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Full Length Article

The impact of posterior corneal astigmatism on the surgical planning of toric multifocal intraocular lens implantation

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ABSTRACT

Purpose: To investigate the influence of posterior corneal astigmatism on the prediction accuracy of toric multifocal intraocular lens (IOL) calculation.
Methods: The keratometric astigmatism measured by Lenstar LS 900 (KCA_L), keratometric astigmatism (KCA_P) and total corneal astigmatism (TCA) measured by Scheimpflug camera (Pentacam HR) were documented and analyzed accordingly. Three deduction models using different parameters were compared. Model 1: KCA_L + keratometric corneal surgically induced astigmatism (KCSIA, 0.30 D @ 50°); Model 2: KCA_P + KCSIA); Model 3: TCA + total CSIA (TCSIA, 0.23 D @ 50°). The prediction errors of each model as the difference vector between the actual and the intended residual astigmatism were compared.
Results: Seventy-six eyes implanted with toric multifocal IOLs were included in this study. The vector differences of the actual KCSIA and TCSIA were statistically significant in the total sample and against-the-rule (ATR) subgroup (both $P < 0.05$). Model 1 deduced the smallest mean values of prediction error, while that of Model 3 were smaller than that of Model 2, both in the total sample and the ATR subgroups (all $P < 0.05$). Meanwhile, in the total sample and ATR subgroups, the centroid vector magnitudes of Model 3 were smaller than that of Model 1 (0.31 ± 0.76 D and 0.39 ± 0.76 D).
Conclusions: The calculation of toric multifocal IOL should be individualized especially in the ATR eyes for the impact of PCA on the estimation of the preoperative corneal astigmatism and the CSIA.

1. Introduction

The modern advancements in surgical technique and intraocular lens (IOL) design for the correction of corneal astigmatism and presbyopia in refractive cataract surgery provide the opportunity for patient to be spectacle independent with excellent visual performance. The precise measurement and calculation of pre-operative and post-operative astigmatism is critical for optimized clinical outcome.[1] It is generally accepted that a predicted postoperative residual astigmatism of more than 0.75 D should be addressed for patients choosing to receive multifocal IOL implantation.[2,3] However, the precise prediction of astigmatism correction using toric IOLs remains to be a challenge.[4] Hirnschall et al. suggested that the main source of prediction error in toric IOL calculation is the preoperative measurement of the corneal astigmatism.[5] The assumption that the anterior corneal astigmatism dictates the overall corneal astigmatism is one of the important issues that could potentially induce error. Previous reports showed that the posterior corneal astigmatism (PCA) measurements derived from Scheimpflug camera (Pentacam HR, Oculus, Arlington, WA) can be incorporated into toric IOL calculations for the optimization of the residual astigmatism.[6] Through the retrospective deduction models, this study aimed to analyze the impacts of PCA on the accuracy of residual astigmatism prediction for toric multifocal IOL.

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2. Methods

2.1. Patients

This was a retrospective observational study. All data for this study were collected and analyzed in accordance with the policies and procedures of the Institutional Review Board of the Tianjin Medical University Eye Hospital and the ethical principles of the Declaration of Helsinki. All patients voluntarily joined this study with informed consents.

Retrospectively, patients' clinical data from October 2017 to October 2018 which met the following inclusion criteria were enrolled: (1) over 40 years with primarily diagnosed as age-related cataract, (2) preoperative keratometric corneal astigmatism (KCA) measured by Lenstar LS 900 (Haag-Streit, Inc.) was between 0.75 and 2.50 D, (3) axial length (AL) was between 22.00 and 26.00 mm without posterior scleral staphyloma, (4) uncomplicated cataract phacoemulsification with toric multifocal IOL (AcrySof® IQ ReSTOR® +3.0 D Multifocal Toric IOL, models SND1T2-T5, Alcon Laboratories, Inc.)was implanted, (5) Lenstar and Pentacam within 1 day before surgery, Pentacam with reliable quality results (95% or more valid data, automatically marked "OK") and subjective refraction 3 months after surgery were documented. All eyes with corneal or retinal disease, a history of corneal or intraocular surgery, severe dry eye symptoms or irregular corneal astigmatism, occurred before or after surgery, rotation of toric alignment over 5° from the intended meridian were excluded from the study.

2.3. Corneal astigmatism definition and acquirement

KCA was obtained by substituting the curvature radii of the anterior corneal surface on the steep (R_s) and flat (R_f) meridians into equation (1), in which the air refractive index is 1 and n_{KCA} is 1.3375. It should be noted that the R_s and R_f data used to calculate KCA_L (KCA from Lenstar) were derived from the 32 measuring points arranged in two concentric rings (outer 2.3 mm and inner 1.65 mm) of 16 measuring points each, while that of KCA_P (KCA from Pentacam) were derived from the 15° ring around the corneal vertex.

$$\frac{n_{KCA}-1}{R_S \text{ of anterior corneal surface}}-\frac{n_{KCA}-1}{R_f \text{ of anterior corneal surface}} \tag{1}$$

PCA was calculated with equation (2), where the $n_{cornear}$ is 1.376 and the $n_{aqueous}$ is 1.336. The measured by Pentacam R_s and R_f of posterior corneal surface were also set on the 15° ring.

$$\frac{n_{aqueous}-n_{cornear}}{R_S \text{ of posterior corneal surface}}-\frac{n_{aqueous}-n_{cornear}}{R_f \text{ of posterior corneal surface}} \tag{2}$$

Total corneal power was obtained by the ray tracing technique of Pentacam, which propagates incoming parallel rays and uses Snell law to refract the rays through the anterior and posterior corneal surfaces. Total corneal astigmatism (TCA) used the difference of total corneal power between the steep and flat meridian along the 3 mm diameter ring centered on the corneal vertex, which was chosen to match the 15° ring of KCA_P.

2.4. IOL selection and surgical technique

Toric multifocal IOLs with the cylindrical powers 0.68 D, 1.03 D, 1.55 D and 2.06 D at the corneal plane for SND1T2, SND1T3, SND1T4 and SND1T5 were used in all cases, respectively. The IOL cylindrical power and alignment axis was originally calculated using the manufacturer's online calculator (http://www.acrysoftoriccalculator.com) with the automated keratometry values obtained by Lenstar. All surgeries were performed by the same experienced surgeon (H.Z.) using a micro co-axial phacoemulsification technique with a 2.2-mm clear corneal incision along the 140° meridian. The central horizontal meridian of the cornea was marked in the sit-up position immediately before the operation on the surgical table using crescent corneal marker. The estimated corneal surgically induced astigmatism (CSIA) of 0.3 D @ 50° was previously calculated based on this surgeon's (H.Z.) personal data on Dr. Hill's website (www.doctor-hill.com).

2.5. Retrospective deduction models

Three models of measuring and calculating preoperative corneal astigmatism and toric IOL were compared:

Model 1 (KCA_L + KCSIA): The KCA_L and estimated keratometric CSIA (KCSIA, 0.30 D @ 50°).
Model 2 (KCA_P + KCSIA): The KCA_P and KCSIA.
Model 3 (TCA + TCSIA): TCA and total CSIA (TCSIA). We calculated the vector difference of the TCA in each eye before and after the operation. The magnitude of the centroid was used as the TCSIA (0.23 D @50°) for the IOL calculation. This model was intended to exclude the errors derived from the influence of PCA in both corneal astigmatism measurement and the CSIA calculation.

The original cylindrical power and target alignment axis for each eye preoperatively were used in all three models.

2.6. Vector analysis

In this study, astigmatism was calculated and analyzed according to the Alpins vector analysis and the standardized method described by American National Standards Institute (ANSI) Standard Subcommittee on Astigmatism Analysis.[7,8] Before vector analysis, all initial astigmatism data, consist of cylinder (C) and axis (A) values, were firstly converted to the corneal plane. Then the astigmatism vectors were converted to X and Y vector components according to trigonometric function principle in a double-angle plot.

Difference vector (DV): (1) the magnitude (C_{DV}) of DV (C_{DV} @ A_{DV}) between astigmatism 1 (C_1 @ A_1) and astigmatism 2 (C_2 @ A_2) was calculated with equations (3) and (4):

$$X_1 = C_1{*}\cos(2{*}A_1) \quad X_2 = C_2{*}\cos(2{*}A_2)$$

$$Y_1 = C_1{*}\sin(2{*}A_1) \quad Y_2 = C_2{*}\sin(2{*}A_2) \tag{3}$$

$$|C_{DV}| = \sqrt{\left([X_1 - X_2]^2 + [Y_1 - Y_2]^2\right)} \tag{4}$$

(2) The axis (A_{DV}) of DV was calculated with equation (5), where $X_{DV} = X_1 - X_2$ and $Y_{DV} = Y_1 - Y_2$:

$$\theta = 0.5{*}\arctan\left(\frac{Y_{DV}}{X_{DV}}\right) \tag{5}$$

If $Y_{DV} \geq 0$ and $X_{DV} > 0$, then $A_{DV} = \theta$

if $Y_{DV} < 0$ and $X_{DV} > 0$, then $A_{DV} = \theta + 180°$

if $X_{DV} < 0$, then $A_{DV} = \theta + 90°$

if $X_{DV} = 0$ and $Y_{DV} > 0$, then $A_{DV} = 45°$

if $X_{DV} = 0$ and $Y_{DV} < 0$, then $A_{DV} = 135°$

Centroid: The centroid of a group of astigmatism vectors represents the "center of gravity" of their distribution and were plotted at the mean X component and mean Y component position. First, $X_{centroid}$ and $Y_{centroid}$ were calculated with equation (6), where *n* was the number of vectors. Then the magnitude and axis of centroid were derived according to the same principle as equations (4) and (5).

$$X_{centroid} = \frac{\sum_{i=1}^{n} X_i}{n}, Y_{centroid} = \frac{\sum_{i=1}^{n} Y_i}{n} \quad (6)$$

CSIA: The actual $KCSIA_n$ or $TCSIA_n$ of each eye was calculated with equation (7) or 8 according to the above DV calculation method.

$$\overrightarrow{KCSIA_n} = \overrightarrow{KCA_{postop}} - \overrightarrow{KCA_{preop}} \quad (7)$$

$$\overrightarrow{TCSIA_n} = \overrightarrow{TCA_{postop}} - \overrightarrow{TCA_{preop}} \quad (8)$$

Prediction error: The DV between actual residual astigmatism (ARA) and targeted residual astigmatism (TRA), regarded as the prediction error of each eye, was evaluated among the three models. Firstly, the TRA of each model was calculated with equations (9)–(11), respectively, where IOLA represented the astigmatism of IOL at corneal plane. Then, DV was calculated with equation (12), where ARA used the subjective refraction at corneal plane 3 month after surgery.

$$\overrightarrow{TRA_{model\ 1}} = \overrightarrow{KCA_L} + \overrightarrow{KCSIA} + \overrightarrow{IOLA} \quad (9)$$

$$\overrightarrow{TRA_{model\ 2}} = \overrightarrow{KCA_P} + \overrightarrow{KCSIA} + \overrightarrow{IOLA} \quad (10)$$

$$\overrightarrow{TRA_{model\ 3}} = \overrightarrow{TCA} + \overrightarrow{TCSIA} + \overrightarrow{IOLA} \quad (11)$$

$$\overrightarrow{DV_{model\ 1/2/3}} = \overrightarrow{ARA} - \overrightarrow{TRA_{model\ 1/2/3}} \quad (12)$$

2.7. Change of toric IOL cylindrical type according to model 2 and model 3

The cylindrical powers at corneal plane of each toric IOL cylindrical type were substituted back into the prediction error equations (equations (10) and (11)) of Model 2 and Model 3, respectively. The toric IOL cylindrical type with minimal magnitude of TRA was chosen and recorded for each eye. The changes of IOL cylindrical type selection from Model 2 to Model 3 for each eye was analyzed.

2.8. Statistical analyses

A sample size calculation was performed using PASS software (version 15.0, NCSS, LLC, USA) set for repeated measures. The result indicated that 33 eyes were required for a significance level of 5% and a test power of 90%. Statistical tests were performed using SPSS software (version 20.0, IBM Inc., USA). The normality of the distribution of all data sets was verified using the Kolmogorov–Smirnov test (K–S test). The pairwise comparison of the magnitude between KCSIA and TCSIA was performed using the paired Student *t*-test and the Wilcoxon signed-rank test. Repeated-measures analysis of variance (RM ANOVA), One-way RM ANOVA or Friedman RM ANOVA on ranks, was used to analyze the differences of parameters among three models after the normal distribution was determined with the K–S test. Student-Newman-Keuls Method was performed to make further multiple pairwise comparisons between any two models when there was a statistical difference among three models. Linear relationship between the magnitude of preoperative PCA and prediction error was analyzed by univariate linear regression, and their statistical correlation was evaluated by Pearson or Spearman correlation coefficient. *P* values less than 0.05 were considered statistically significant.

3. Results

The study comprised 61 patients (76 eyes) who had toric multifocal IOL implantation with a mean age of 67.57 ± 9.58 years (range 42–87 years). Patients' demographics in total and each subgroup were summarized in Table 1. Eyes were divided into 3 groups depending on the anterior corneal steep meridian as follows: with-the-rule (WTR; 60°–120°), against-the-rule (ATR; 0° and 30° or 150° and 180°) and oblique (between 30° and 60° or 120° and 150°).[9]

Table 1
Patient demographics. ($\bar{x} \pm s$).

Group	Number (subjects/eyes)	Gender (male/femal)	Age (years)	AL (mm)	IOL (D)
Total	61/76	27/34	67.57 ± 9.58	23.98 ± 1.54	19.58 ± 3.61
WTR	15/20	7/8	63.07 ± 10.55	24.11 ± 1.54	18.83 ± 3.33
ATR	38/46	18/20	69.47 ± 9.43	23.71 ± 1.55	20.10 ± 3.72
Oblique	10/10	4/6	68.60 ± 6.08	24.42 ± 1.32	18.70 ± 3.51

AL = axial length; IOL = intraocular lens; D = diopters; WTR = with-the-rule; ATR = against-the-rule.

3.1. Preoperative measurement results

Table 2 shows the preoperative corneal astigmatism measured by Lenstar and Pentacam. Among them, 17.11% (13/76 eyes) of the total, 35.00% (7/20 eyes) of the WTR, 10.87% (5/46 eyes) of the ATR and 10.00% (1/10 eyes) of the oblique subgroups had the PCA value of 0.50 D or more. The average value of vector difference between TCA and KCA_P was 0.25 ± 0.15 D. The percentage of eyes in which the value of vector difference exceeding 0.50 D in each subgroup were 9.21% (7/76) in total, 5.00% (1/20) in WTR and 13.04% (6/46) in ATR.

3.2. Actual KCSIA and TCSIA

Table 3 showed the mean values and the centroids of actual KCSIA and TCSIA based on 3-month follow-up data. Vector analyses showed the mean values of vector difference in the total, WTR, ATR and oblique subgroups were 0.27 ± 0.25 D, 0.23 ± 0.14 D, 0.30 ± 0.26 D and 0.25 ± 0.32 D, respectively. The differences were statistically significant in the total and ATR subgroup. The mean value of vector difference between actual KCSIA and TCSIA was 0.27 ± 0.25 D in the total sample. Additionally, 40.79% (31/76 eyes) had difference more than 0.25 D, while 10.53% (8/76 eyes) had difference more than 0.50 D. In ATR subgroup,

Table 2
Mean magnitude (D) and mean steep meridian (°) of preoperative corneal astigmatism measured by Lenstar and Pentacam. ($\bar{x} \pm s$).

Group	KCA_L (D, °)	KCA_P (D, °)	ACA_P (D, °)	PCA (D, °)	TCA (D, °)
Total (N = 76)	1.33 ± 0.48, 104.98 ± 63.70	1.14 ± 0.63, 82.28 ± 63.76	1.03 ± 0.56, 82.28 ± 63.76	0.28 ± 0.18, 95.40 ± 29.88	1.25 ± 0.63, 82.81 ± 65.25
WTR (N = 20)	1.28 ± 0.59, 95.37 ± 31.83	1.50 ± 0.90, 95.72 ± 13.32	1.34 ± 0.81, 95.72 ± 13.32	0.40 ± 0.20, 89.24 ± 11.67	1.36 ± 0.92, 97.11 ± 14.07
ATR (N = 46)	1.37 ± 0.46, 108.56 ± 75.76	1.07 ± 0.42, 78.31 ± 78.70	0.96 ± 0.38, 78.31 ± 78.70	0.22 ± 0.16, 99.52 ± 35.58	1.29 ± 0.49, 79.86 ± 79.12
Obliqe (N = 10)	1.27 ± 0.36, 107.70 ± 51.94	0.78 ± 0.48, 73.67 ± 44.43	0.70 ± 0.43, 73.67 ± 44.43	0.32 ± 0.13, 88.74 ± 24.52	0.86 ± 0.41, 67.82 ± 54.94

KCA_L = Keratometric corneal astigmatism measured by Lenstar; KCA_P = Keratometric corneal astigmatism measured by Pentacam; ACA_P = Anterior corneal astigmatism measured by Pentacam; PCA = Posterior corneal astigmatism; TCA = Total corneal astigmatism; D = diopters; ° = degrees; WTR = with-the-rule; ATR = against-the-rule.

Table 3
Comparison of the mean magnitude (D) ($\bar{x} \pm s$) and centroid (D @ °) between KCSIA and TCSIA.

Group	KCSIA (D, D @ °)	TCSIA (D, D @ °)	t/z	P
Total (N = 76)	0.75 ± 0.64, 0.20 @75.72	0.87 ± 0.69, 0.23 @ 71.73	z = −3.762	<0.001
WTR (N = 20)	0.72 ± 0.73, 0.31 @ 42.37	0.81 ± 0.77, 0.34 @ 47.29	t = −1.816	0.085
ATR (N = 46)	0.73 ± 0.63, 0.27 @ 85.44	0.77 ± 0.69, 0.29 @ 80.91	z = −3.258	0.002
Oblique (N = 10)	0.91 ± 0.59, 0.17 @ 111.04	0.94 ± 0.59, 0.08 @ 109.64	t = −0.666	0.522

KCSIA = Keratometric corneal surgically induced astigmatism; TCSIA = Total corneal surgically induced astigmatism; D = diopters; ° = degrees; WTR = with-the-rule; ATR = against-the-rule.

the mean value of vector difference was 0.30 ± 0.26 D.

3.3. Prediction error in residual astigmatism

Fig. 1 compared the magnitudes of prediction error in residual astigmatism of the three models. Model 1 deduced the smallest mean values of prediction error both in the total group (0.71 ± 0.39 D) ($\chi^2 = 16.525$, $P \leq 0.001$) and the ATR subgroup (0.74 ± 0.40 D) ($\chi^2 = 8.615$, $P = 0.013$), while that of Model 3 (1.06 ± 0.80 D for total and 1.01 ± 0.64 D for ATR) were smaller than that of Model 2 (1.11 ± 0.81 D for Total and 1.06 ± 0.64 D for ATR) ($q = 4.867$ and 2.919, $P < 0.001$ and = 0.039).

The vector distribution of prediction errors and their centroids were shown in Fig. 2 using double-angle plots. In the total sample, WTR, ATR and oblique subgroups, the centroid vector magnitudes of Model 3 (0.25 ± 1.31 D, 0.55 ± 1.38 D, 0.23 ± 1.18 D and 0.74 ± 1.49 D) were all smaller than that of Model 2 (0.45 ± 1.31 D, 0.66 ± 1.37 D, 0.40 ± 1.18 D and 0.88 ± 1.55 D). Meanwhile, in the total sample and ATR subgroups, the centroid vector magnitudes of Model 3 were even smaller than that of Model 1 (0.31 ± 0.76 D and 0.39 ± 0.76 D).

3.4. Correlation between preoperative PCA and prediction error DV

The linear regression, goodness of fit (R^2) and regression equation (y = A + Bx) of preoperative PCA values and prediction error DV values of total sample and each subgroup in Model 2 were shown in Fig. 3. Pearson correlation analysis showed a positive correlation between the magnitudes of preoperative PCA and prediction error DV in the ATR subgroup ($r = 0.324$, $P = 0.028$).

3.5. Alteration of toric IOL cylindrical type calculated with TCA + TCSIA instead of KCA + KCSIA

For the calculation and selection of toric IOL cylindrical type, Fig. 4 shows that 63.16%, 75.00%, 54.35% and 80.00% eyes of the total sample, WTR, ATR and oblique subgroups kept unchanged (Tn) when Model 3 (TCA + TCSIA) instead of Model 2 (KCA_P + KCSIA) was used during surgical planning, respectively. 9.21%, 25.00%, 2.17% and 10.00% eyes decreased from Tn to Tn-1.26.32%, 0.00%, 41.30% and 10.00% eyes increased from Tn to Tn+1, while 1.32%, 0.00%, 2.17% and 0.00% eyes increased from Tn to Tn+2.

4. Discussion

Our results suggested that PCA play an influential role in the accurate prediction of toric multifocal IOL implantation, especially in the eyes with against-the-rule astigmatism measured by Lenstar, namely, the ATR eyes.

In our series, 13.04% eyes in ATR group had more than 0.50 D vector difference between TCA and KCAp. The results indicated that the corneal astigmatism of the ATR eyes are more likely to be falsely estimatied if the PCA was not considered. This is consistent with the results of previous study done by Ho et al. using Pentacam for the measurement of posterior corneal a stigmatism.[10] Their study showed that 28.8% of eyes had a TCA magnitude estimation error of more than 0.50 D when the PCA was considered. Koch et al. presented their seminar work on the contribution of PCA in the planning of toric IOL implantation by proposing a new nomogram for the estimation of TCA based on the finding that 5% eyes had the prediction error of TCA more than 0.50 D when the PCA was neglected.[11] Hosny et al. reported that the PCA was 0.11 ± 0.24 D in the ATR eyes contributing to 8% to the TCA, which is less compared to our result.[12] This discrepancy may be due to the fact that the patients enrolled in their study were younger population aged from 18 to 45 years

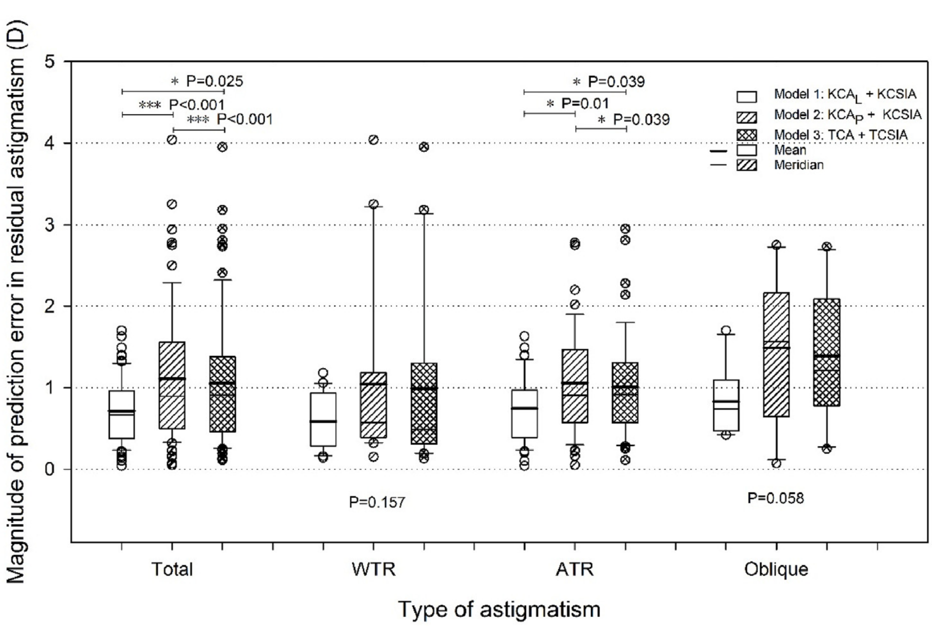

Fig. 1. The magnitudes of prediction error in residual astigmatism of the three models. (The boxes show the 25% and 75% quartiles, the bold lines represent the mean magnitudes, and the thin lines represent the medians of the magnitudes.)

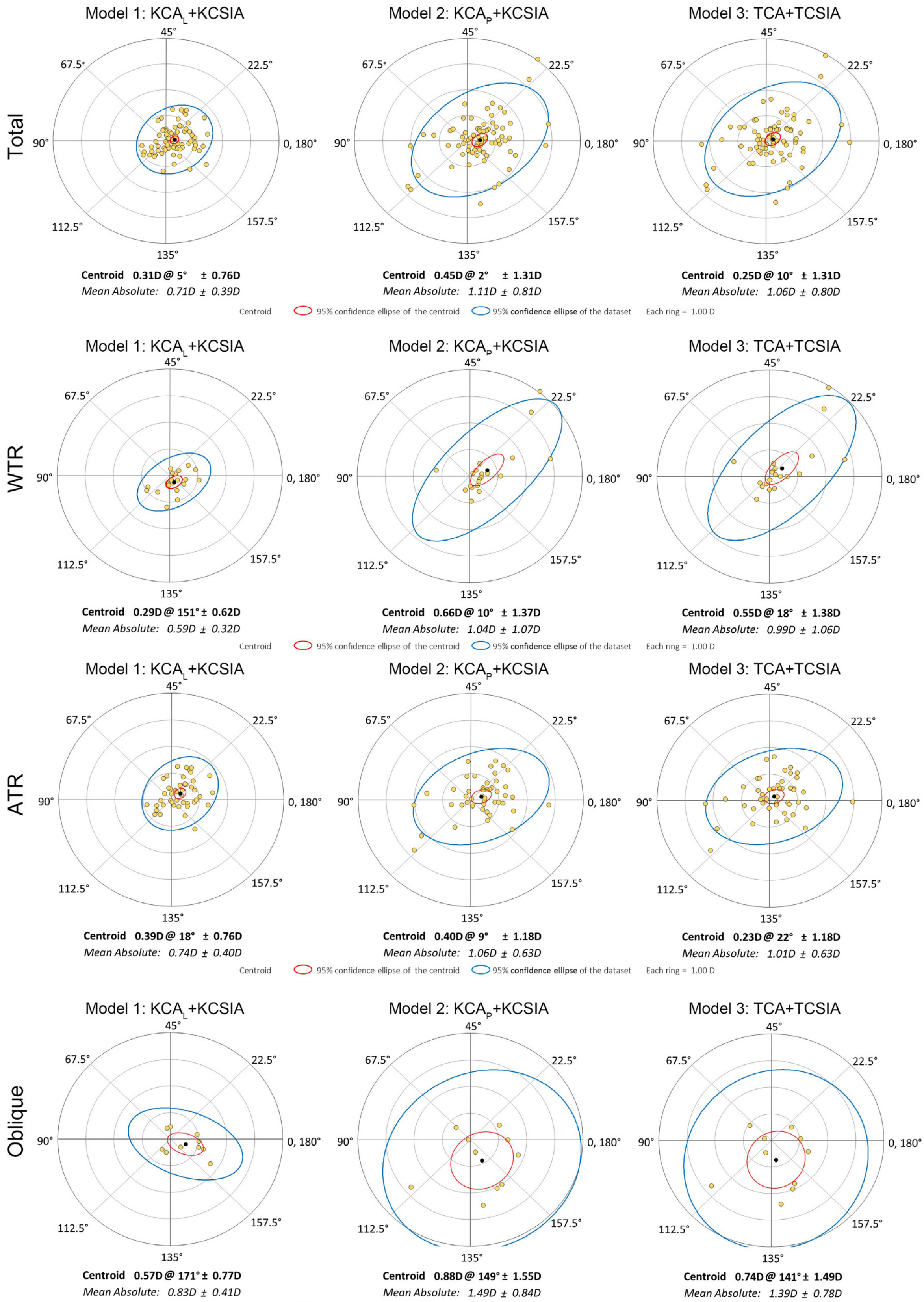

Fig. 2. The vector distribution of prediction errors and their centroids of the three models in double angle plots.

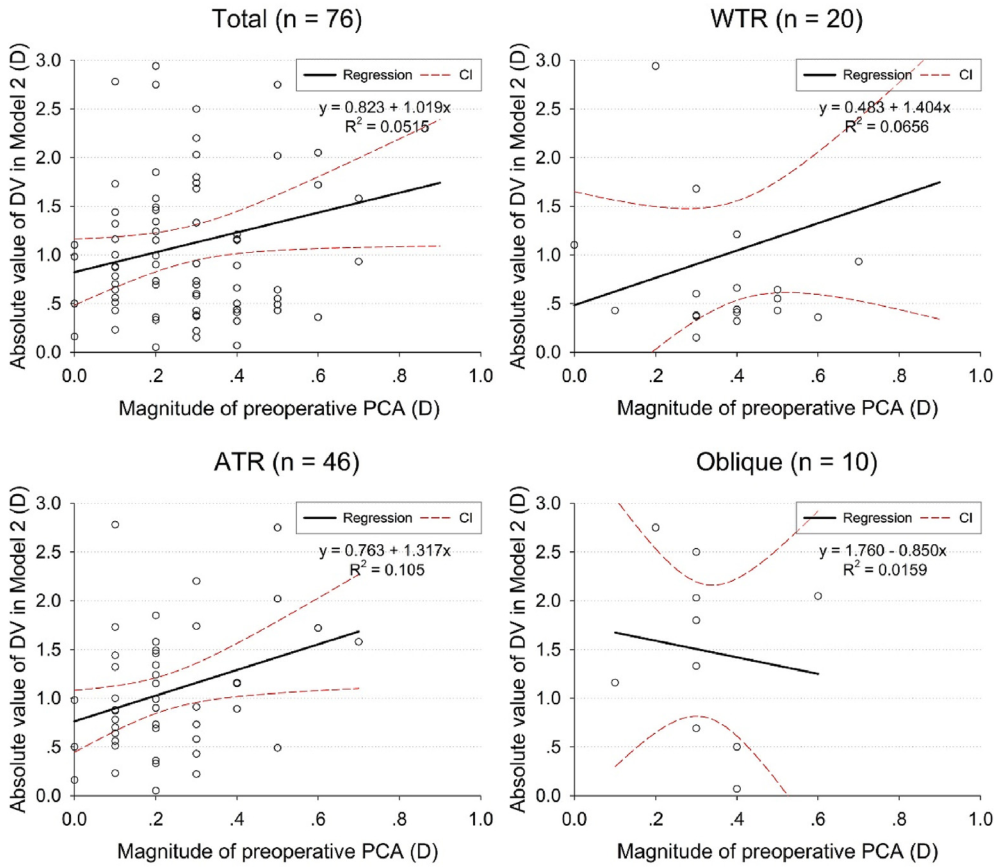

Fig. 3. Scatter plots and linear regression of correlation between the magnitudes of preoperative PCA and the prediction error DV in Model 2.

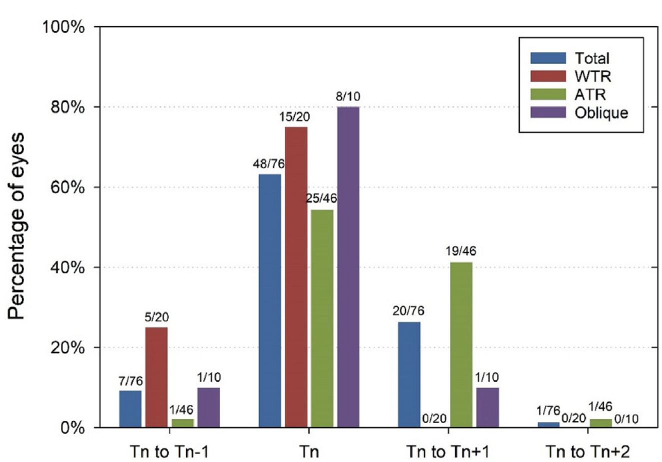

Fig. 4. Alteration of toric IOL cylindrical type calculated with TCA + TCSIA instead of KCA + KCSIA.

old. As various studies had established that the ACA gradually shifted from WTR to ATR while the change of the posterior surface of the cornea is much less.[13,14]

Besides the pre-operative corneal astigmatism, the estimation of CSIA can also be optimized by considering the influence of PCA. In our study, the KCSIA derived from Pentacam measurement was significantly lower than the TCSIA at 3 months after the operation, especially in the ATR eyes. Liang et al. also reported significant difference between the CSIA based on simulated keratometry or total corneal refractive power derived from Pentacam up to 3 month post-operatively.[15] Li et al. reported that the SIA of the posterior corneal surface will increase in the eyes with higher pre-operative corneal astigmatism on either the anterior or the posterior surface.[16] However, there are controversial conclusions in other authors' observation. Kohnen et al. reported minimal difference of the astigmatic changes in ACA, PCA and TCA.[17] Their study focusing on the eyes that underwent femtosecond laser-assisted cataract surgery with 2.2 mm temporal clear corneal incisions which could minimize the variation of the incision created by manual keratome. Our results indicated that taking the PCA into consideration in ATR eyes with superior corneal incision could be beneficial for the estimation of CSIA.

The prediction could be further improved in ATR eyes with the incorporation of the information of PCA. The current toric predictive method remains to be more accurate based on our results. The mean arithmetic value and the centroid of prediction error in model 1 were significantly lower than that of model 2 and 3. However, in our study, the ATR group had a higher chance of error in prediction because the high number of eyes with significant larger PCA that do not fit the conventional presumption. Therefore, researchers suggested that the calculations based on total corneal referactive power could improve the prediction of the residual astigmatism. Holladay et al. suggested that the toric IOL calculation should treat WTR, ATR and oblique astigmatism differently.[18] Their conclusion agrees with our observation that the prediction error could be reduced if the PCA were considered both in the measurement of the cornea and the estimation of SIA in ATR group instead of only the anterior corneal astigmatism. Savini and Næser investigated the influence of PCA in the accuracy of toric IOL prediction using the similar deduction approach found that the improvement of prediction error was only in ATR eyes.[9] Additionally, the linear correlation between the PCA and the prediction error in model 2 further suggested that the important role of PCA in the prediction accuracy in the ATR eyes.

The current study showed that the prediction error DV in Model 1 resulted in the least variation with the lowest deviation both in the mean of magnitude and the centroid. The results indicated that the keratometric values measured by Lenstar could result in a more consistent and accurate refractive outcome compared to that of Pentacam. This finding is in line with the report of Arruda et al. that the Lenstar measurements resulted in a more consistent refractive outcomes compared to that of the Pentacam.[19] However, on contrary to our findings, Fityo et al. found that Scheimpflug system produced higher repeatability in the corneal refractive power measurements.[20] Therefore, further investigation to evaluate the accuracy of keratometric value measured by various instruments are warranted.

Furthermore, our results showed that the PCA has impact on the toric IOL cylinder calculation, especially in eyes with PCA over 0.5 D. The lack of consideration of the PCA could result in overcorrection in the WTR eyes and undercorrection in the ATR eyes. This findings is consistent with previous reports. Savini et al. found that overcorrection of 0.59 ± 0.34 D in 25 WTR eyes and undercorrection of 0.32 ± 0.42 D in 15 ATR eyes. The correction errors decreased to 0.13 ± 0.42 D in WTR eyes and 0.07 ± 0.59 D in ATR eyes if the TCA value were used.[21] Zhang et al. also reported that the calculation of toric power based on anterior corneal surface alone can induce overcorrection in WTR eyes and undercorrection in ATR eyes.[22] The deviations are significant especially in multifocal IOL patients that need small amount of astigmatism correction which could results in the different of toric type choosing.

One of the major limitations of the current study is that the sample size of WTR and oblique group was relatively small. Hence the results conclude from the current study should be interpreted with caution in clinical practice. Additionally, previous reports suggested that the tear film play an influential role in pre-operative measurement of the corneal astigmatism.[23,24] Although the severe form of dry eye patients were excluded from the study based on the guideline of TFOS DEWS II, there were some patients received dry eye treatment during the perioperative period.[25] Previous reports indicated that the topic application of artificial tears could interfere the reading of the keratometry resulting in the large variation of the corneal astigmatism measurement.[26,27] However, these reports also showed that the variation of corneal astigmatism after topical application of lubricants were not predictable at present. Therefore, a larger sample size with detailed grouping with the consideration of ocular surface status could provide further information to optimize the corneal astigmatism meausurement and the preditive accuracy. Furthermore, future studies that foucs the actual amount of variations induced by dry eye in the measurement of corneal astigmatism could also be of benefit for clinical practice.

In conclusion, the PCA should be considered because it is more likely to affect the prediction error and the toric IOL cylindrical type selection by influencing the estimation of the TCA and the CSIA. Employing the PCA values has been shown to reduce the prediction error in toric IOL calculation.[28] The Barrett toric calculator has also advanced to include the option to incorporate measured PCA in preoperative calculation, although this has proven to not always result in statistically significant improvement in residual astigmatism.[29] Our results suggested that the calculation of toric IOL should be individualized especially in the ATR eyes.

Study approval

The authors confirm that any aspect of the work covered in this manuscript that involved human patients was conducted with the ethical approval of all relevant bodies and the study was performed in accordance with the Declaration of Helsinki, and the protocol was approved by the Ethics Committee of Tianjin Medical University Eye Hospital (approval number: 2020KY-38). All patients voluntarily joined this study with informed consents.

Author contributions

The authors confirm contribution to the paper as follows: Conception and design of study: SB, HZ, FT; Data collection: YG, YJ; Analysis and interpretation of results: SB, XB, XC; Drafting the manuscript: SB, YJ; All authors reviewed the results and approved the final version of the manuscript.

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Declaration of completing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Authorship

All authors attest that they meet the current ICMJE criteria for authorship.

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Abbreviations

IOL	intraocular lens
PCA	posterior corneal astigmatism
KCA	keratometric corneal astigmatism
AL	axial length
KCA_L	keratometric corneal astigmatism measured by Lenstar
KCA_P	keratometric corneal astigmatism measured by Pentacam
TCA	total corneal astigmatism
CSIA	surgically induced corneal astigmatism
KCSIA	keratometric corneal surgically induced astigmatism
TCSIA	total corneal surgically induced astigmatism
ANSI	American National Standards Institute
DV	difference vector
ARA	actual residual astigmatism
TRA	targeted residual astigmatism
WTR	with-the-rule
ATR	against-the-rule
ACA	anterior corneal astigmatism

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