Accuracy of Toric Intraocular Lens Calculators with Predicted and Measured Posterior Corneal Astigmatism Across Different Types of Astigmatism

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ABSTRACT

Introduction: This study is a retrospective case series to compare the accuracy of the Barrett toric calculator using predicted posterior corneal astigmatism (PCA) and PCA measurements using swept-source optical coherence tomography (SS-OCT) and a Scheimpflug camera. This evaluation was conducted across different types of anterior and posterior astigmatism.

Methods: A total of 146 eyes from 146 patients implanted with toric intraocular lenses were included. Mean absolute prediction error, standard deviation of prediction error, and the percentage of eyes with prediction errors within

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±0.50 diopters (D) were calculated using vector analysis. Biometric measurements were conducted using the IOLMaster 700 and Pentacam HR. A subgroup analysis was conducted based on the orientation of both anterior and posterior corneal astigmatism.

Results: The Barrett toric calculator with predicted PCA yielded the best results, with 78.1% having a prediction error ≤ 0.50 D, which was a significantly higher percentage than the Barrett formula with the two versions of measured PCA ($P < 0.05$). In the subgroup with a horizontally steep meridian PCA using the IOLMaster 700, the Barrett formula with predicted PCA yielded the best results, with 78.3% of cases having a prediction error of less than 0.5 D. This percentage was significantly higher than the other two measured PCA subgroups ($P < 0.05$).

Conclusion: The Barrett toric formula with predicted PCA demonstrated a statistically significantly higher proportion of cases with a prediction error ≤ 0.5 D compared to the two measured PCA formulas (from the IOLMaster 700 or Pentacam). This trend persisted even when the posterior corneal astigmatism was horizontally steep.

Keywords: Toric; Intraocular lens; Barrett formula; Posterior corneal astigmatism

Key Summary Points

Why carry out this study?

To date, there has been no clear outcome regarding the superiority of the Barrett toric formula, whether it be the predicted posterior corneal astigmatism (PCA) formula or the measured PCA formula.

It was anticipated that using predicted values of PCA versus measured PCA values within the Barrett toric formula could lead to different clinical outcomes, and that changing the measuring device might also result in varying results.

What was learned from the study?

The Barrett toric formula with predicted PCA outperformed the formula with measured PCA values from the IOLMaster 700 or Pentacam, showing significantly more cases with prediction errors under 0.5 diopters, even in horizontally steep posterior corneal astigmatism.

The Barrett toric formula with predicted PCA is expected to yield more accurate clinical outcomes than that using measured PCA values.

INTRODUCTION

Astigmatism is a prevalent refractive error characterized by an uneven curvature of the cornea or lens, leading to distorted or blurred vision [1]. Among patients undergoing cataract surgery, around 40% exhibit corneal astigmatism of 1.0 diopter (D) or higher, with reports indicating that 20% have corneal astigmatism of 1.5 D or greater [2–6]. Precise anticipation and correction of astigmatism are pivotal facets of successful cataract surgery and the implantation of intraocular lenses (IOLs). The emergence of toric IOLs has enhanced visual outcomes markedly for individuals with preexisting astigmatism [7]. Various methods and formulas have been devised to compute the suitable toric IOL power and axis orientation for optimal refractive results [8]. However, achieving consistently accurate outcomes across different types of astigmatism and measurement devices remains a formidable challenge.

The fundamental principle of correcting astigmatism using a toric IOL is that the majority of aphakic astigmatism originates from corneal astigmatism [8]. Therefore, accurately measuring the total corneal astigmatism before surgery can be considered of paramount importance. Moreover, it is widely acknowledged through various research findings that considering posterior corneal astigmatism (PCA) is crucial when measuring total corneal astigmatism [9–17]. There are two methods for performing toric IOL calculation that incorporate PCA. The first is the estimation method, which involves using nomograms (e.g., Baylor nomogram [10]) or regression formulas based on population-based estimates (e.g., Barrett toric calculator with predicted PCA [18]). The second method involves directly inputting the measured posterior astigmatism of individual patients into the formula [12, 13, 15, 16]. Several devices have recently been developed, such as swept-source optical coherence tomography (SS-OCT) and a Scheimpflug camera capable of directly measuring posterior corneal astigmatism [19–22]. In the updated Barrett toric IOL formula, measurements for posterior corneal astigmatism obtained from these various devices are directly integrated into the formula to calculate results [23].

Logically, if the measured posterior astigmatism for each individual is directly input into the formula, an expectation of improved clinical outcomes can be considered reasonable. However, based on the existing body of reported research, no definitive conclusion has yet been reached regarding whether outcomes yielded by the Barrett toric calculator formula with measured PCA are superior to those obtained using the formula with predicted PCA [12, 13, 15–17, 24, 25].

The current toric intraocular lens (IOL) calculator relies on population estimates and assumes that the orientation of the posterior

corneal astigmatism (PCA) is predominantly aligned with or close to the vertical meridian [10, 18]. However, recent studies have challenged this assumption, revealing that the steep axis of PCA is less frequently aligned vertically, in contrast to earlier research findings. Additionally, there have been reports indicating variations in these results based on the measurement devices used [12, 20, 26, 27]. Consequently, the aim of this study was to compare the accuracy of the Barrett toric calculator with predicted PCA against the measured PCA values obtained using either the IOLMaster 700 or Pentacam devices, taking into consideration the type of anterior and posterior astigmatism.

METHODS

This study was approved by the Institutional Review Board (IRB) of Seoul St. Mary's Hospital, the Catholic University of Korea (IRB No. KC23RISI0645), with the informed consent requirement waived due to the retrospective nature of the study. The investigation adhered to the principles set forth in the Declaration of Helsinki. A comprehensive retrospective examination of all cataract surgeries undertaken between 2019 and 2022 was performed by a single experienced surgeon (S.H-C.) at Seoul St. Mary's Hospital. The study methodology aligns with the editorial guidelines recommended for toric IOL studies as outlined by the *Journal of Cataract & Refractive Surgery* [28].

The inclusion criteria comprised uncomplicated cataract surgeries involving a temporal clear corneal incision, with the implantation of either the Alcon SN6AT(2-9) IOL (Alcon Laboratories, Inc., Fort Worth, TX, USA) or the Tecnis DIU (150–375) toric IOL (Johnson & Johnson Vision, Inc., Santa Ana, CA, USA). Exclusion criteria encompassed the presence of any corneal disease (such as keratoconus, other ectasias, pterygium, or previous trauma), ocular disease (including pseudoexfoliation syndrome, macular degeneration, or glaucoma), prior ophthalmic surgeries (such as laser vision correction, vitrectomy, pterygium surgery, penetrating glaucoma surgery, or scleral buckling procedures), intraoperative or postoperative complications, or postoperative corrected distance visual acuity worse than 6/9. A targeted surgically induced astigmatism (SIA) of approximately 0.2 D was sought. Preoperative biometry involved the use of the IOLMaster 700 (software version 1.80; Carl Zeiss Meditec, AG, Jena, Germany), and the subjective manifest refraction was assessed by any of the orthoptists participating in the practice. The precise postoperative alignment axis of the IOL was determined through slit lamp examination and photography during the same visit, typically around 2 months after the surgery (with a minimum postoperative period of 1 month).

Preoperative assessment of best-corrected visual acuity (BCVA) utilized Snellen charts, and standard anterior and posterior segment examinations were conducted prior to surgery. The presence of irregular astigmatism was determined through Scheimpflug corneal topography (Oculus Pentacam HR, Wetzlar, Germany), which served as an exclusion criterion. Optical biometry, encompassing the measurement of posterior corneal astigmatism (PCA), was performed using the IOLMaster 700 (Carl Zeiss Meditec AG, Jena, Germany) and Pentacam HR (software version 1.14r01; Oculus, Wetzlar, Germany). To ensure measurement repeatability, an experienced technician evaluated all parameters twice. The placement axis for implantation was manually indicated with support from the toriCAM application (Graham Barrett, App Store, USA) [29]. The calculation of IOL power utilized optimized constants obtained from the User Group for Laser Interference Biometry (ULIB) website, selected in accordance with surgical preferences. The lens factor of the Barrett formula was determined using the Barrett Universal II calculator, as provided by the Asia-Pacific Association of Cataract and Refractive Surgeons (APACRS) website [23].

All calculations were conducted using vector addition, following the methodology outlined by Holladay et al. [30] The postoperative refractive astigmatism prediction error (PE), was calculated as the vector difference between the actual and predicted postoperative refractive astigmatism. Various metrics were derived, including the mean absolute prediction error

(MAE), median absolute prediction error (MedAE), standard deviation (SD) of the absolute prediction error, centroid of the prediction error, standard deviation of the centroid, and the proportion of eyes within a prediction error of ±0.50 D, ±0.75 D, and ±1.00 D.

A subgroup analysis was conducted based on the orientation of both anterior and posterior corneal astigmatism. Eyes were categorized as having with-the-rule (WTR) astigmatism if the anterior corneal steep meridian ranged between 60° and 120°. Against-the-rule (ATR) astigmatism was defined when the anterior corneal steep meridian fell between 0° and 30° or between 150° and 180°. Oblique astigmatism was identified for the remaining cases. For cases of posterior corneal astigmatism, a very limited number of eyes exhibited oblique or horizontal steepness. Therefore, posterior corneal astigmatism was classified as vertically steep meridian PCA when the steep axis fell between 45° and 135° and as horizontally steep meridian PCA when the steep axis was within the range of 0°–45° or 135°–180°.

Statistical analysis adhered to the editorial recommendations outlined by the *Journal of Cataract & Refractive Surgery* [28]. A sample size calculation was conducted to detect a difference equivalent to half the standard deviation of differences in prediction errors between groups. With a significance level of 5% and a test power of 90%, a minimum of 43 eyes was determined to be necessary. This study included 146 eyes, ensuring statistical significance for a minimum detectable mean difference between groups of 0.13 D. The normality of distributions was assessed using the Shapiro–Wilk test, considering univariate or multivariate normality depending on the nature of the data being tested. For multivariate statistical analysis of centroid errors, the Hotelling t^2 test was employed. Differences between the mean absolute prediction errors among formulas were evaluated using the nonparametric Friedman test. A homogeneity test was applied to analyze differences in the variances of the prediction error for each formula. Cochran's Q test was utilized to assess the proportion of prediction errors less than 0.50 D among formulas. All calculations were conducted using Excel (Microsoft Corp.,

USA) or SPSS software (version 22.0, IBM Corp., Armonk, NY, USA).

RESULTS

The study included a total of 146 eyes from 146 patients. Among these, 70 eyes (47.9%) exhibited WTR anterior corneal astigmatism, 69 eyes (47.2%) had ATR astigmatism, and four eyes (0.05%) showed oblique astigmatism. Table 1 presents baseline demographic information for the study cohort.

Supplementary Fig. 1A features double-angle plots illustrating preoperative corneal astigmatism, postoperative refractive astigmatism at the corneal plane, and a cumulative histogram comparing the preoperative and postoperative refractive astigmatism. Supplementary Fig. 1B displays the percentage of eyes within a prediction error of ±0.50 D, ±0.75 D, and ±1.00 D. Figure 1 illustrates double-angle plots of the prediction error for each formula in the total, WTR, and ATR groups.

Table 2 summarizes the overall clinical outcomes for each formula. The Barrett toric calculator with predicted PCA yielded the best results, with 78.1% having a prediction error less than 0.50 D, significantly greater than the Barrett formula with two versions of measured PCA ($P < 0.05$). The centroid of the prediction error for the Barrett with measured PCA from the IOLMaster 700 was not significantly different from 0 ($P = 0.35$). There was no significant difference in MAEs in the prediction error calculated using three versions of the Barrett toric formula (predicted PCA, measured PCA from the IOLMaster 700, and measured PCA from the Pentacam) ($P > 0.05$). The prediction errors for each formula were normally distributed according to the Shapiro–Wilk multivariate normality test ($P < 0.001$).

In the subgroup analysis stratified by the orientation of anterior corneal astigmatism, no statistically significant disparities in MAE were discerned between the WTR and ATR astigmatism groups. The prediction errors for all three formulas exhibited a normal distribution within each subgroup ($P < 0.001$). Notably, all three formulas displayed a centroid error significantly

Table 1 Baseline demographics of eyes included in the analysis

Parameter	No./average ± SD (range)
No. of patients	146
No. of eyes	146
No. of eyes with WTR astigmatism	70
No. of eyes with ATR astigmatism	69
No. of eyes with oblique astigmatism	7
Kflat	43.35 ± 1.53 D (38.5, 47.79)
Ksteep	45.32 ± 1.69 D (39.92, 49.74)
Mean K	44.32 ± 1.47 (39.21, 48.77)
Axial length	24.45 ± 1.75 mm (21.29, 30.21)
Anterior chamber depth	3.14 ± 0.50 mm (1.98, 4.16)
Lens thickness	4.50 ± 0.49 mm (3.33, 5.53)
White-to-white	11.72 ± 0.51 mm (9.9, 12.9)
Central corneal thickness	549.50 ± 37.67 μm (484, 663)

All results are expressed as the absolute average ± standard deviation (SD)

Range is given in brackets

deviating from 0 in both the WTR and ATR astigmatism subgroups. Specifically, centroid errors in the WTR astigmatism subgroup were found to be proximal to 0 when juxtaposed with those observed in the ATR astigmatism subgroup. Within the WTR astigmatism subgroup, the Barrett toric calculator incorporating measured PCA via the Pentacam demonstrated exemplary performance, boasting a notable 78.6% with a prediction error less than 0.50 D. In contrast, the ATR astigmatism subgroup showed optimal outcomes with the Barrett toric calculator integrating predicted PCA, achieving an impressive 82.6% with a prediction error less than 0.50 D.

The posterior astigmatism measurements from both instruments, along with the orientation of the steep axis, are shown in Supplementary Table 1. The IOLMaster 700 consistently measured flatter corneal curvatures than the Pentacam HR, both in the flat and steep meridians. This difference was statistically significant ($P < 0.001$). There was a statistically significant difference in the orientation of the steep axis between the two groups, and the percentage of steep axes that were vertically oriented was lower in the IOLMaster 700 (73.97%) than in the Pentacam HR (85.60%).

Table 3 and Fig. 2A, B summarize the MAE, MedAE, and the mean centroid value for the two subgroups (horizontally steep meridian PCA and vertically steep meridian PCA) according to the orientation of the posterior steep axis measured by the IOLMaster 700. In the horizontally steep meridian PCA subgroup (IOLMaster 700, $N = 23$), the Barrett formula with predicted PCA showed the best results, with 78.3% less than 0.5 D prediction error, which was a significantly higher percentage than the other two measured PCA subgroups ($P < 0.05$). Despite the lack of a statistically significant difference in MAE within the horizontally steep meridian PCA group (IOLMaster 700, $N = 23$), the Barrett formula with predicted PCA yielded a slightly lower value than the measured PCA subgroups. In the vertically steep meridian PCA subgroup (IOLMaster 700, $N = 123$), there were no statistically significant differences in the MAE or the proportion of PE of 0.5 D or less among the three groups.

Table 4 and Fig. 2C, D depict the MAE, MedAE, and the mean centroid value for the two subgroups according to the orientation of the posterior steep axis measured by the Pentacam. While there was no statistically significant distinction in MAE among the horizontally steep meridian PCA group (Pentacam, $N = 15$), the Barrett formula with predicted PCA demonstrated a lower value than the measured
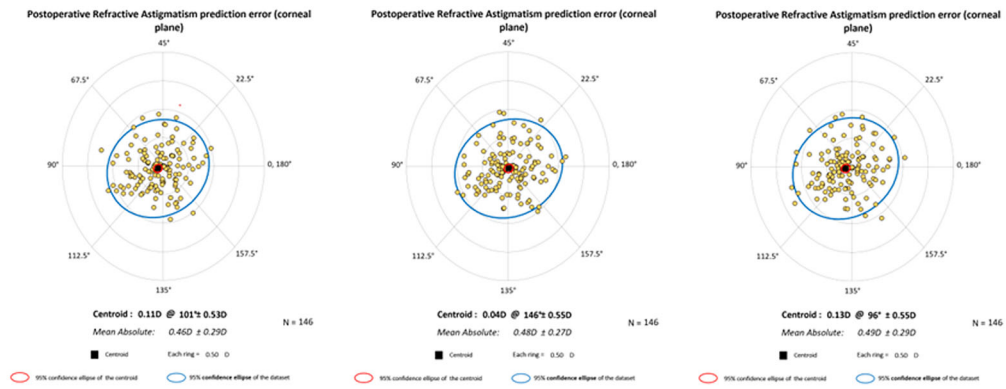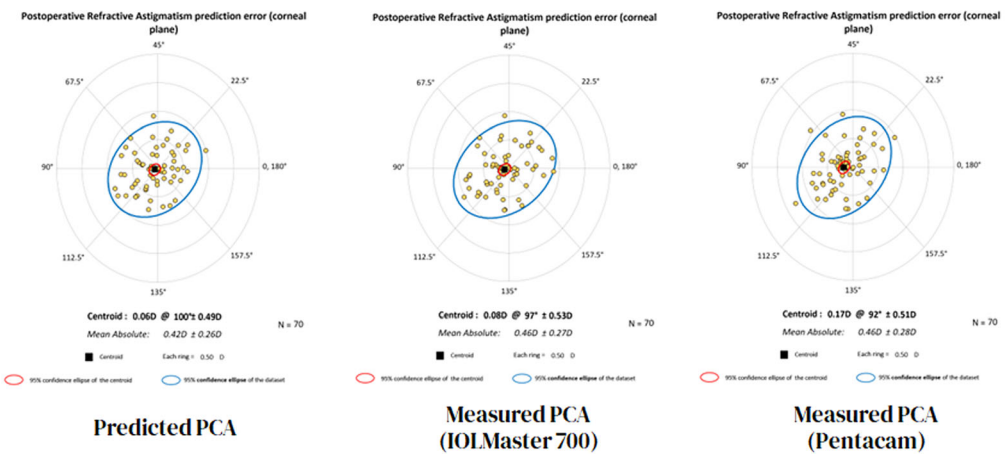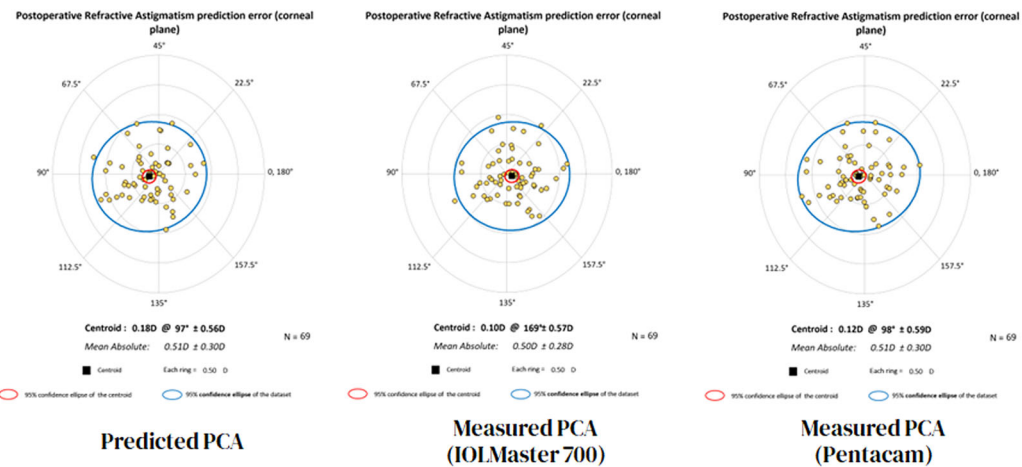
◄**Fig. 1** Double-angle plots of the prediction error for each of the formulas, illustrating centroid errors in predicted residual astigmatism **A** in total eyes, **B** in WTR eyes, and **C** in ATR eyes. Left: the Barrett formula with predicted posterior corneal astigmatism. Middle: the Barrett formula with measured posterior corneal astigmatism from the IOLMaster 700. Right: the Barrett formula with measured posterior corneal astigmatism from the Pentacam HR

PCA subgroups. Furthermore, despite the absence of a statistically significant difference, the likelihood of cases having a PE of less than 0.5 D appeared to be greater when utilizing the Barrett formula with predicted PCA in comparison to the other two formulas using measured PCA within the horizontally steep meridian PCA group (Pentacam, $N = 15$). In the vertically steep meridian PCA subgroup (Pentacam, $N = 131$), there were no statistically significant differences in the MAE or the proportion of PE of 0.5 D or less among the three groups.

DISCUSSION

This study demonstrated that the Barrett toric calculator with predicted PCA produced better clinical outcomes than the formula utilizing measured PCA (utilizing measurements from IOLMaster 700 and Pentacam). Specifically, when the anterior corneal astigmatism was ATR, the Barrett formula with predicted PCA outperformed the other two Barrett formulas with measured PCA. Even in cases where the steep axis of posterior astigmatism was aligned with the horizontal meridian, the Barrett toric calculator with predicted PCA exhibited better clinical outcomes than the other two Barrett formulas with measured PCA.

The debate over whether the Barrett toric calculator with predicted PCA surpasses the Barrett toric formula with measured PCA remains inconclusive [12, 13, 15–17, 24, 25]. Furthermore, the recently updated Barrett toric calculator offers options to input measurements from different devices such as IOLMaster,

Table 2 Overall clinical outcomes for each formula using the postoperative keratometry and the measured postoperative IOL axis ($N = 146$)

Formula	Mean absolute prediction error (MAE)	Median absolute prediction error (MedAE)	Mean centroid (diopters @ degrees) ± SD	Prediction error ≤ 0.50 diopters (%)
Total ($N = 146$)				
Barrett (predicted PCA)	0.35	0.32	0.11 D @101° ± 0.53 D	78.1*
Barrett (measured PCA, IOLm)	0.37	0.32	0.04 D @146° ± 0.55 D*	75.3
Barrett (measured PCA, Pentacam)	0.34	0.30	0.13 D @96° ± 0.55 D	77.4
WTR ($N = 70$)				
Barrett (predicted PCA)	0.38	0.35	0.06 D @100° ± 0.49 D	72.9
Barrett (measured PCA, IOLm)	0.39	0.34	0.08 D @97° ± 0.53 D	74.3
Barrett (measured PCA, Pentacam)	0.35	0.31	0.17 D @92° ± 0.51 D	78.6*
ATR ($N = 69$)				
Barrett (predicted PCA)	0.33	0.31	0.18 D @97° ± 0.56 D	82.6*
Barrett (measured PCA, IOLm)	0.35	0.30	0.10 D @169° ± 0.57 D	75.4
Barrett (measured PCA, Pentacam)	0.34	0.31	0.12 D @98° ± 0.59 D	75.4

PCA posterior corneal astigmatism, *IOLm* IOLMaster 700®
*Statistically significant

Table 3 Overall clinical outcomes for each formula using the postoperative keratometry and the measured postoperative IOL axis according to the orientation of the posterior steep axis measured by the IOLMaster 700®

Formula	Mean absolute prediction error (MAE)	Median absolute prediction error (MedAE)	Mean centroid (diopters @ degrees) ± SD	Prediction error ≤ 0.50 diopters (%)
Horizontally steep meridian PCA (IOLm) (N = 23)				
Barrett (Predicted PCA)	0.34	0.36	0.28 D @108° ± 0.56 D	78.3*
Barrett (Measured PCA, IOLm)	0.38	0.35	0.25 D @160° ± 0.53 D	65.2
Barrett (Measured PCA, Pentacam)	0.38	0.37	0.21 D @114° ± 0.63 D	65.2
Vertically steep meridian PCA (IOLm) (N = 123)				
Barrett (Predicted PCA)	0.35	0.32	0.08 D @96° ± 0.52 D	78.0
Barrett (Measured PCA, IOLm)	0.36	0.31	0.02 D @111° ± 0.54 D	77.2
Barrett (Measured PCA, Pentacam)	0.34	0.28	0.13 D @91° ± 0.54 D	79.7

Horizontally steep meridian PCA = steep axis orientation from 0° to 45° and from 135° to 180°. Vertically steep meridian PCA = steep axis orientation from 45° to 135°, *PCA* posterior corneal astigmatism, *IOLm* IOLMaster 700®

*Statistically significant

Pentacam, Galilei, and Optovue for the measured PCA [8]. This necessitates a discussion on which device's measurements might offer higher accuracy. Among the statistically significant findings of this study involving a total of 146 eyes, the Barrett toric formula with predicted PCA group exhibited a substantial 78.1% of cases with a PE of ≤ 0.5 D. This percentage notably exceeded the corresponding figures for the other two groups utilizing the Barrett toric formula with measured PCA (from IOLMaster 700 and Pentacam). This trend aligns with a similar observation reported in a study by Shammas et al., which involved 122 eyes [12]. However, a notable distinction between this study and Shammas et al.'s lies in the fact that while no statistically significant difference in cases with PE ≤ 0.5 D was noted among the three groups in Shammas et al.'s research, the current study demonstrated a significant difference. Furthermore, in three previous studies, no significant differences were discerned between the Barrett toric formula with predicted PCA and measured PCA [13, 16, 17]. However, it is important to note that all of these studies had relatively small sample sizes ranging
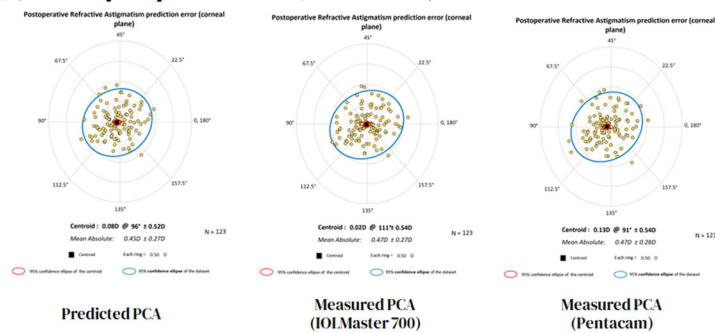
from 30 to 57 eyes, which could have contributed to these outcomes.

Conversely, there are studies indicating that the Barrett toric formula with measured PCA outperformed the Barrett toric formula with predicted PCA [15, 25]. Wang and Koch conducted a study involving 602 eyes undergoing non-toric IOL cataract surgery. Their study's strength lies in its relatively extensive sample size; however, it introduced complexities by incorporating three different types of IOLs,
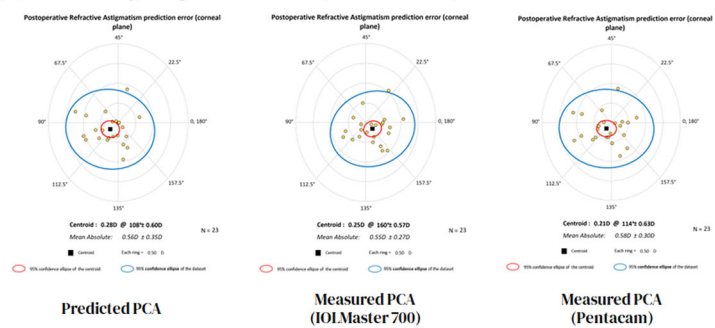
Fig. 2 Double-angle plots of the prediction error for each ▶ of the formulas, illustrating centroid errors in predicted residual astigmatism according to the orientation of the posterior steep axis **A** in vertically steep meridian PCA eyes measured by the IOLMaster 700, **B** in horizontally steep meridian PCA eyes measured by the IOLMaster 700, **C** in vertically steep meridian PCA eyes measured by the Pentacam HR, and **D** in horizontally steep meridian PCA eyes measured by the Pentacam HR. Left: the Barrett formula with predicted posterior corneal astigmatism. Middle: the Barrett formula with measured posterior corneal astigmatism from the IOLMaster 700. Right: the Barrett formula with measured posterior corneal astigmatism from the Pentacam HR

**(A) Vertically steep meridian PCA (IOLMaster 700)**

Predicted PCA | Measured PCA (IOLMaster 700) | Measured PCA (Pentacam)

(B) Horizontally steep meridian PCA (IOLMaster 700)

Predicted PCA | Measured PCA (IOLMaster 700) | Measured PCA (Pentacam)

(C) Vertically steep meridian PCA (Pentacam)

Predicted PCA | Measured PCA (IOLMaster 700) | Measured PCA (Pentacam)

(D) Horizontally steep meridian PCA (Pentacam)
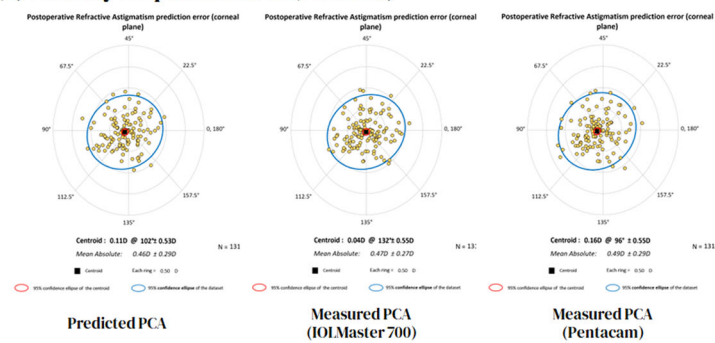
Predicted PCA | Measured PCA (IOLMaster 700) | Measured PCA (Pentacam)
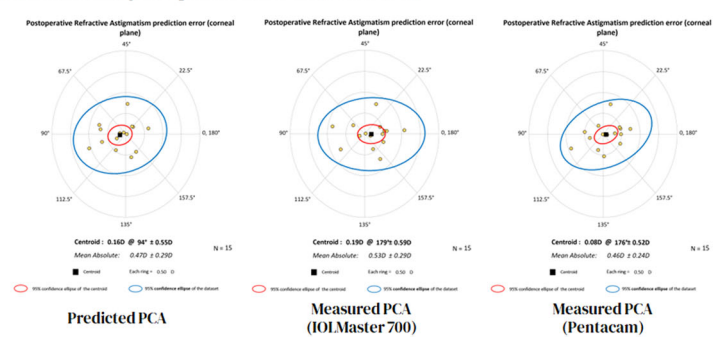
Table 4 Overall clinical outcomes for each formula using the postoperative keratometry and the measured postoperative IOL axis according to the orientation of the posterior steep axis measured by the Pentacam HR®

Formula	Mean absolute prediction error (MAE)	Median absolute prediction error (MedAE)	Mean centroid (diopters @ degrees) ± SD	Prediction error ≤ 0.50 diopters (%)
Horizontally steep meridian PCA (Pentacam) (N = 15)				
Barrett (predicted PCA)	0.36	0.31	0.16 D @94° ± 0.55 D	73.3
Barrett (measured PCA, IOLm)	0.39	0.27	0.19 D @179° ± 0.59 D	66.7
Barrett (measured PCA, Pentacam)	0.41	0.33	0.08 D @176° ± 0.52 D	66.7
Vertically steep meridian PCA (Pentacam) (N = 131)				
Barrett (predicted PCA)	0.35	0.32	0.11 D @102° ± 0.53 D	78.6
Barrett (measured PCA, IOLm)	0.36	0.34	0.04 D @132° ± 0.55 D	76.3
Barrett (measured PCA, Pentacam)	0.34	0.28	0.16 D @96° ± 0.55 D	78.6

Horizontally steep meridian PCA = steep axis orientation from 0° to 45° and from 135° to 180°. Vertically steep meridian PCA = steep axis orientation from 45° to 135°, *PCA* posterior corneal astigmatism, *IOLm* IOLMaster 700®

encompassing cases with bilateral eyes from the same patient. Moreover, the study adopted a multicenter approach involving multiple surgeons performing the surgeries, thereby potentially introducing variations in the SIA. Additionally, the study analyzed a range of anterior corneal astigmatism from 0 to 7.14 D, with a mean of 0.90 ± 0.70 D. Although the study does not provide a breakdown of corneal astigmatism values within specific ranges, it can be inferred that the sample consisted primarily of eyes with relatively low levels of corneal astigmatism. This aspect raises the possibility of limitations in accurately assessing the toric calculator's efficacy for eyes with astigmatism levels of 1.5 D or higher [15].

In the present study, only the Barrett toric formula with measured PCA from the IOL-Master 700 did not exhibit a significant difference from zero in the centroid. However, as highlighted by Tello et al., the centroid signifies the amalgamated vector of astigmatism, akin to an arithmetic average [31]. This similarity introduces a quandary when contrary values counterbalance each other, potentially masking the extent of scattered data. Hence, it becomes imperative not only to appraise the centroid in

isolation but also to juxtapose it with the mean absolute value of astigmatism magnitude. In accordance with these deliberations, the outcomes of our study similarly underscore that the mean absolute magnitude of astigmatism exhibited no significant difference among the three test groups.

When analyzing posterior corneal astigmatism as horizontally steep meridian PCA and vertically steep meridian PCA, based on measurements from IOLMaster 700 as the reference, the results showed that for the horizontally steep meridian PCA group, the predicted PCA formula demonstrated significantly higher accuracy than the other two measured PCA formulas. This finding aligns with results reported by Shammas et al., and similarly, it becomes evident that even in cases where the posterior astigmatism is horizontally steep, the predicted PCA formula outperforms the other two measured PCA formulas [12].

So, why is it that the Barrett toric calculator with measured PCA fails to yield better results compared to the Barrett toric formula with predicted PCA? One reason is the significant variation in PCA measurements between devices [12, 19, 20, 27, 32]. In this study, both Kflat

and Ksteep (posterior corneal curvature) showed statistically flatter results when measured using IOLMaster 700 compared to Pentacam. Additionally, the orientation of the steep axis also exhibited a significant difference between the two devices. This discrepancy is likely due to differences in how each device measures and the range of posterior curvature. The IOLMaster 700 calculates the posterior curvature by measuring at three diameters—1.5 mm, 2.5 mm, and 3.5 mm—then taking the arithmetic mean. Pentacam HR, on the other hand, calculates the posterior curvature primarily using a 3.0 mm diameter measurement [27]. Dr. Jack Kane, the creator of the Kane toric formula, considered one of the most accurate formulas in use, noted that the greatest obstacle in implementing measured PCA into the Kane formula was the significant differences in measurements across devices (J.X. Kane, personal communication, July 29, 2020). Similar to the findings of this study, previous research has also reported that posterior curvature measurements from different devices are not interchangeable, suggesting that this characteristic has likely influenced the accuracy of the Barrett toric formula with measured PCA [19, 27, 32]. Secondly, there is another factor in toric IOL calculation, apart from PCA, that could potentially influence the results [8, 26]. According to a study by Goggin et al. involving 103 eyes undergoing cataract surgery with toric IOLs, they employed vector calculation to determine the value of posterior corneal astigmatism by subtracting "anterior corneal astigmatism" from "calculated non-lenticular astigmatism." In principle, this resultant value should correspond to the measured posterior corneal astigmatism. The practical calculation was executed, thereby delineating the discrepancy existing between the values of calculated non-lenticular, non-anterior corneal astigmatism, and the actual measured posterior corneal astigmatism. This discerned distinction was coined "leftover astigmatism." The reported value was substantial, averaging 0.71 ± 0.43 D, significantly higher than the typical reported average of around 0.3 D for measured posterior corneal astigmatism, including the findings of this study. The authors suggested possible causes for leftover astigmatism such as IOL tilt or decentration, and speculated about other contributing factors. However, no concrete additional correlations were confirmed [26]. Considering that a 5° IOL tilt results in approximately 0.10 D of astigmatic effect, it appears that leftover astigmatism cannot be fully explained by IOL tilt alone [33].

This study has several notable strengths, which include the following: (1) To our knowledge, this study provides the most extensive sample size ($N = 146$) for comparing the accuracy of the Barrett toric formula with predicted PCA and the measured PCA using toric IOLs. (2) Only cases performed by a single surgeon using consistent surgical techniques and a uniform SIA were included.

However, there are limitations to this study: (1) When measuring posterior corneal astigmatism, there was a difference in the measurement ranges between the devices. IOLMaster 700 calculates the average of measurements at 1.5 mm, 2.5 mm, and 3.5 mm diameters, whereas Pentacam presents measurements from the central 3.0 mm diameter. (2) Two different models of IOLs were used. However, Abulafia et al. noted that using more than one IOL is acceptable when the data size is limited [28]. Furthermore, both types of IOLs are known for their excellent rotational stability [34, 35].

CONCLUSIONS

In conclusion, when comparing the Barrett toric formula with predicted PCA against the two measured PCA formulas (from the IOL-Master 700 or Pentacam), the former demonstrated a statistically significant higher proportion of cases with prediction error less than 0.5 D. This trend persisted even when the posterior corneal astigmatism was horizontally steep.

Declarations

Conflict of Interest. The authors have no potential conflicts of interest to declare. All authors have completed and submitted the ICMJE form for disclosure of potential conflicts of interest, and none were reported.

Ethical Approval. The study was approved by the Institutional Review Board of Seoul St. Mary's Hospital, the Catholic University of Korea (IRB No. KC23RISI0645), and the requirement for informed consent was waived due to the retrospective nature of the study. The study adhered to the principles of the Declaration of Helsinki.

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