



# Comparison of the accuracy of four Pentacam corneal astigmatism values in non-toric pseudophakic eyes

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## Abstract

**Purpose** To compare the accuracy of different corneal astigmatism values measured by Scheimpflug keratometry (Pentacam), including Simulated Keratometry (SimK) and three total corneal astigmatism values, equivalent K reading (EKR), true net power (TNP), and total corneal refractive power (TCRP).

**Methods** We enrolled 168 eyes of 168 patients with non-toric IOL implantation. Pentacam examination and subjective refraction were performed 3 months after surgery. The agreement, arithmetic difference, and vector difference between refractive astigmatism (RA) and different corneal astigmatism values were compared.

**Results** Differences in astigmatism magnitude were significant between SimK and RA in the against-the-rule (ATR) and with-the-rule (WTR) groups but not in total corneal measurements. The meridians of SimK and RA differed significantly in the oblique astigmatism group. The correlations between total corneal astigmatism values and RA were stronger than that between SimK and RA in the total, WTR, and oblique astigmatism groups in Pearson's correlation test. Bland-Altman plots revealed more data points exceeding the limits of agreement (LoA) in SimK measurement in total and WTR subjects. In the ATR group, fewer data points exceeded LoA in EKR. The mean difference vector between SimK and RA was larger than that of other measurements in each astigmatism group. The arithmetic mean of difference vector was significantly smaller in EKR in the total, WTR, and oblique groups.

**Conclusions** Among different Pentacam readings, corneal astigmatism measurements considering anterior and posterior corneal surfaces were more representative of total ocular astigmatism than SimK, and EKR showed markedly better performance in astigmatism estimation.

**Keywords** Pentacam · Corneal astigmatism · Simulated Keratometry · Equivalent K reading · True net power · Total corneal refractive power · Non-toric

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Tianyu Zheng and Jie Xu contributed equally to this work.

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## Introduction

Corneal astigmatism can be addressed at the time of cataract surgery with toric intraocular lens (IOL) to achieve better uncorrected visual acuity [1–3]. However, a mean overcorrection or undercorrection of 0.3–0.4D by toric IOL was demonstrated by previous studies [4–6].

The preoperative estimation error of corneal astigmatism caused by neglecting the posterior corneal surface has been considered as an important reason for the correction error of toric IOL. Conventionally, corneal astigmatism was solely derived from anterior corneal curvature (Simulated Keratometry, SimK) [7]. Currently, posterior corneal curvature can be examined by scanning-slit imaging, Scheimpflug imaging, and optical coherence tomography (OCT) [8]. With these tools, total corneal refractive power and total corneal

astigmatism can be calculated by the methods of ray tracing or the Gaussian optics thick lens formula [9].

In theory, this corneal astigmatism calculated by both corneal surfaces should be a better representation of total corneal astigmatism than SimK. Previous studies applied a convenient method to evaluate the accuracy of different corneal astigmatism measurement [10–12]. In these studies, refractive astigmatism (RA) was compared with corneal astigmatism by different measurements in non-toric pseudophakia eyes. Considering that astigmatism is derived entirely from the cornea in non-toric IOL insertion eyes (without lens-derived astigmatism), RA should be equal to corneal astigmatism in these eyes. Therefore, the difference between RA and the measured postoperative corneal astigmatism value is considered to be the deviation (error) of the corneal astigmatism measurement. Using this method, previous studies found the difference between RA and total corneal astigmatism was significantly smaller than that between RA and keratometric astigmatism using anterior corneal astigmatism alone [10–12]. In these studies, total corneal astigmatism was measured by anterior segment OCT [10–12] or as total corneal refractive power (TCRP) astigmatism by Scheimpflug keratometry (Pentacam) [12].

In addition to TCRP measurement, Pentacam offers other “total corneal astigmatism” values, including equivalent K reading (EKR) and true net power (TNP). Pentacam also provides SimK astigmatism values. The Pentacam anterior corneal power (ACP, i.e., “SimK”) is measured with a 3 mm corneal diameter and is comparable to automated keratometry (AK; using a standard keratometric index of 1.3375). The TNP represents the corneal power calculated by using the anterior and posterior corneal curvatures and Gaussian optics formula for thick lenses, where actual refractive index of the air, cornea, and aqueous humor is entered. The TCRP uses ray tracing to calculate corneal power. In ray tracing method, the parallel light beams are transmitted through the cornea, and the focal length resulting from their refraction at the anterior and posterior surface is calculated according to Snell’s law of refraction. The EKR uses information from both the anterior and the posterior cornea to generate a range of central corneal power values. It was originally designed especially for the eyes after corneal refractive surgery. To date, no studies have compared the accuracy of these Pentacam values in estimating corneal astigmatism.

The purpose of this study was to compare discrepancies between RA and different corneal astigmatism values measured by Pentacam, including SimK, EKR, TNP, and TCRP, in non-toric pseudophakia eyes to analyze the accuracy of these values in estimating corneal astigmatism.

## Methods

This study was approved by the ethics committee of the Eye and Ear, Nose, and Throat (ENT) Hospital of Fudan

University and was conducted according to the principles of the Declaration of Helsinki. One hundred sixty-eight eyes of 168 patients with age-related cataracts who were preparing for cataract removal and non-toric IOL implantation were enrolled. All patients provided informed consent. All eyes with a history of corneal or intraocular surgery or wearing contact lenses, corneal or retinal disease, or irregular corneal astigmatism were excluded. Subjects who had poor quality Pentacam scans were also excluded.

## Surgery

A standard phacoemulsification surgery was performed through a 2.6-mm temporal clear corneal incision under topical anesthesia by one experienced surgeon (L.Y.). No further paracentesis were performed. Aspheric and non-toric IOLs were implanted in all patients.

## Examinations and calculations

Preoperative biometry was carried out with an IOL Master (Zeiss Meditec, Jena, Germany). Three months after surgery, all eyes underwent slit lamp microscopy examination and Scheimpflug keratometry (Pentacam; Oculus Inc., Wetzlar, Germany) examination. The slit lamp microscopy examination confirmed the clarity of the cornea, and the IOL was in the right position without significant decentration or tilt. Pentacam examination was performed by an experienced technician with more than 10 years of biometric experience and 6-year Pentacam examination experience. During the examination, the examiner maintained the patient’s head upright. The Scheimpflug keratometer readings were taken and repeated until 3 “OK” quality outputs were obtained. Difference between the measurement differences above 0.2D will also be excluded from this study. Measurements obtained by Pentacam included central corneal thickness, the flat (Rf), and steep (Rs) central radii of the anterior and posterior corneal surfaces and its meridian, and four corneal astigmatism values, including SimK, EKR, TNP, and TCRP. In this study, all measurements were based on data within the 3 mm diameter ring around the corneal apex, because the 3-mm data were sufficient to analyze astigmatism patterns [13, 14].

Additionally, subjective refraction (cross-cylinder method) measurements were performed. Subjective refraction was converted from the spectacle plane (12-mm vertex distance) to the corneal plane:  $D_c = \frac{D_s}{1-0.012 \cdot D_s}$ , where DC is the power at the corneal plane and DS is the power at the spectacle plane.

The vector differences between postoperative RA and each measurement of corneal astigmatism (SimK, EKR, TNP, and TCRP) were calculated and compared. The difference vector was calculated by double angle vector analysis (calculation

formulas as described in previous studies [15], shown in the supplementary data).

### Definition of astigmatism type

Astigmatism was defined as with-the-rule (WTR) astigmatism when the steepest anterior meridian was between 60° and 119° or against-the rule (ATR) with the steepest anterior meridian of 0° to 29° or 150° to 179°. All others were oblique astigmatism.

### Conversion method for left eyes

For data analysis, we used the standard conversion method for left eyes as recommended by Eydelman et al. [16] in case that the errors due to cyclotorsion might cancel out when averaging data from right and left eyes. The converted axis of all left eyes is equal to 180° minus the original axis.

### Statistical analysis

RA and each corneal astigmatism value (SimK, EKR, TNP, and TCRP) were compared using paired t-tests among all subjects, as well as among the ATR, WTR, and oblique groups. Using Pearson's correlation and Bland-Altman plots, the correlation between postoperative RA and each corneal astigmatism measurement was examined. Furthermore, one-way ANOVA with Fisher's least significant difference (LSD) test was used to analyze the difference in the magnitude of astigmatism and the arithmetic means of the magnitude of the difference vector among the WTR, ATR, and oblique groups. *P* values < 0.05 were considered statistically significant. All statistical analyses were conducted using SPSS for Windows (Version 13.0; SPSS Inc., Chicago, USA).

## Results

### Patient data

One hundred sixty-eight eyes of 168 patients (62 male and 106 female) with an age range of 48 to 91 years (mean ± SD: 66.3 ± 10.9 years) were enrolled. The number of eyes for the ATR, WTR, and oblique astigmatism groups was 55, 99, and 14, respectively. The axial length, spherical equivalent refraction, anterior and posterior corneal radii and meridian, and central corneal thickness are provided in Supplementary Table 1.

### Comparisons between refractive and corneal astigmatism measurements

Table 1 shows the magnitude of RA and four calculations of corneal astigmatism. Among all subjects, compared with RA, TNP and TCRP showed significant differences ( $p < 0.05$  by paired t-test), while SimK and EKR did not. However, when divided into the ATR, WTR, and oblique groups, differences were significant between RA and SimK measurement in the ATR and WTR groups ( $p < 0.05$ ) but not between RA and EKR, TNP, and TCRP measurements ( $p > 0.05$  for EKR in the ATR and WTR group; for TNP and TCRP in the WTR group). In addition, the average magnitude of all total corneal astigmatism measurements was relatively larger than the SimK value in the ATR group and smaller than that in the WTR group. In the oblique astigmatism group, the astigmatism magnitude did not differ significantly between RA and each corneal astigmatism measurement ( $p > 0.05$ ).

Regarding the meridian of astigmatism, there was no significant difference between each corneal measurement and RA in total, ATR, and WTR subjects (all  $p > 0.05$  by paired t-test). In the oblique group, only the meridian of SimK differed significantly from that of RA ( $p < 0.05$  by paired t-test).

When comparing the magnitude of astigmatism among the ATR, WTR, and oblique groups by one-way ANOVA and the LSD test, both RA and EKR measurements detected significant differences between the WTR and ATR groups, while SimK, TNP, and TCRP measurements did not find any significant differences among the three groups.

### Agreements between refractive astigmatism and corneal astigmatism measurements

According to Pearson's correlation test, all corneal astigmatism measurements were significantly correlated with RA in both magnitude and meridian in total subjects, as well as in the ATR, WTR, and oblique groups (all  $p < 0.05$ ) (Fig. 1), with the exception of the meridian in the ATR group ( $p > 0.05$ ) (Table 2). The correlation between total corneal astigmatism values and RA seemed stronger than that between SimK and RA in the total, WTR, and oblique astigmatism groups according to Pearson's correlation coefficient. In contrast, the correlation between SimK and RA seemed stronger than that between total corneal astigmatism values and RA in the ATR group.

Figure 2 shows Bland-Altman plots illustrating the agreement between each corneal astigmatism measurement and RA, with the mean values of individual measurements plotted on the horizontal axis and the differences of

**Table 1** Arithmetic means of the magnitude of refractive and corneal astigmatism (mean  $\pm$  SD)

	RA (D)	SimK (D)	EKR (D)	TNP (D)	TCRP (D)
Total	0.92 $\pm$ 0.74	0.95 $\pm$ 0.63	0.92 $\pm$ 0.72	1.04 $\pm$ 0.69*	1.07 $\pm$ 0.70*
p value (corneal astigmatism vs RA, paired t-test)	–	0.122	0.339	0.001*	<0.001*
ATR	1.18 $\pm$ 0.71	0.89 $\pm$ 0.70*	1.17 $\pm$ 0.88	1.15 $\pm$ 0.77	1.18 $\pm$ 0.78
p value (corneal astigmatism vs RA, paired t-test)	–	<0.001*	0.119	0.053	0.102
WTR	0.78 $\pm$ 0.75	0.99 $\pm$ 0.60*	0.79 $\pm$ 0.59	0.97 $\pm$ 0.64*	0.99 $\pm$ 0.66*
p value (corneal astigmatism vs RA, paired t-test)	–	<0.001*	0.314	<0.001*	<0.001*
Oblique	0.89 $\pm$ 0.57	0.89 $\pm$ 0.51	0.87 $\pm$ 0.59	1.05 $\pm$ 0.62	1.10 $\pm$ 0.63
p value (corneal astigmatism vs RA, paired t-test)	–	0.146	0.266	0.810	0.944
p value (one-way ANOVA among ATR, WTR and oblique group)	<0.001* (LSD: WTR vs ATR: $p < 0.001^*$ )	0.594	0.007* (LSD: WTR vs ATR: $p = 0.002^*$ )	0.294	0.289

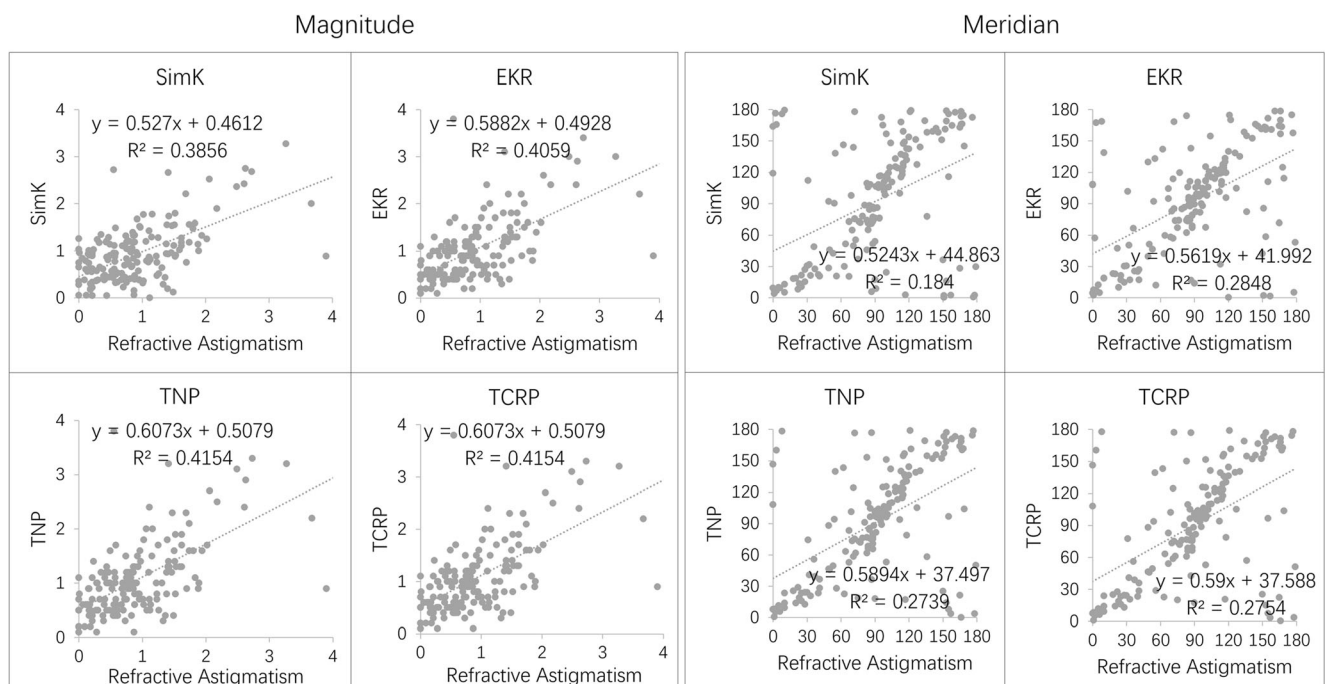
\*Statistically significant difference ( $p < 0.05$ )

RA = refractive astigmatism; SimK = simulated keratometry; EKR = equivalent K reading; TNP = true net power; TCRP = total corneal refractive power

individual measurements plotted on the vertical axis. In the total and WTR subjects, more data points exceeded the limits of agreement (LoA) in the SimK measurement than in other corneal astigmatism values for both magnitude and meridian. In the ATR group, fewer data points exceeded LoA in the EKR measurement for magnitude, while fewer data points exceeded LoA in SimK and EKR measurements for meridian. In oblique astigmatism subjects, the number of data points exceeding LoA was the same in each measurement (Table 2).

### Vector difference between refractive astigmatism and corneal astigmatism measurements

The vector differences between RA and corneal astigmatism by different measurements are shown in Fig. 3 and Table 2. The mean vector of the difference between SimK and RA was larger than that between other corneal measurements and RA in the total, ATR, WTR, and oblique groups, indicating that the mean difference vector in total corneal measurements was closer to 0 D.



**Fig. 1** Correlations between different corneal astigmatism values and refractive astigmatism among total subjects according to Pearson's correlation test. SimK = simulated keratometry; EKR = equivalent K reading; TNP = true net power; TCRP = total corneal refractive power

**Table 2** Comparison of the agreement between refractive astigmatism and corneal astigmatism measurements

	SimK vs RA	EKR vs RA	TNP vs RA	TCRP vs RA	Comments
Pearson's correlation coefficient					
Magnitude					
Total	0.569*	0.585*	0.601*	0.609*	*Significantly correlated
ATR	0.630*	0.445*	0.497*	0.508*	*Significantly correlated
WTR	0.531*	0.619*	0.557*	0.566*	*Significantly correlated
Oblique	0.647*	0.668*	0.669*	0.702*	*Significantly correlated
Meridian					
Total	0.429*	0.534*	0.523*	0.525*	*Significantly correlated
ATR	0.172	0.064	0.140	0.136	
WTR	0.432*	0.567*	0.547*	0.548*	*Significantly correlated
Oblique	0.493	0.602*	0.636*	0.627*	*Significantly correlated
Data points that exceed the limits of agreement (LoA)					
Magnitude					
Total	7/168 (4.2%)	4/168 (2.4%)	5/168 (3.0%)	4/168 (2.4%)	
ATR	2/55 (3.6%)	1/55 (1.8%)	2/55 (3.6%)	2/55 (3.6%)	
WTR	5/99 (5.0%)	4/99 (4.0%)	3/99 (3.0%)	3/99 (3.0%)	
Oblique	0/14 (0%)	0/14 (0%)	0/14 (0%)	0/14 (0%)	
Meridian					
Total	16/168 (9.5%)	14/168 (8.3)	14/168 (8.3)	14/168 (8.3)	
ATR	3/55 (5.5%)	3/55 (5.5%)	4/55 (7.3%)	4/55 (7.3%)	
WTR	13/99 (13.1%)	9/99 (9.1%)	10/99 (10.1%)	10/99 (10.1%)	
Oblique	1/14 (7.1%)	1/14 (7.1%)	1/14 (7.1%)	1/14 (7.1%)	
Mean vector (D) of the difference between RA and corneal astigmatism measurements					
Total	0.15 × -43.0°	0.13 × 54.9°	0.08 × 99.8°	0.07 × 73.9°	
ATR	0.19 × 128.1°	0.09 × 70.7°	0.04 × 52.9°	0.03 × 108.6°	
WTR	0.22 × -9.8°	0.17 × 43.1°	0.03 × 73.8°	0.10 × 57.5°	
Oblique	0.76 × 97.1°	0.22 × -60.8°	0.36 × 120.7°	0.16 × 99.7°	
Comparisons of the arithmetic means of the magnitude of difference vector (D)					
Total	1.33 ± 1.00	1.19 ± 1.00*	1.31 ± 1.01	1.34 ± 0.97	*Significantly smaller than the other three parameters by paired t-test
ATR	1.45 ± 1.19	1.47 ± 0.81	1.38 ± 0.84	1.34 ± 0.83	No statistically significant differences among different corneal measurements
WTR	1.23 ± 0.89	1.02 ± 0.78*	1.16 ± 0.83	1.19 ± 0.77	*Significantly smaller than the other three parameters by paired t-test
Oblique	1.59 ± 0.97	1.02 ± 0.54*	1.34 ± 1.00	1.35 ± 1.03	*Significantly smaller than the difference vector of simK by paired t-test
p value	0.268	0.005* (LSD: ATR vs WTR: $p = 0.001^*$ )	0.051	0.033* (LSD: ATR vs WTR: $p = 0.009^*$ )	p value of one-way ANOVA on vector differences among ATR, WTR and oblique group

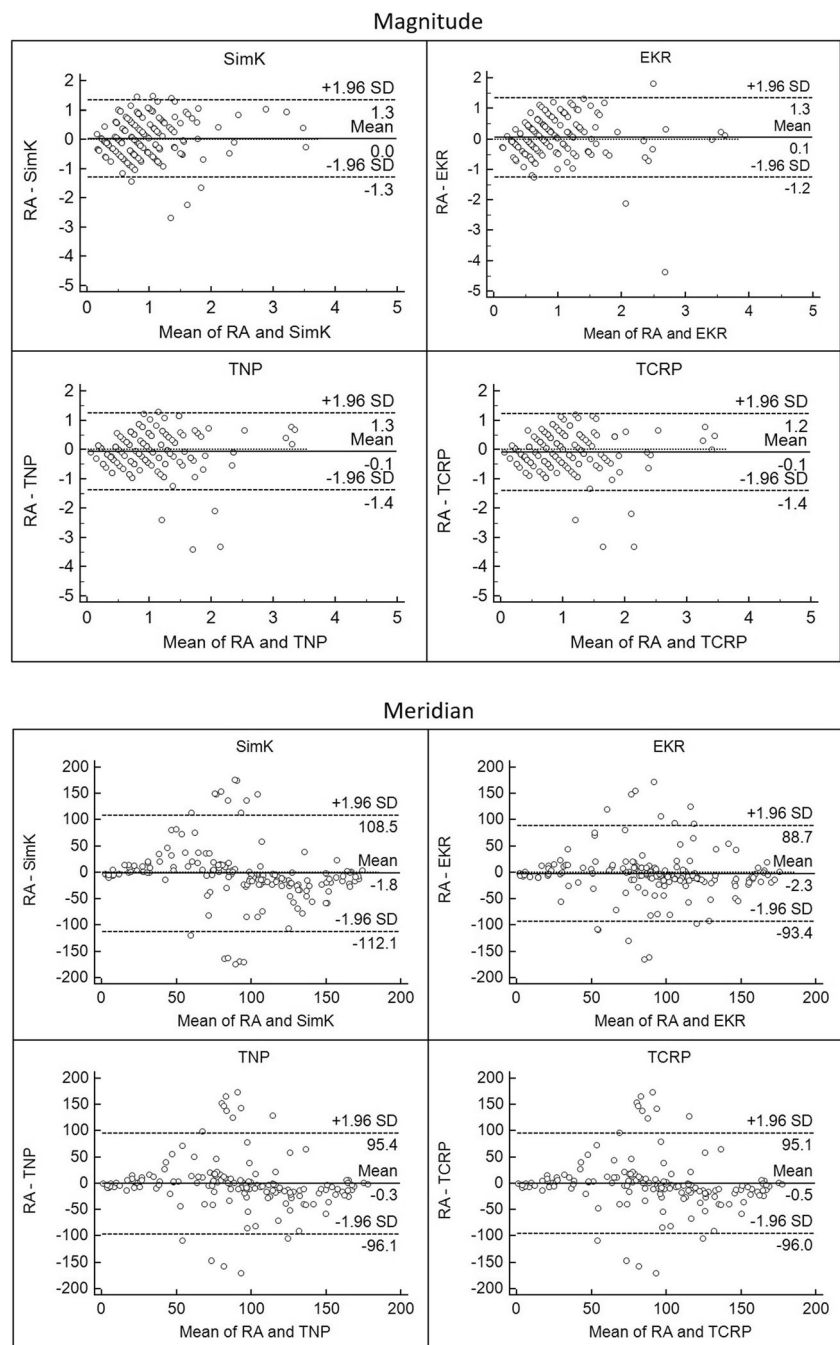
\*Statistically significant difference ( $p < 0.05$ )

RA = refractive astigmatism; SimK = simulated keratometry; EKR = equivalent K reading; TNP = true net power; TCRP = total corneal refractive power

We also compared the arithmetic means of the magnitude of the difference vector between each corneal measurement and RA by one-way ANOVA and the LSD test (Table 2). The arithmetic mean of the magnitude of the difference vector was significantly smaller in the EKR measurement than in other corneal measurements in the total, WTR, and oblique groups. No significant difference was found in the ATR group among different corneal

measurements. In the comparison of the arithmetic means of the magnitude of the difference vector between the same corneal measurement and RA among different astigmatism groups (WTR, ATR, and oblique), all the astigmatism values revealed larger arithmetic means in the magnitude of the difference vector in the ATR group compared with that in the WTR group, with statistical significance in EKR and TCRP measurements.

**Fig. 2** Bland-Altman plots illustrating the agreement between each corneal astigmatism measurement and refractive astigmatism among total subjects. SimK = simulated keratometry; EKR = equivalent K reading; TNP = true net power; TCRP = total corneal refractive power



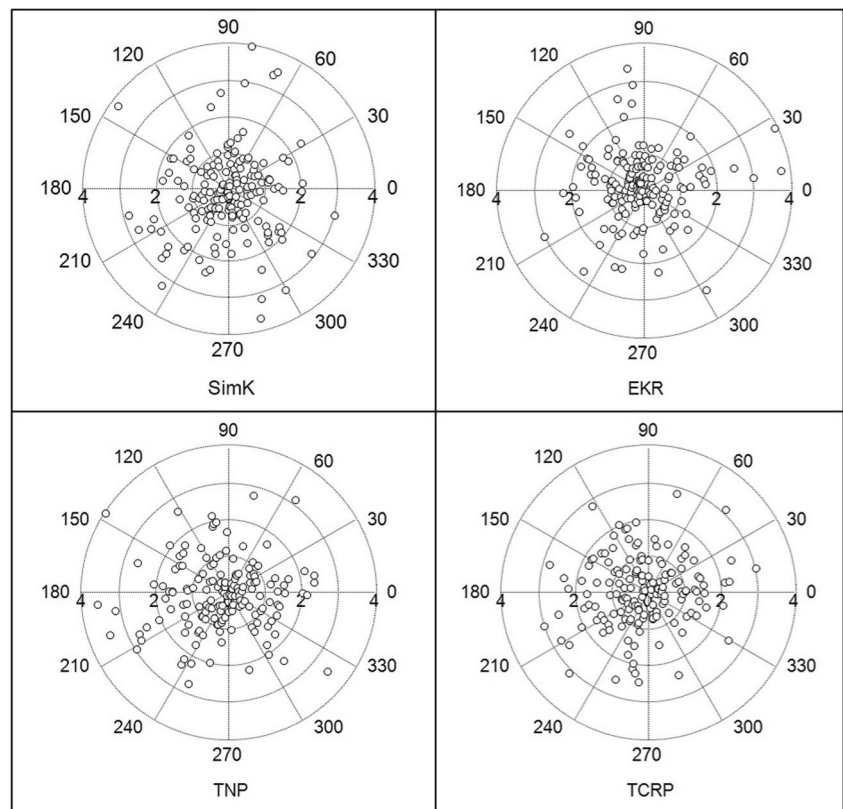
## Discussion

This study compared the predictive accuracy of different corneal astigmatism values measured by Pentacam, including keratometric astigmatism and total corneal astigmatism values (EKR, TNP, and TCRP). Essentially, the results indicate better predictive accuracy by total corneal astigmatism values than by SimK astigmatism in each group of astigmatism types.

The method to evaluate the accuracy of different corneal astigmatism measurements in this study is to compare the postoperative corneal astigmatism with postoperative RA in

non-toric pseudophakic eyes. Postoperative RA (converted to the corneal plane) is the vector sum of postoperative corneal astigmatism and the internal astigmatism derived from the toric IOL (if used). Since non-toric IOLs were used in this study, IOL-derived astigmatism was zero. Thus, the postoperative RA (converted to the corneal plane) should be equal to the postoperative corneal astigmatism. And the difference between them is considered to be the deviation (error) of the corneal astigmatism measurement. It is a convenient method to evaluate the accuracy of corneal astigmatism measurement [10–12].

**Fig. 3** Vector difference between the refractive astigmatism and corneal astigmatism of different measurements among total subject. SimK = simulated keratometry; EKR = equivalent K reading; TNP = true net power; TCRP = total corneal refractive power. The mean vector:  $0.15 \times -43.0^\circ$  in SimK measurement,  $0.13 \times 54.9^\circ$  in EKR measurement,  $0.08 \times 99.8^\circ$  in TNP measurement, and  $0.07 \times 73.9^\circ$  in TCRP measurement



Our study found that, in WTR subjects, all values of total corneal astigmatism measurements showed better agreement with RA than SimK did. In paired t-tests, differences in the magnitude were significant between the SimK measurement and RA, while EKR, TNP, and TCRP measurements were not significantly different from RA. Additionally, Pearson's correlation coefficient indicated a stronger correlation between total corneal astigmatism values and RA than that between SimK and RA. In Bland-Altman plots, more data points exceeded LoA in the SimK measurement than in all other measurements for both magnitude and meridian. Furthermore, the mean vector of the difference between SimK and RA was larger than that between other corneal measurements and RA.

In oblique astigmatism subjects, total corneal measurements also performed better than SimK. Possibly due to the small sample size of this group, paired t-test found no significant difference between the magnitude of any corneal astigmatism measurement and RA. However, regarding the meridian of astigmatism, only the meridian of SimK differed significantly from RA. The correlation between total corneal astigmatism values and RA was stronger than that between SimK and RA according to Pearson's correlation coefficient. The mean difference vector in total corneal measurements was closer to 0 D than that in SimK measurement.

In ATR subjects, EKR presented the best performance. In paired t-test, differences between corneal astigmatism and RA

were nonsignificant only in the EKR measurement. Additionally, fewer data points exceeded LoA in the EKR measurement for both magnitude and meridian compared with those in other measurements. Furthermore, only the EKR measurement found the same changes between the ATR and WTR groups as those detected in RA, while the SimK, TNP, and TCRP measurements did not find any significant difference among the three groups.

In addition, in the WTR and oblique groups, the arithmetic mean of the magnitude of the difference vector was significantly smaller in the EKR measurement than in all other corneal measurements.

Our results are consistent with previous studies [10–12] in which the difference between RA and total corneal astigmatism was significantly smaller than that between RA and keratometric astigmatism using anterior corneal astigmatism alone. The authors attributed this finding to the influence of posterior corneal astigmatism, and we agree with this assessment. The total cylinder may change considerably when the posterior surface is taken into account and become closer to actual astigmatism.

However, the mean difference vector between RA and total corneal astigmatism values was not zero, which might be ascribed to several reasons. First, there might be other sources of internal astigmatism other than posterior corneal astigmatism, such as IOL decentration and tilt [17], and the influence of these sources cannot be entirely ruled out in this study.

Second, measuring errors of the device may play a role [11]. Additionally, the softness of the cornea together with fluctuations in the tear film could be an important source of deviation [11, 12]. Finally, estimation errors might occur because all measurements fitted the relatively irregular corneal surface into a theoretically ideal model of astigmatism [11].

In addition, all the astigmatism values revealed larger arithmetic means in the magnitude of the difference vector in the ATR group compared with that in the WTR group, with statistical significance in EKR and TCRP measurements. A previous study also found that mean differences in magnitude and difference vector were larger in eyes with ATR than in those with WTR or oblique astigmatism, and the authors were unaware of the reason [10]. In this study, one possible reason is that the magnitude of ATR astigmatism was larger than that of WTR astigmatism in our patients (by RA and EKR measurement, Table 1), which might cause relatively larger estimation errors. In our previous study, the magnitude of astigmatism was a significant influential factor associated with estimation errors [18]. However, whether corneal astigmatism values themselves were less accurate in eyes with ATR astigmatism warrants further investigation.

As described above, EKR presented relatively better performance than other total corneal astigmatism values, TNP and TCRP, especially in the eyes with ATR astigmatism. TNP represents the corneal power calculated by using the anterior and posterior corneal curvatures (effect “B,” anterior/posterior surface) and the Gaussian optics formula for thick lenses where the actual refractive index of the air, cornea, and aqueous humor (effect “C”, true refractive index) is entered. TCRP uses ray tracing to calculate corneal power, taking effects “A” (refractive effect), “B” (anterior/posterior surface), and “C” (true refractive index) into account. EKR is another useful method that uses the Oculus Pentacam, taking into account the refractive effect (effect “A”) as well as the effect of the posterior surface (effect “B”). The EKR values are calculated according to Snell’s laws using the refractive indices of the corneal tissue, aqueous, anterior, and posterior power values, which are the first-step true power values. In a second correction step, the EKR map is shifted to adjust the value for IOL formulas that correct for  $n = 1.3375$ . In other words, the “error” that  $n = 1.3375$  creates is now added to the EKR true power values. In this way, the adjusted EKR values can be used in IOL formulas that correct for  $n = 1.3375$ . By these means, the EKR output can be used in IOL formulas based on a refractive index of 1.3375 even for the treatment of post-refractive patients. It avoids double correction while taking the influence of the posterior surface into account. EKR was intended to be used with the Holladay 2 formula for IOL power calculations following keratorefractive surgery. However, in our study, EKR presented commendable accuracy in normal eyes without a history of keratorefractive surgery and was even better than TNP and TCRP, especially in ATR

astigmatism estimation. We suspect that the superior accuracy of EKR could be due to the second step of its reading processing. However, the exact reason must be further studied.

In summary, among different Pentacam readings, the measurements considering both anterior and posterior corneal surfaces may lead to more accurate corneal astigmatism estimation. Moreover, EKR showed markedly better performance in ATR astigmatism estimation. Therefore, using total keratometric values is recommended to minimize the unpredicted effect of residual astigmatism when planning astigmatic correction in cataract surgery. However, estimation errors remain in total corneal astigmatism values, indicating the need for further improvement of corneal astigmatism measurement or the use of intraoperative wavefront aberrometry.

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## Compliance with ethical standards

**Conflict of interest** The authors declare that they have no conflict(s) of interest.

**Ethical approval** All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

**Informed consent** Informed consent was obtained from all individual participants included in the study.

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