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 Purkinje 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
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.
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:

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

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 ($VP_{\text{flat}}$) is $(n_i)/(n_i/P_{s,\text{front}})-d$. The vergence power (created by the anterior corneal surface) at the posterior corneal surface plane in the steep meridian of the anterior corneal surface ($VP_{\text{steep}}$) is $(n_i)/(n_i/P_{s,\text{front}})-d$. Therefore, the astigmatism at the posterior corneal surface plane caused by the anterior corneal surface is $[(VP_{\text{steep}} - VP_{\text{flat}}) \times \text{flat meridian of the anterior corneal surface}]$. 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 $(1.3375/1)/(R_f \text{ of anterior corneal surface})$ and $(1.3375/1)/(R_s \text{ of anterior corneal surface})$, 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)\textsuperscript{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 $\hat{PA}$. The X and Y vector components of $\hat{PA}$ were as follows:

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

and

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

<table>
<thead>
<tr>
<th>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)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Estimation Error for the Total</strong></td>
</tr>
<tr>
<td><strong>Corneal Astigmatism Magnitude</strong></td>
</tr>
<tr>
<td>Mean arithmetic estimation error: $-0.06 \pm 0.28$ D ($-0.59$ to $0.91$)</td>
</tr>
<tr>
<td>Mean absolute estimation error: $0.24 \pm 0.16$ D (0 to $0.91$)</td>
</tr>
<tr>
<td>Within $\pm 0.25$ D: 58.2%</td>
</tr>
<tr>
<td>Within $\pm 0.50$ D: 94.1%</td>
</tr>
<tr>
<td>PA magnitude $&gt;1.0$ D and KA magnitude $&lt;1.0$ D: 5.9%</td>
</tr>
<tr>
<td>PA magnitude $&lt;1.0$ D and KA magnitude $&gt;1.0$ D: 5.7%</td>
</tr>
<tr>
<td><strong>Estimation Error for the Total Corneal Astigmatism Angle</strong></td>
</tr>
<tr>
<td>Mean arithmetic estimation error: $-0.6$ degrees $\pm 12.7$ degrees ($-69.9$ degrees to $83.4$ degrees)</td>
</tr>
<tr>
<td>Mean absolute estimation error: $7.4$ degrees $\pm 10.3$ degrees (0 degrees to $83.4$ degrees)</td>
</tr>
<tr>
<td>Within $\pm 5$ degrees: 58.2%</td>
</tr>
<tr>
<td>Within $\pm 10$ degrees: 76.3%</td>
</tr>
<tr>
<td>Magnitude estimation error within $\pm 0.50$ D and angle estimation error within $\pm 10$ degrees (%): 71.2%</td>
</tr>
<tr>
<td>Magnitude estimation error $&gt;0.50$ D or angle estimation error $&gt;10$ degrees (%): 28.8%</td>
</tr>
</tbody>
</table>

$D =$ diopters; $KA =$ keratometric corneal astigmatism; $PA =$ Pentacam-derived total corneal astigmatism.
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 \( \vec{K}A \). The X and Y vector components of \( \vec{K}A \) were as follows:

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

and

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

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

\[
\vec{E}V = \vec{P}A - \vec{K}A
\]

The error of magnitude (EM) was the arithmetic difference of the magnitude between PA and KA, \(|\vec{P}A| - |\vec{K}A|\). 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 \( \vec{P}A \) and \( \vec{K}A \) vectors. The EA was defined always to be an acute angle). As is conventional mathematically, the EA is negative if the \( \vec{K}A \) is clockwise from the \( \vec{P}A \) and positive if the \( \vec{K}A \) is counterclockwise from the \( \vec{P}A \).

We used the magnitude of \( |\vec{E}V|(|\vec{E}V|) \) 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),

\[
|\vec{E}V| = \sqrt{(X_{PA} - X_{KA})^2 + (Y_{PA} - Y_{KA})^2}.
\]

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 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 \( \pm 0.5 \) D), and the KA angle for the PA angle (eg, within \( \pm 10 \) degrees).

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 \( \pm \) 21.9 years (range, 6 to 85 years). The mean spherical equivalent of these eyes was \(-1.87 \pm 3.25\) D (range, \(-15.375\) to \(6.375\) D). The mean spherical equivalent of the Pentacam-derived and keratometric corneal powers were \(42.4 \pm 1.5\) D (range, 38.5 to 46.4 D) and
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 (ΔEV) 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 ± 0.50 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 \( (P = .259, \text{paired } t \text{ test}) \). 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 \( \pm 5 \) degrees and \( \pm 10 \) degrees of the PA angle, respectively. Totally, 351 eyes (71.2\%) had a KA magnitude within \( \pm 0.50 \) D of the PA magnitude and a KA angle within \( \pm 10 \) 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 \( 0.12 \pm 0.29 \) D (range, \(-0.59 \) to 0.89 D) and \( 0.26 \pm 0.17 \) D (range, \( 0 \) to 0.89 D), respectively. There was a significant difference between the PA magnitude and KA magnitude \( (P < .0001, \text{paired } t \text{ test}) \). 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 \( \pm 0.25 \) and \( \pm 0.50 \) 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 \( \pm 5.3 \) degrees (range, \(-57.8 \) degrees to 13.7 degrees) and \( 3.2 \) degrees \( \pm 4.4 \) degrees (range, \( 0 \) degrees to 57.8 degrees) in those eyes, respectively. There was a significant difference between the PA angle and KA angle \( (P < .0001, \text{paired } t \text{ test}) \). 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 \( \pm 5 \) degrees and \( \pm 10 \) 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 \( \pm 0.50 \) D of the PA magnitude and a KA angle within \( \pm 10 \) 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 31.1\% (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 (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 \( \pm 0.18 \) 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 \( \pm 2.68 \) degrees (range, \( 0 \) degrees to 12.24 degrees).14 \( 0.21 \pm 0.32 \) D (range, \(-0.83 \) to 0.97 D) and 7.4 degrees \( \pm 10.3 \) degrees (range, \( 0 \) degrees to 83.4 degrees) in our study.

Dunne and associates11 and Dubbelman and associates13 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 years (range not reported) and 39 \( \pm 14 \) 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 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 age30–32. 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 astigmatism magnitude estimation error of...
and all laws in Taiwan. The Institutional Review Board of Taipei Medical University Hospital approved this study. This study adhered to the Declaration of Helsinki.

REFERENCES


Jau-Der Ho, MD, PhD, completed medical school from the National Taiwan University (NTU) and completed ophthalmology training at NTU Hospital. Dr Ho received his PhD degree from Chang-Gung University, Taiwan. He is a subspecialist in vitreoretinal diseases, cataract and vitreoretinal surgery. Dr Ho’s research interests include retinal cell biology and ocular pharmacology. He is currently a Associate Professor and Chair of the Department of Ophthalmology, Taipei Medical University Hospital of Taipei, Taiwan.
Shiow-Wen Liou, MD, PhD, graduated from medical school of the National Taiwan University (NTU) and completed ophthalmology training at NTU Hospital, Taipei, Taiwan. Dr Liou received her PhD degree at Dokkyo Medical University in Japan and MHS degree from Johns Hopkins University in Baltimore, Maryland. Dr Liou is a subspecialist in cataract, strabismus, and oculoplastic surgery. Currently, Dr Liou serves as the superintendent of Zhongxing branch, Taipei City Hospital, and is a Professor of Ophthalmology at Taipei Medical University.