} magnitude) as a function of the Pentacam-derived anterior corneal astigmatism magnitude (PA_{front} magnitude) is presented in Figure 1, Top. The regression formula was (PA_{back} magnitude) = 0.0998 × (PA_{front} magnitude) + 0.3073 (r = 0.481, $P < .0001$). The posterior corneal astigmatism resulted in an average reduction of 0.21 ± 0.32 D (range, −0.83 to 0.97 D) and an average percentage reduction of 13.4% ± 32.5% (range, −275.3% to 92.3%) in the magnitude of the anterior corneal astigmatism. Figure 1, Bottom shows the flat meridian orientation of the Pentacam-derived posterior corneal astigmatism (PA_{back} angle) as a function of that of the anterior cornea (PA_{front} angle). It was noted that the flat meridian of the anterior cornea was distributed around the horizontal direction (0 degrees to 30 degrees or 150 degrees to 180 degrees; "with-the-rule" astigmatism) in 354 eyes (71.8%) and around the vertical direction (60 degrees to 120 degrees; "against-the-rule" astigmatism) in 74 eyes (15.0%). On the other hand, the flat meridian of the posterior cornea was distributed around the horizontal direction (0 degrees to 30 degrees or 150 degrees to 180 degrees) in nearly all eyes (96.1%, 474 eyes), and around the vertical direction (60 degrees to 120 degrees) in only 10 eyes (2.0%).

The mean arithmetic and absolute difference between the spherical equivalent of the Pentacam-derived corneal power and that of the keratometric corneal power were −1.19 ± 0.18 D (range, −1.92 to −0.46 D) and 1.19 ± 0.18 D (range, 0.46 to 1.92 D). Figure 2 shows the doubled-angle plot for the error vectors ($\vec{EV}$) of the studied eyes along with the centroid and standard deviation ellipse. The centroid was 0.28 D × 87.2 degrees ± 0.16 D. The mean blurring strength of the corneal astigmatism estimation error caused by neglecting the posterior corneal surface measurement was 0.33 ± 0.16 D (range, 0 to 0.94 D).

Estimation results for the PA using the KA (which neglects the posterior corneal surface measurement) are summarized in Table 1. The mean arithmetic and absolute estimation errors of the magnitude were −0.06 ± 0.28 D (range, −0.59 to 0.91 D) and 0.24 ± 0.16 D (range, 0 to 0.91 D), respectively. There was a significant difference between the PA magnitude and KA magnitude ($P < .0001$, paired *t* test). Figure 3, Top shows the Bland-Altman plot comparing the PA magnitude and the KA magnitude. The 95% limits of agreement (LoA) were −0.62 to 0.50 D. Of these eyes, 287 (58.2%) and 464 (94.1%) had a KA magnitude that was within ± 0.25 and ± 0.50 D of the PA magnitude, respectively. Among all eyes, 29 (5.9%) had a PA magnitude of > 1.0 D and a KA magnitude < 1.0 D. In contrast, 28 eyes (5.7%) had a PA magnitude of < 1.0 D and a KA magnitude > 1.0 D. The mean arithmetic and absolute estimation errors of the KA angle for the PA angle were −0.6 degrees ± 12.7 degrees (range, −69.9 degrees to 83.4 degrees) and 7.4 degrees ± 10.3 degrees (range, 0 degrees to 83.4 degrees), respectively. There was no significant difference between the PA angle and KA angle ($P = .259$, paired t test). Figure 3, Bottom shows the Bland-Altman plot comparing the PA angle and the KA angle. The 95% LoA were −25.5 degrees to 24.2 degrees. Of these eyes, 287 (58.2%) and 376 (76.3%) had a KA angle that was within ± 5 degrees and ± 10 degrees of the PA angle, respectively. Totally, 351 eyes (71.2%) had a KA magnitude within ± 0.50 D of the PA magnitude and a KA angle within ± 10 degrees of the PA angle; 142 eyes (28.8%) had either a KA magnitude that differed by > 0.50 D from the PA magnitude or a KA angle that differed by > 10 degrees from the PA angle.

Since intraoperative correction of a preexisting astigmatism may be considered in eyes with an astigmatism exceeding 1.0 D (clinically, this astigmatism is usually the KA) when patients are undergoing cataract surgery, we evaluated the relationship between the KA and the PA in eyes with KA exceeding 1.0 D (282 eyes in this study). The estimation results of the KA for the PA are summarized in Table 2. The mean arithmetic and absolute estimation errors of the KA magnitude for the PA magnitude were 0.12 ± 0.29 D (range, −0.59 to 0.89 D) and 0.26 ± 0.17 D (range, 0 to 0.89 D), respectively. There was a significant difference between the PA magnitude and KA magnitude ($P < .0001$, paired t test). Of those eyes with KA exceeding 1.0 D (ie, 282 eyes), 151 (53.5%) and 262 (92.9%) had a KA magnitude that was within ± 0.25 and ± 0.50 D of the PA magnitude, respectively. The mean arithmetic and absolute estimation errors of the KA angle for the PA angle were −0.9 degrees ± 5.3 degrees (range, −57.8 degrees to 13.7 degrees) and 3.2 degrees ± 4.4 degrees (range, 0 degrees to 57.8 degrees) in those eyes, respectively. There was a significant difference between the PA angle and KA angle ($P < .0001$, paired t test). Of those eyes with KA exceeding 1.0 D (ie, 282 eyes), 220 (78.0%) and 271 (96.1%) had a KA angle that was within ± 5 degrees and ± 10 degrees of the PA angle, respectively. Collectively, for those eyes with KA exceeding 1.0 D, 253 eyes (89.7%) had a KA magnitude within ± 0.50 D of the PA magnitude and a KA angle within ± 10 degrees of the PA angle; and 29 eyes (10.3%) had either a KA magnitude that differed by > 0.50 D from the PA magnitude or a KA angle that differed by > 10 degrees from the PA angle.

DISCUSSION

IN THIS STUDY, WE USED THE DATA OBTAINED BY A ROTATING Scheimpflug camera (Pentacam; Oculus) to derive the measurement of the total corneal astigmatism. We show that the astigmatism of the posterior corneal surface resulted in an average 13.4% reduction of the astigmatism of the anterior corneal surface. Of all the 493 eyes, 29 eyes (5.9%) had a PA magnitude of > 1.0 D that was estimated to be < 1.0 D with the KA magnitude. On the contrary, 28 eyes (5.7%) had a PA magnitude of < 1.0 D that was estimated to be > 1.0 D with the KA magnitude. Among all studied eyes, 142 eyes (28.8%) had either a KA magnitude that differed by > 0.50 D from the PA magnitude or a KA angle that differed by > 10 degrees from the PA angle. For the 282 eyes with a KA magnitude exceeding 1.0 D (that are candidates for intraoperative correction of a preexisting astigmatism during cataract surgery), 29 eyes (10.3%) had either a KA magnitude that differed by > 0.50 D from the PA magnitude or a KA angle that differed by > 10 degrees from the PA angle.

It was found in previous studies that the astigmatism of the posterior corneal surface resulted in an average compensation of the astigmatism of the anterior corneal surface of 12.9% to 31%.[11,13,14,29] (13.4% in our study). It was found in Dunne and associates' study (including 60 eyes) that in 81.7% of eyes, the posterior corneal surface astigmatism brought about a decrease in the total corneal astigmatism.[11] (77.1% in our study). In Prisant and associates study (including 40 eyes), using vector summation of the posterior and anterior corneal astigmatisms resulted in a mean reduction of 0.29 ± 0.18 D (range, −0.25 to 1.32 D) compared with the anterior corneal astigmatism, and the mean change in the axis was 2.63 degrees ± 2.68 degrees (range, 0 degrees to 12.24 degrees).[14] [0.21 ± 0.32 D (range, −0.83 to 0.97 D) and 7.4 degrees ± 10.3 degrees (range, 0 degrees to 83.4 degrees) in our study].

Dunne and associates[11] and Dubbelman and associates[13] studies reported that both the anterior and posterior corneal surfaces were flatter horizontally than vertically (This resulted in a "with-the-rule" corneal astigmatism). Their findings somewhat differed from ours. In our study, 74 eyes (15.0%) had a flat meridian of the anterior corneal surface in the vertical orientations (This resulted in an "against-the-rule" astigmatism). One possible cause for this difference in the orientation of the flat meridian of the anterior corneal surface is the difference in the age distribution of subjects between our study and theirs. In Dunne and associates and Dubbelman and associates studies, the mean ages were 22.04 ± 3.24 (range not reported) and 39 ± 14 years (range, 18 to 65 years), respectively. In our study, the age distribution was wider and we included more elderly subjects in our study. The mean age of subjects in our study was 41.1 ± 21.9 years (range, 6 to 85 years). It has been shown that the astigmatism axis (of the anterior corneal surface) turns to "against-the-rule" with age.[30–32] This may explain why the proportion of eyes with a flat meridian of the anterior corneal surface in the vertical orientations ("against-the-rule" astigmatism) was higher in our study than in those other studies.

Conventionally, the total corneal astigmatism is obtained by measuring the anterior corneal curvature and omitting the posterior corneal measurement. One of the reasons might be the difficulty in measuring the posterior corneal surface in clinical settings, especially before the advent of the Orbscan and Pentacam. Another reason might be that the difference in the refractive indices across the posterior corneal surface ($1.336 - 1.376 = -0.04$) is relatively small compared with that across the anterior corneal surface ($1.376 - 1 = 0.376$); therefore, the astigmatism of the posterior corneal surface might be assumed to be small enough to be neglected. However, it was found in our study that measuring only the anterior corneal surface may have resulted in either a total corneal astigmatism magnitude estimation error of > 0.50 D or an angle estimation error of > 10 degrees in 142 eyes (28.8%). It was found in another study that taking the posterior corneal surface astigmatism into consideration improved the prediction of the magnitude of the refractive astigmatism.[14] Dunne and associates reported that had the toricity of the posterior corneal surface been purely governed by that of the anterior corneal surface, the reduction of the anterior corneal surface astigmatism by the posterior corneal surface astigmatism would have been 5%. However, in their study, the posterior corneal surface exhibited additional toricity causing a greater reduction in the total corneal astigmatism amounting to approximately 14%.[11] All these results suggest that neglecting the contribution of the posterior corneal surface may cause a significant error in estimating the total corneal astigmatism.

It is interesting to note that the Bland-Altman plot in Figure 3, Bottom looks like a sine function. The sine function can be explained as follows: Most of the posterior surface has its flat meridian in the horizontal direction (as shown in Figure 1, Bottom). That is, most of the posterior corneal surface has an against-the-rule astigmatism (Note that the D power of the posterior corneal surface is negative). By using the doubled-angle vector analysis,[26] when the anterior astigmatism is in the with-the-rule or against-the-rule orientation (KA angle of around 0 degrees, 180 degrees, or 90 degrees), the vectors representing the anterior and posterior corneal astigmatisms will be nearly in the same or opposite directions (the vector of the anterior corneal astigmatism is in the direction of either around 0 degrees or 180 degrees, while the vector of the posterior corneal astigmatism is in the direction of around 180 degrees). In addition, the vector representing the anterior corneal astigmatism is usually longer than that representing the posterior corneal astigmatism (since the refractive index difference across the anterior corneal surface is much larger than that across the posterior corneal surface). Therefore, the vector sum of the vectors representing the anterior and posterior corneal astigmatisms (ie, the vector representing the PA) will be in a direction close to that of the vector of the anterior corneal astigmatism. In such cases, the difference between the KA angle and PA angle (ie, y-axis in Figure 3, Bottom) will be around 0 degrees, and the mean of the KA angle and PA angle (ie, x-axis in Figure 3, Bottom) will be around 0 degrees, 180 degrees, or 90 degrees because both the KA angle and PA angle are nearly the same and their values are around 0 degrees, 180 degrees, or 90 degrees.

When the anterior corneal surface has an oblique astigmatism (for example, with the KA angle at 45 degrees) and the posterior corneal surface has an against-the-rule astigmatism, the vectors representing the anterior and posterior corneal astigmatisms will be neither in nearly the same nor in nearly the opposite direction (in this case, 90 degrees for the vector of the anterior corneal astigmatism and 180 degrees for the vector of the posterior corneal astigmatism). Therefore, the vector sum of the vectors representing the anterior and posterior corneal astigmatisms will have a direction that deviates more from the direction of the vector representing the anterior corneal astigmatism than when the vector representing the anterior corneal astigmatism is more parallel to (ie, in nearly the same or opposite direction) the vector representing the posterior corneal astigmatism (ie, when the anterior cornea has a with-the-rule or against-the-rule astigmatism). That is, the difference between the KA angle and PA angle (ie, y-axis in Figure 3, Bottom) will deviate more from 0 degrees.

Reducing the preexisting astigmatism may further improve the uncorrected visual acuity after cataract surgery. The outcome of all the astigmatism-reducing methods depends upon accurate estimation of the total corneal astigmatism. Of the 282 eyes with KA exceeding 1.0 D in our study (that are candidate eyes for intraoperative correction of astigmatism during cataract surgery), 29 eyes (10.3%) had either a total corneal astigmatism magnitude estimation error of > 0.50 D or an angle estimation error of > 10 degrees. In such eyes, not considering the posterior corneal surface in the estimation of the total corneal astigmatism might lead to a suboptimal result for the intraoperative astigmatism correction.[33]

In summary, our study found that the astigmatism of the posterior corneal surface might significantly contribute to the total corneal astigmatism. Omission of the posterior corneal surface measurement in calculating the total corneal astigmatism can lead to significant inaccuracies in estimating the magnitude or axis of the total corneal astigmatism in some eyes. As the demand for intraoperative correction of a preexisting astigmatism during cataract surgery rises, further studies are needed to evaluate if including measurements of the posterior corneal surface in estimating the total corneal astigmatism improves the accuracy of the total corneal astigmatism estimation, and thus enhances the result of intraoperative correction of astigmatisms.

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the data (J.D.H., C.Y.T., S.W.L.), preparation (J.D.H., S.W.L.), review (J.D.H., C.Y.T., S.W.L.), and approval of the manuscript (J.D.H., C.Y.T., S.W.L.). The Institutional Review Board of Taipei Medical University Hospital approved this study. This study adhered to the Declaration of Helsinki and all laws in Taiwan.

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Biosketch

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Biosketch

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