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Comparison of Prediction Accuracy of Six Toric IOL Power Calculation Formulas, Including Four Available on the ESCRS Online Calculator

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Purpose: To evaluate and compare the prediction accuracy of toric IOL power calculation formulas available on the ESCRS online calculator, the Abulafia-Koch combined with Hill-RBF and Castrop formulae, and assess their effectiveness in predicting actual postoperative refractive outcomes.

Patients and Methods: The preoperative and 4–5 week postoperative records of 131 patients who underwent phacoemulsification and implantation of enVista toric (MX60T) IOL were reviewed retrospectively. The IOL power calculation formulas available on the ESCRS online calculator (Kane, EVO, Hoffer QST, and Barrett), Abulafia-Koch combined with Hill-RBF and Castrop formulae, were used to obtain predicted postoperative refraction for the implanted IOL. Spherical equivalent and residual astigmatism prediction errors (SEQ-PE and RA-PE) were compared statistically using Eyetemis. Results were expressed as trueness, accuracy, and precision.

Results: Mean corneal astigmatism decreased from 2.47 ± 0.95 D preoperatively to 0.34 ± 0.28 D postoperatively; 88.6% of eyes achieved cylinder ≤ 0.50 D. For SEQ-PE, trueness was comparable for Abulafia-Koch combined with Hill-RBF, Castrop, EVO, and Barrett, with trimmed means ranging between -0.02 to 0.02 D. Precision was similar for EVO, Kane, and Barrett (0.16 – 0.18 D) and lower for Abulafia-Koch combined with Hill-RBF and Hoffer QST formulas. Accuracy was comparable among Barrett, Castrop, EVO, and Kane, with Barrett, EVO, and Kane formulas achieving the highest proportion of eyes ($>93\%$) within ± 0.50 D of prediction error. For RA-PE, the trueness and precision of Abulafia-Koch combined with Hill-RBF, Hoffer QST, EVO, Kane, and Barrett formulas were high and comparable. Trueness ranged from 0.08 to 0.14 D and precision from 0.34 D to 0.37 D. All formulas except Castrop showed good astigmatic prediction accuracy, with more than two-thirds of eyes achieving absolute RA-PE within 0.50 D.

Conclusion: Among the evaluated formulas, the EVO, Barrett, and Kane formulas showed high refractive and astigmatic predictability, supporting their reliability for toric IOL power calculation.

Keywords: prediction accuracy, toric intraocular lens, enVista toric, IOL power calculation, residual astigmatism, eyetemis analysis tool

Introduction

Astigmatism correction during cataract surgery is critical to optimizing visual outcomes tailored to the patient's needs. During cataract surgery, toric intraocular lenses (IOLs) facilitate management of preexisting astigmatism, especially in cases of moderate or high astigmatism. In recent years, the availability of low-powered toric IOLs has enabled surgeons to precisely correct even small amounts of clinically significant astigmatism, expanding the range of preexisting astigmatism amenable to correction with toric IOLs. The efficacy of toric IOLs is influenced by many factors, such as biometric measurements, measurement devices, formula selection, alignment of toric IOLs, and postoperative toric IOL rotation.^{1,2} Inaccurate biometry measurements and incorrect IOL power calculations can lead to significant postoperative

residual error, negatively influencing the visual outcomes and patient satisfaction after surgery. There is evidence that 73.7% of eyes showed refractive prediction error within 0.50 D after cataract surgery,^{3,4} and that anterior chamber depth (ACD), axial length (AL), and corneal power (K) contribute to 42%, 36%, and 22% of the total measurement error, respectively.^{5,6}

The evolution of biometers has greatly influenced the precision of these calculations. Optical biometers utilizing optical coherence tomography (OCT) and swept-source technology have significantly improved the accuracy of pre-operative data collection. Some of them provide detailed corneal topography, including posterior corneal measurements, which are becoming more and more critical for the selection and alignment of toric IOLs.

IOL calculation formulas have undergone significant advancements over the decades, transitioning from basic empirical methods to sophisticated algorithms that account for individual anatomical considerations.^{7,8} The incorporation of additional variables and the use of increasingly sophisticated computational techniques have improved the prediction of the effective lens position (ELP). Both the anterior and posterior corneal surfaces are used by some formulae, potentially reducing the risk of over- or under-correcting astigmatism. Furthermore, recent formulas—such as Kane, Hoffer QST—use artificial intelligence to refine their results.

Many toric IOL calculators, including Barrett Toric, Abulafia-Koch combined with Hill-RBF's, Kane's, Castrop's, Hoffer QST, and EVO, have long been accessible via their respective web platforms or embedded in certain biometers. Recently, some authors granted access to their toric IOL formulae, which were included in the ESCRS toric IOL Calculator and have become the preferred calculation method for many phaco-refractive surgeons.⁹ The ESCRS IOL calculator automatically forwards its input (biometric data) to online IOL calculators and retrieves their results. This approach has significantly enhanced the workflow by permitting the comparison of refractive predictions of cutting-edge IOL power calculation formulae.

Despite significant advancements in modern toric IOL formulas, several underlying mathematical, anatomical, and biometric limitations prevent perfect astigmatism correction across all patient cohorts.¹⁰ Although several studies have already been published,^{11–14} there is still considerable debate about which formula provides the best prediction accuracy for the calculation of toric IOLs. Assessment and comparison of the performance of toric IOL calculators are vital, as they provide insights into expected outcomes and help surgeons choose an appropriate calculator.¹⁵ The purpose of the current study was to explore and compare the early postoperative prediction accuracy of six toric IOL power calculators, including the 4 IOL formulas available on the ESCRS online calculator (Barrett Toric, Kane, Hoffer QST, and EVO), Abulafia-Koch combined with Hill-RBF, and the Castrop formula, in predicting the actual postoperative refractive outcomes.

Methods

This retrospective case series included consecutive case records of patients who underwent cataract surgery with the implantation of aberration-free aspheric enVista toric IOL MX60T (Bausch + Lomb, Inc., Rochester, NY, USA) from February 2022 to November 2023 at ARCCA, Department of Ophthalmology, Hospital Nuestra Señora de Gracia, Zaragoza (Spain). The study adhered to the tenets of the Declaration of Helsinki and was approved by the Research Ethics Committee of Aragon (CEICA, C.I. PI23/629). CEICA waived the requirement for specific informed consent due to the retrospective nature of the study, which was based on data collected during routine clinical practice. All patients had previously provided standard informed consent for their surgical procedures, and no further intervention was undertaken for this study.

Medical records of patients receiving cataract surgery were reviewed, and those with uneventful surgery, implanted with enVista toric IOL into the capsular bag, and an available postoperative manifest refraction performed at 4–5 weeks after the cataract surgery were selected. Eyes with previous ocular or corneal surgery, irregular astigmatism, abnormal corneal topography, any intra or postoperative complication, or presenting with IOL tilt or decentration were excluded. Eyes that had postoperative visual acuity of 20/40 or worse (0.3 logMAR or worse) assessed on the Early Treatment Diabetic Retinopathy Study (ETDRS) visual acuity chart were also excluded.

If only one eye of the patient was eligible, it was considered the study eye. If both eyes were eligible, the first-operated eye was considered the study eye, and data from that eye were included in the analysis.

Anonymized data from preoperative examinations and 4–5 week postoperative examinations were collected, including age, sex, and postoperative refraction. Ocular biometry measurements were obtained with the Lenstar LS900 (Haag-Streit AG, AG, Koeniz, Switzerland). To minimize variability, surgeries were performed by a single senior experienced surgeon (FJCA) through a 2.4 mm clear corneal incision.

The predicted refraction for the implanted IOL power was calculated using the four toric IOL formulas available on the ESCRS online calculator (Kane, EVO, Hoffer QST, and Barrett). The Castrop formula was evaluated separately using the dedicated online calculator. The Abulafia-Koch combined with the Hill-RBF algorithm was evaluated separately using the implementation available on the Lenstar biometer. In this combined approach, the Hill-RBF algorithm determines the spherical-equivalent IOL power, whereas the Abulafia-Koch regression algorithm determines the toric cylinder power and the implantation axis. The default IOL constant of each formula, as summarized in Table 1, was used. Target refraction was set to plano in all cases and enVista toric IOL with power recommended by the Barrett toric IOL calculator was implanted in all patients.

The prediction errors (PEs) of each of the above formulas were compared. For each formula, the spherical equivalent prediction error (SEQ-PE) was computed as the difference of the actual and predicted postoperative SEQ refraction (actual postop SEQ-predicted SEQ).

Residual astigmatism prediction error (RA-PE) was defined as the vector difference between predicted residual astigmatism and postoperative refractive astigmatism. This was determined by converting the predicted and postoperative astigmatism vectors to Cartesian coordinates and then subtracting their respective x- and y-components, following Holladay's method.¹⁶ The paired x- and y-differences were then converted back to polar coordinates to obtain a clinically relevant, practical measure of the residual astigmatism prediction error.

Sample Size

Due to the retrospective observational nature of the present study, no formal sample size calculation was performed. The sample size of 131 eyes was obtained from all consecutive cases that met the predefined inclusion and exclusion criteria during the study period.

Statistical Analysis

Statistical tests were carried out using Eyetemis, an online analysis tool endorsed by ESCRS.¹⁷ The Eyetemis tool provides automated statistical and graphical analysis to determine refractive prediction errors. It evaluates three key aspects of formula performance according to ISO standards: Trueness, Precision and Accuracy. The online analysis tool employs the robust *t*-test and the robust Hotelling T^2 test for univariate and bivariate analyses. Robust *t*-tests are calibrated by standardizing the trimmed means, and bootstrap resampling enables them to handle non-normal, skewed, or heteroscedastic distributions.¹⁴

Table 1 Constants Used for IOL Power Calculations with Various IOL Formulas

IOL Formula	IOL Constant
Barrett	119.1
EVO	119.1
Hoffer QST (pACD)	5.61
Kane	119.1
Abulafia-Koch combined with Hill-RBF	119.1
Castrop	C: 0.36689 H: 0.156 R: -0.12516

For spherical equivalent refraction outcomes, trueness was assessed by comparing the trimmed mean of the SEQ-PE (per formula) to zero using the one-sample robust *t*-test and to each other using the robust two-sample *t*-test. To compare the spread of the data (precision) of two or more groups, the trimmed mean values of the distances between the SEQ-PEs and the trimmed mean of the SEQ-PE are compared for every two groups using the robust two-sample test. To compare the accuracy of two or more groups, the trimmed mean of absolute SEQ-PE is compared between every two groups using the robust two-sample *t*-test. In addition, the differences in the percentage of eyes within a certain range of SEQ-PE (within ± 0.25 D and ± 0.50 D) were evaluated using Cochran's Q test.

For astigmatic outcomes, trueness is evaluated by comparing the centroid RA-PEs individually against zero and against each other by applying Robust Hotelling's T^2 tests. Precision indicates the proximity between observations and is evaluated by comparing the trimmed-mean values of the distances between the RA-PEs and the centroid RA-PE for each method by applying the robust *t*-test. Accuracy is evaluated by comparing the trimmed-mean values of the RA-PE magnitudes by applying the robust *t*-test as well. The RA-PE magnitudes are also analyzed by comparing the percentage of eyes within 0.50 D. Double-angle plots were used to depict RA-PE centroid error and 95% confidence areas using convex polygons.

Results

Data from 131 eyes of 131 patients were analyzed. The demographics and baseline characteristics of participants are presented in Table 2.

Table 2 Demographic and Baseline Characteristics

Demographics	
Patients, n	131
Eyes, n	131
OD, n (%)	75 (57.25)
OS, n (%)	56 (42.75)
Age (years), Mean $\pm$ SD	75.9 $\pm$ 9.8
Sex, n (%)	
Female	57 (43.5)
Male	74 (56.5)
Baseline Characteristics, Mean $\pm$ SD (range)	
Axial length (mm)	23.73 $\pm$ 1.58 (21.18–30.70)
Anterior chamber depth (mm)	3.08 $\pm$ 0.40 (2.03–4.12)
Steep Keratometry (D)	45.35 $\pm$ 1.73 (41–49.36)
Flat Keratometry (D)	42.89 $\pm$ 1.59 (38.65–47.3)
Mean keratometry (D)	44.12 $\pm$ 1.59 (39.83–48.57)
Astigmatism (D)	2.47 $\pm$ 0.96 (1.09–5.72)
IOL spherical power (D)	20.21 $\pm$ 4.40 (7–30)
IOL toric IOL power (D)	3.24 $\pm$ 1.11 (1.25–5.75)
IOL implanted (cylinder power, D), n (%)	
MX60T cyl 1.25	4 (3.1)
MX60T cyl 2	21 (16.0)
MX60T cyl 2.75	51 (38.9)
MX60T cyl 3.5	22 (16.8)
MX60T cyl 4.25	14 (10.7)
MX60T cyl 5	11 (8.4)
MX60T cyl 5.75	8 (6.1)

Abbreviations: OD, Right eye; OS, Left eye; SD, Standard deviation; D, diopter.

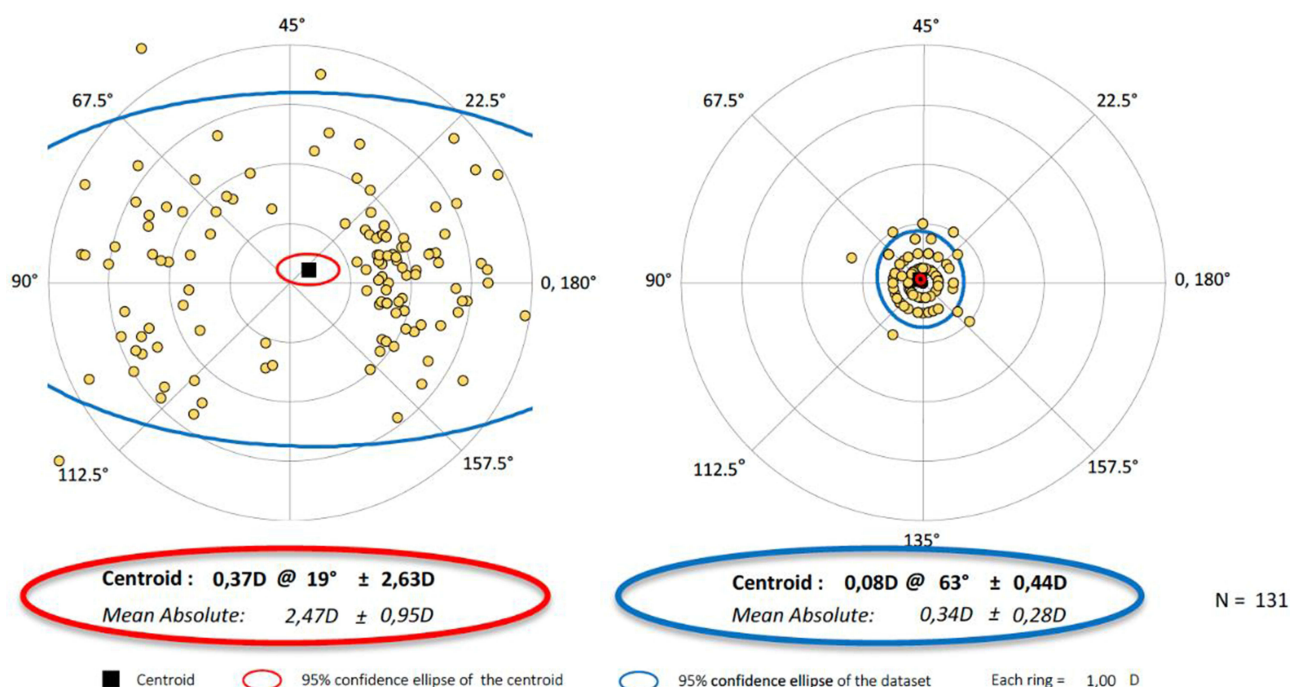


Figure 1 Double-angle vector plots of preoperative and postoperative astigmatism. The centroid of preoperative and postoperative astigmatism represents the vector average (the mean magnitude and axis) of all individual astigmatism vectors in the study population.

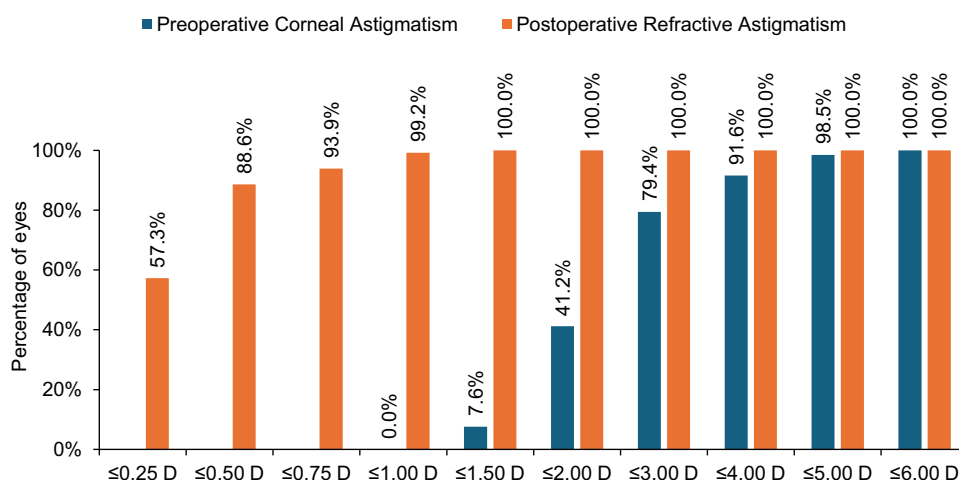


Figure 2 Preoperative and postoperative astigmatic accuracy.

Mean corneal astigmatism decreased from 2.47 ± 0.95 D preoperatively to a postoperative refractive astigmatism of 0.34 ± 0.28 D. The centroid of postop astigmatism was closer to 0.0 D and had a smaller standard deviation (SD) (represented by a smaller ellipse) (Figure 1). Postoperative refractive astigmatism below 0.50 D was achieved by 88.6% of eyes, and 93.9% were below 0.75 D (Figure 2).

Spherical Equivalent Prediction Error (SEQ-PE)

Trueness

The trimmed mean SEQ-PE of the various formulas is presented in Figure 3. The trimmed mean SEQ-PE of four study formulas (Abulafia-Koch combined with Hill-RBF, Barrett, Castrop, and EVO) ranged between -0.02 to 0.02 D and were

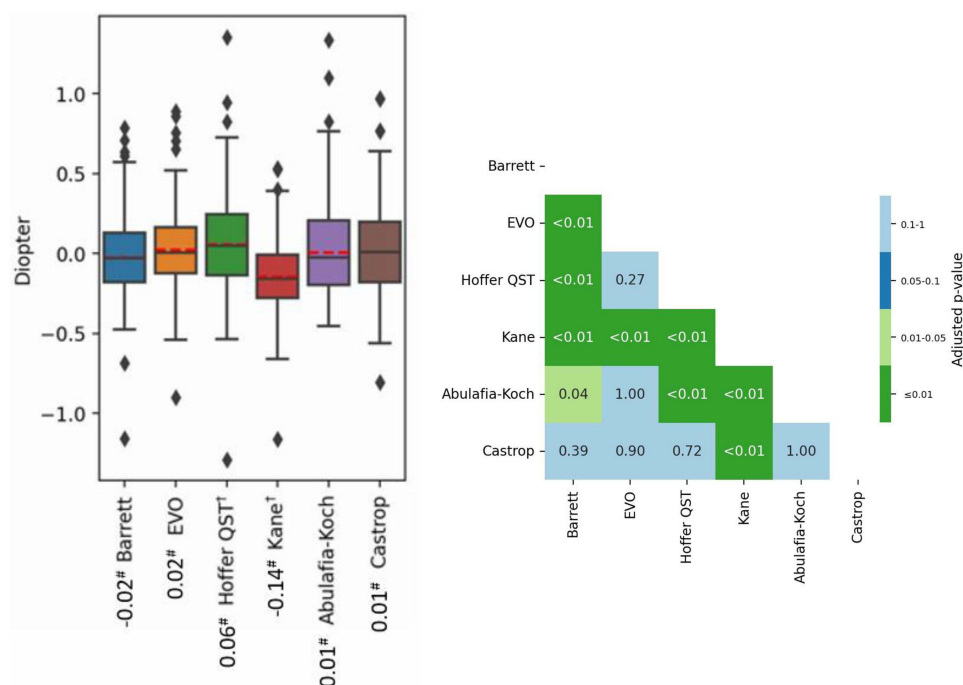


Figure 3 Box plot of spherical equivalent refractive prediction error (SEQ-PE) (trueness). The heatmap provides adjusted P values for paired comparisons. † indicates that the trimmed mean is significantly different from zero. # indicates trimmed mean.

close to zero (all $p > 0.05$). For the other two formulas, the trimmed mean SEQ-PE was 0.06 D (Hoffer QST) and -0.14 D (Kane), which were significantly different from zero ($p < 0.05$).

On the one hand, pairwise comparisons of the trimmed mean SEQ-PE of Abulafia-Koch with Hill-RBF (0.01 D), Castrop (0.01 D), and EVO (0.02 D) formulas showed no significant differences between each pair of IOL formulae tested. On the other hand, the Hoffer QST formula (with SEQ-PE of 0.06 D) was comparable to the EVO and Castrop formulas, but there were significant differences from the Barrett, Abulafia-Koch combined with Hill-RBF, and Kane formulae. Finally, the Kane formula, with trimmed mean SEQ-PE of -0.14 D, was significantly different from the other five study formulae.

Precision

Figure 4 presents the precision of the SEQ-PEs. The trimmed means of the Kane, EVO, and Barrett formulas were comparable (range 0.16 D to 0.18 D), with no significant differences. The Abulafia Koch combined with Hill-RBF and Hoffer QST formulas showed the highest trimmed mean (0.22 D), which was significantly higher than those of Barrett, EVO, and Kane formulae.

Accuracy

The early postoperative prediction accuracy of SEQ-PE is presented in Figure 5. The trimmed mean absolute SEQ-PE of four IOL formulas (EVO, Barrett, Castrop, and Kane) were comparable (0.16 D to 0.20 D), with no significant differences between the pairwise comparisons. Abulafia-Koch combined with Hill-RBF and Hoffer QST formulas showed the highest (0.22 D) trimmed mean absolute SEQ-PE, which was significantly higher than the trimmed mean absolute SEQ-PE of the EVO formula (0.16 D) (both p values < 0.01).

The proportion of eyes achieving absolute SEQ-PE within ± 0.25 D and ± 0.50 D is presented in Figure 6. While the EVO and Barrett formulas showed the highest proportion of patients achieving SEQ-PE within ± 0.25 D, the proportions were comparable ($p = 0.239$) between the different formulas. The proportion of eyes achieving absolute SEQ-PE within ± 0.50 D (range 89.3% to 93.9%) with different formulas was also comparable ($p = 1.000$).

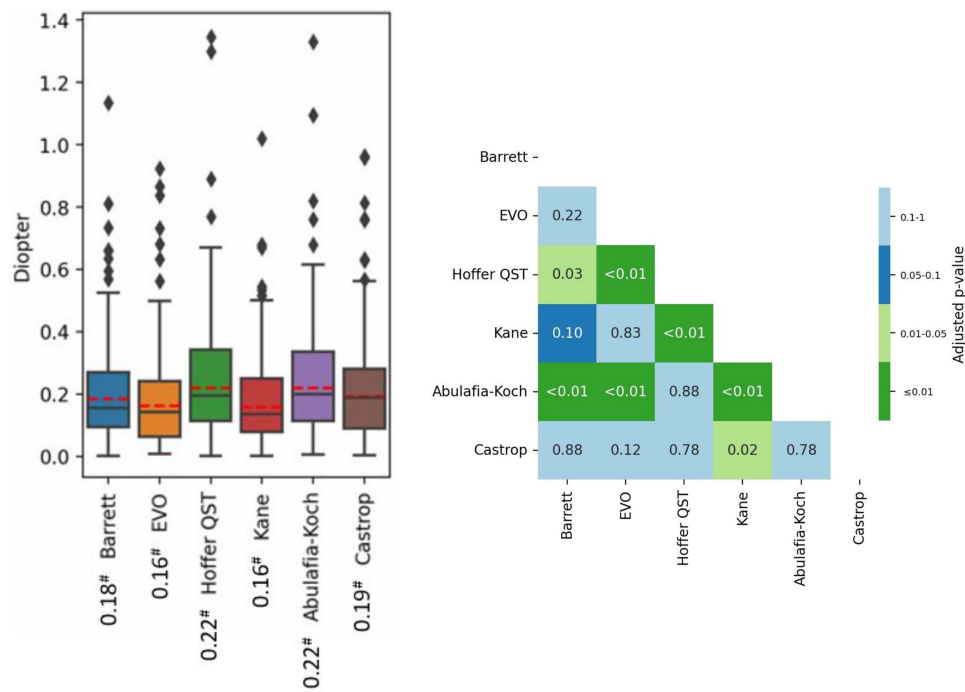


Figure 4 Box plot showing the precision of spherical equivalent refractive prediction error (SEQ-PE). The heatmap provides adjusted P values for paired comparisons. # indicates trimmed mean.

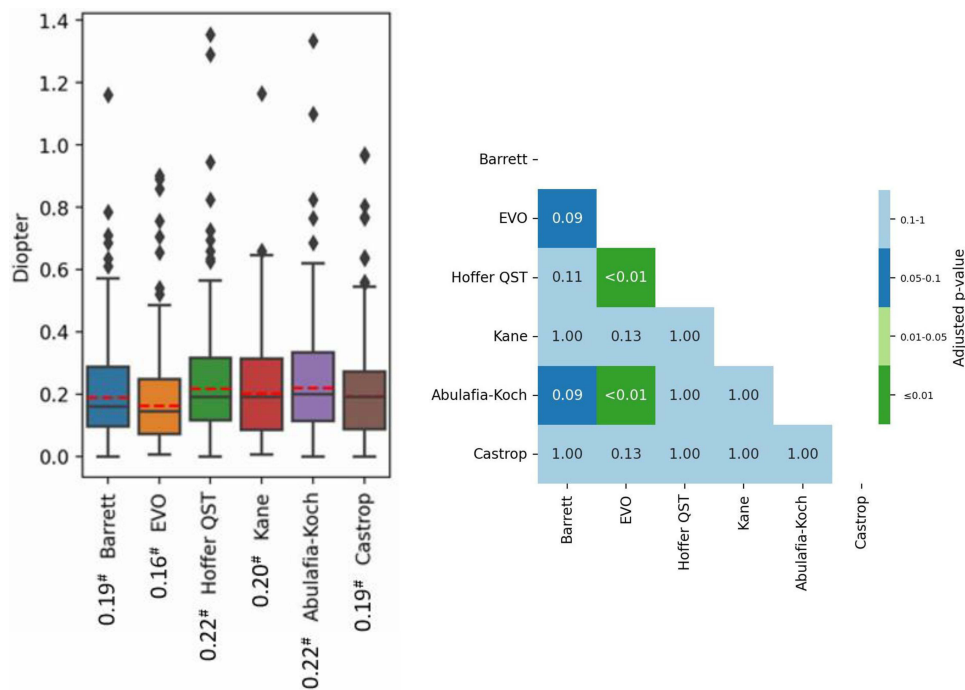


Figure 5 Box plot showing the accuracy of the spherical equivalent refractive prediction error (SEQ-PE). The heatmap provides adjusted P values for paired comparisons. # indicates trimmed mean.

Refractive Astigmatism Prediction Error (RA-PE)

Trueness

The trimmed centroid RA-PEs of the Abulafia-Koch combined with Hill-RBF (0.08 D), Hoffer QST (0.08 D), EVO (0.10 D), and Kane (0.10 D) formulas were numerically similar. The trimmed centroid RA-PE of the Barrett formula was 0.14

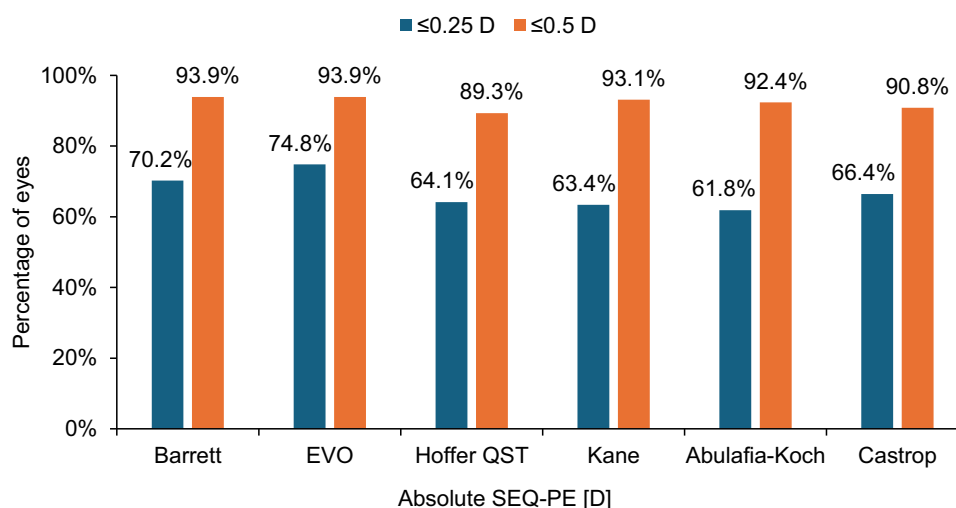


Figure 6 Proportion of eyes achieving absolute spherical equivalent prediction error within 0.25 and within 0.50 D with various IOL formulas.

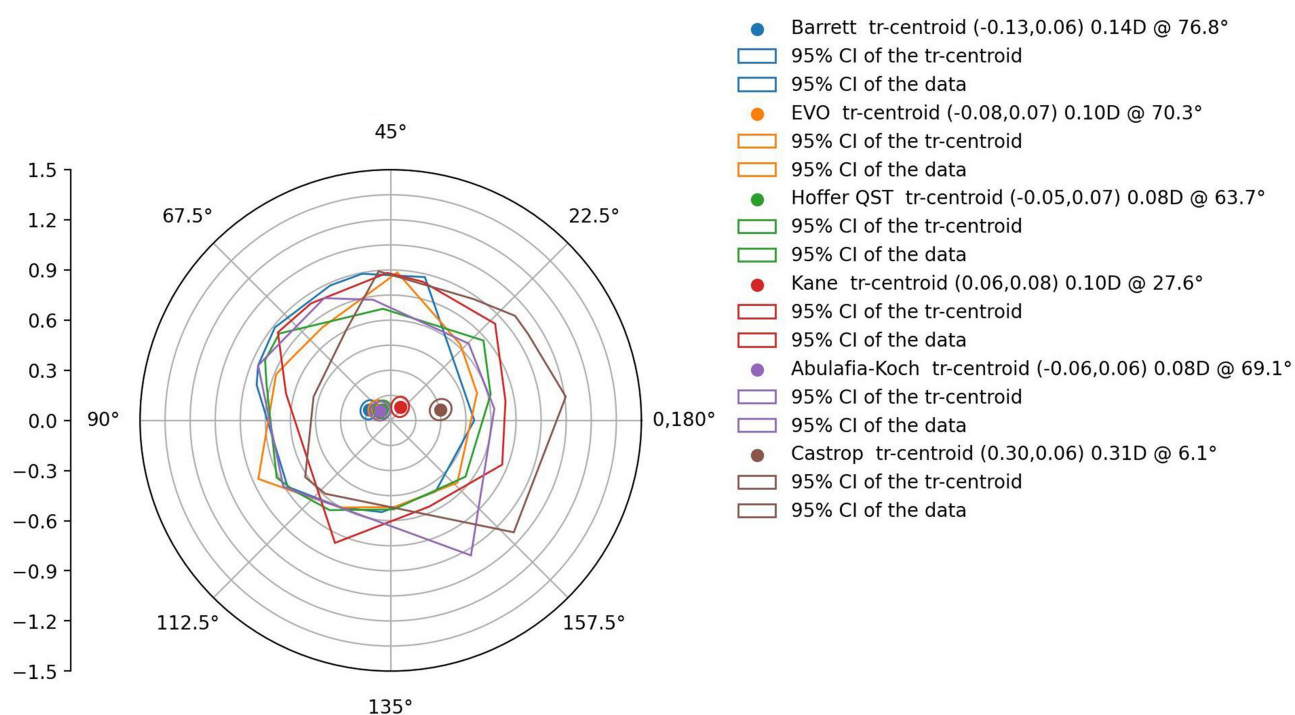


Figure 7 Double-angle plots of the refractive astigmatism prediction error (trueness) of various IOL formulas.

D, and Castrop's was the worst (with the highest trimmed centroid RA-PE of 0.31 D) (Figure 7). These were all significantly different from zero (all $p < 0.05$). For pairwise comparisons, the trimmed centroid RA-PE of the Abulafia-Koch combined with Hill-RBF formula was found to be comparable to the EVO formula and Hoffer QST formula ($p > 0.05$). For all other comparisons, the differences in trimmed centroid RA-PE between the two formulas were statistically significant.

Precision

The precision of RA-PE for the various IOL formulas is presented in Figure 8. The trimmed mean of four formulas available on the ESCRS online calculator (Barrett, EVO, Hoffer QST, and Kane) and Abulafia-Koch combined with Hill-RBF was comparable and ranged from 0.34 D to 0.37 D. Pairwise comparisons of the trimmed means of these formulas

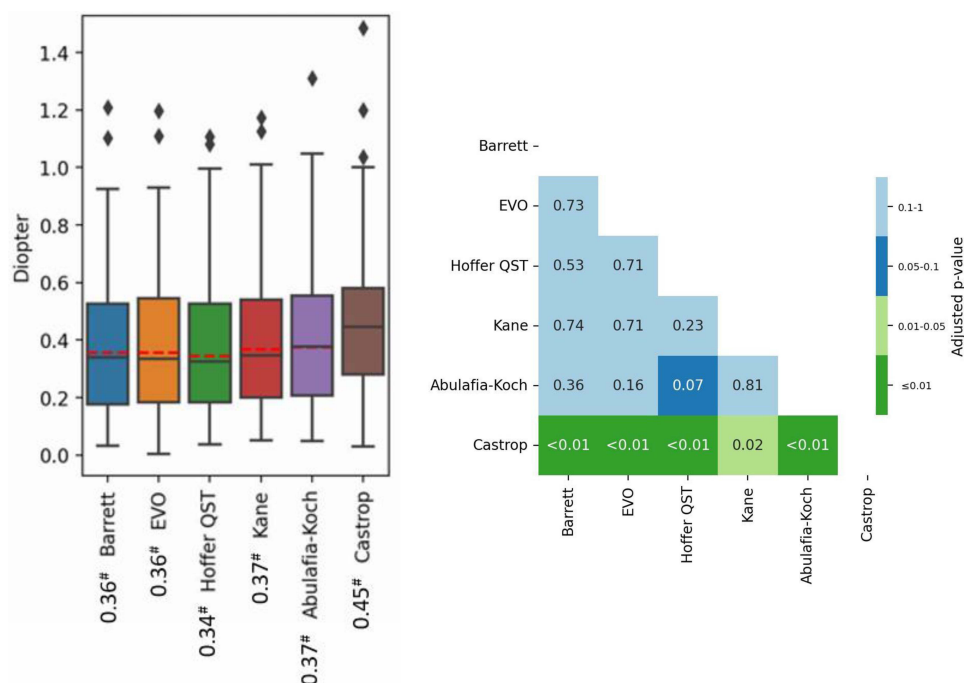


Figure 8 Box plot showing the precision of refractive astigmatism prediction error (RA-PE). The heatmap provides adjusted P values for paired comparisons. # indicates trimmed mean.

showed no significant difference either. Castrop formula showed the worst trimmed mean (0.45 D), significantly higher than the trimmed mean of the rest of the formulas.

Accuracy

The early postoperative prediction accuracy of RA-PE for the various IOL formulas is presented in Figure 9. Four IOL formulae (Barrett, EVO, Hoffer QST, and Kane) had comparable trimmed means that ranged from 0.35 D to 0.37 D, with no significant differences between pairs. Castrop's IOL formula showed a higher PE of 0.51 D, significantly worse than the other formulas (all $p = 0.005$).

The proportion of eyes achieving absolute RA-PE within 0.50 D is presented in Figure 10. The proportions achieved with Barrett, EVO, Hoffer QST, Kane, and Abulafia-Koch combined with Hill-RBF formulas (range 66% to 73%) were comparable ($p > 0.05$). The Castrop IOL formula achieved the lowest proportion of patients (49%), achieving absolute RA-PE within 0.50 D, significantly worse than Hoffer QST and Kane formulae ($p < 0.001$).

Discussion

Toric IOLs effectively correct preexisting corneal astigmatism during cataract surgery. However, postoperative residual error, even after uncomplicated surgery, is not uncommon and adversely affects postoperative toric IOL outcomes. In the present study, we evaluated how well the IOL formulas available on the ESCRS online calculator (Barrett, EVO, Kane, Hoffer's QST), Abulafia-Koch combined with the Hill-RBF, and Castrop formulas predict the optimal toric IOL power in eyes implanted with the enVista toric IOL. The online analysis tool, Eyetemis, designed to calculate the prediction errors of IOL power calculation formulas after cataract surgery, was used to evaluate trueness (mean), precision (SD), and accuracy (mean absolute error (MAE)), as well as the percentage of eyes within predefined absolute PE thresholds.¹⁸

The Eyetemis tool allows for a thorough assessment of predictive performance for each formula. It uses robust statistical methods to calculate trimmed means of Spherical Equivalent Prediction Error (SEQ-PE) and Refractive Astigmatism Prediction Error (RA-PE) after cataract surgery. It identifies and mathematically shaves off or down-weights severe statistical anomalies or extreme structural outliers. Some recent investigations have reported the root mean square absolute error (RMSAE), which also penalizes large prediction errors and outliers, providing a more

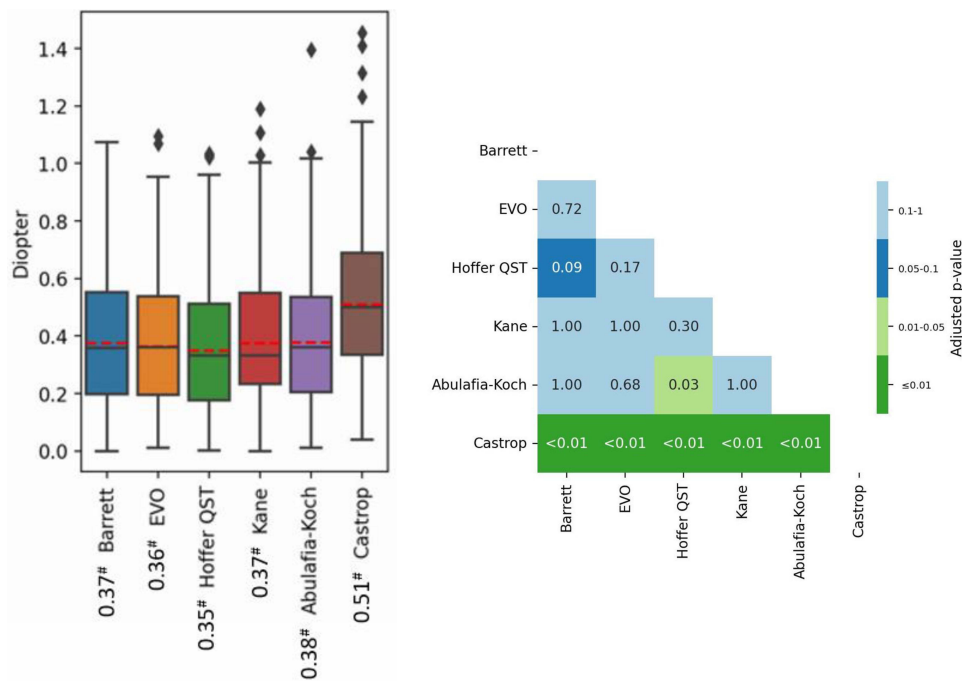


Figure 9 Box plot showing the accuracy of the refractive astigmatism prediction error (RA-PE). The heatmap provides adjusted P values for paired comparisons. # indicates trimmed mean.

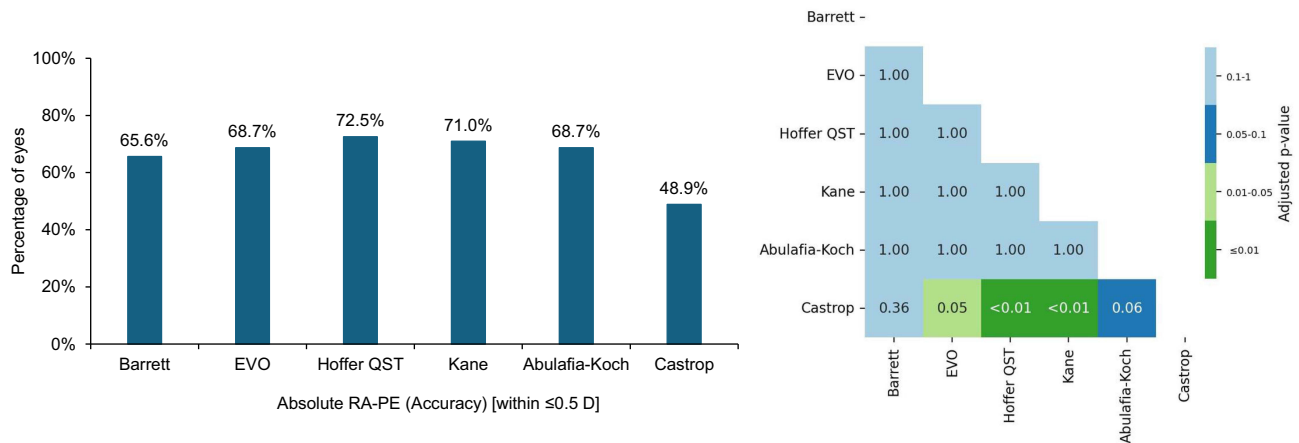


Figure 10 Proportion of eyes with absolute refractive astigmatism prediction error (RA-PE) within 0.50 D. The heatmap provides adjusted P values for paired comparisons.

realistic measure of prediction error.^{19–21} Like numerous other studies in recent years,^{13,22–26} the current study used Eyetemis for comparing multiple IOL formulas.

For SEQ-PE, trueness was found to be comparable for Abulafia-Koch combined with Hill-RBF, Castrop, EVO, and Barrett formulas, with the trimmed mean SEQ-PE ranging between -0.02 and 0.02 D for these formulas. The near-zero trimmed mean SEQ-PE values for these four formulas confirm that the default IOL constants were already well calibrated, making further optimization unnecessary. While the precision of EVO, Kane, and Barrett formulas was similar and ranged between 0.16 D and 0.18 D, the precision of Abulafia Koch combined with Hill-RBF and Hoffer QST formulas was found to be worse. Similar to precision, the accuracy of Barrett, Castrop, EVO, and Kane was comparable with Barrett, EVO, and Kane formulas, showing the highest percentage ($>93\%$) of eyes achieving absolute SEQ-PE within 0.50 D. All the other study formulas also showed high accuracy, with almost 90% or higher proportion of patients

achieving SEQ-PE within 0.50 D. For SEQ-PE within 0.25 D, the proportion of eyes achieving SEQ-PE within 0.25 D was ~8 to 13% higher with the EVO and ~4 to 7% higher with the Barrett formulas compared to other study formulas.

These proportions were higher than those reported previously with different formulas, such as 74 to 88% with Barrett,^{2,27–31} 88% with EVO,³¹ 85% with Hoffer QST,³¹ and 68 to 84% with the Kane formula.^{29,31}

The superior performance of EVO and Barrett may be explained by their ability to model individual variability of the posterior corneal surface and by their advanced ELP-prediction algorithms. These characteristics appear especially advantageous in clinical settings where posterior corneal astigmatism (PCA) is estimated rather than measured, a common scenario in many ophthalmic centers and across most standard biometry workflows.

For RA-PE, the trueness and precision of the four formulas available on the ESCRS online calculator (Hoffer QST, EVO, Kane, and Barrett) and (Abulafia Koch combined with Hill-RBF) were high and essentially comparable. Trueness in the present study ranged between 0.08 D to 0.14 D, and the precision of these formulas ranged between 0.34 D to 0.37 D. All the formulas except Castrop showed good prediction accuracy, with more than 2/3rd of eyes achieving absolute RA-PE within 0.50 D when IOL power calculations were performed using these formulas. Hoffer QST had the highest prediction accuracy, and the Castrop formula had the lowest. More than 30% higher proportion of eyes achieved RA-PE within 0.50 D when IOL power calculations were performed using Hoffer QST formula compared to Castrop formula (73% vs 49%). The prediction accuracy of the Kane (71% of eyes achieved absolute RA-PE within 0.50 D) and EVO formula (69% of eyes achieved absolute RA-PE within 0.50 D) in the present study was found to be better than that reported previously in the literature (59.2% to 60% for the Kane formula and 46% to 54.9% for the EVO formula).^{32–35} The prediction accuracy of Barrett (66% within 0.50 D) and Abulafia Koch combined with the Hill-RBF formula (69% within 0.50 D) was found to be comparable to the literature-reported range of 53.7% to 71% (with Barrett) and 53.8% to 81% (with Abulafia Koch combined with Hill-RBF), respectively.^{32–34,36}

The consistently poorer performance observed with the Castrop formula is likely related to its reliance on a fixed anterior–posterior corneal ratio and a constant corneal thickness, assumptions that do not reflect true inter-individual variability. These simplifications may become increasingly problematic in eyes with moderate or higher corneal toricity, where small deviations in PCA can significantly alter the final refractive outcome. Such limitations may explain the reduced prediction accuracy observed when compared with more dynamic, patient-specific models.³⁷ While the Castrop formula in the present study showed inferior astigmatic prediction accuracy, it is important to note that the formula's performance may vary depending on population characteristics, biometric devices, and IOL models. In the present study, the EVO, Barrett, and Kane formulas appear to provide more consistent astigmatic prediction performance for eyes implanted with the enVista toric IOL.

With toric IOL, there was a statistically significant reduction in astigmatism from preop to postop, and ~89% of eyes achieving residual refractive astigmatic error within 0.50 D. Many factors, including the accurate preoperative IOL power calculations, precise implantation of the toric IOL on the intended axis, and postoperative rotational stability of the IOL within the capsular bag affect the efficacy of toric IOLs in correcting preexisting astigmatism. The good astigmatic outcomes achieved in the present study show that IOL constants and IOL formulas used to calculate preoperative IOL power were accurate. Furthermore, the enVista IOL incorporates modified-C haptics that form a large contact angle with the capsular bag (110°), thereby increasing IOL stability within the capsule.³⁸

While the use of a single toric IOL model strengthens the internal validity of the study, it also means that the generalization of these results to other IOL designs—especially those with different haptic geometries or rotational stability profiles—should be done with caution. However, this design choice ensures that the comparative performance reflects intrinsic differences among formulas, rather than variability in lens mechanics.

One of the main strengths of this study is the high degree of standardization across all procedures. All surgeries were performed at the same center by a single high-volume surgeon, using the same surgical technique, the same toric intraocular lens model, and identical biometry and calculation methodologies. This methodological homogeneity substantially minimizes potential sources of clinical and surgical variability and, consequently, strengthens the internal validity and reliability of the comparisons between formulas.

However, our study has certain limitations. First, the sample size is not large enough to allow subgroup analyses by the degree or orientation (with-the-rule vs against-the-rule) of preoperative astigmatism. Future long-term research

involving larger samples that concurrently use both Eytamis and RMSAE may help assess how accurately these IOL formulas predict outcomes in patients with different levels and orientations of preexisting astigmatism. Second, the IOL power calculations in the present study were performed using standard IOL formulas, and no IOL optimization was performed. Additionally, the present study included a highly selected cohort because eyes with poor postoperative visual acuity, intraoperative or postoperative complications, IOL tilt or decentration, abnormal corneal topography, or incomplete follow-up were excluded. Although these criteria are commonly adopted in studies evaluating IOL prediction accuracy to minimize confounding factors unrelated to the calculation formulas, they may lead to more favorable refractive outcomes than those observed in routine clinical practice. Therefore, the present findings should be interpreted in the context of a retrospective, single-center, single-surgeon study with a selected patient cohort and limited follow-up. The retrospective study design also precluded estimation of the IOL's postoperative rotational stability, although a previously published study of this IOL reported good rotational stability.³⁸ Further prospective, multicenter studies are needed to confirm these results and assess their generalizability.

We did not include measurements of posterior corneal astigmatism in our calculations. The primary objective of this study was to compare formula performance using estimates of posterior corneal astigmatism rather than direct measurements. As such, our findings are highly relevant to clinical settings where posterior corneal data is not routinely available. Many ophthalmology centers lack access to advanced imaging devices capable of directly measuring posterior corneal astigmatism. The majority of published studies also suggest that the prediction accuracy of toric IOL formulas is comparable when using measured or predicted posterior corneal astigmatism values.^{36,39–44} However, some evidence is emerging that measured posterior corneal astigmatism can yield better prediction accuracy than predicted posterior corneal astigmatism values.^{45,46} Therefore, future research should incorporate measured posterior corneal astigmatism to improve the prediction accuracy of IOL power calculation formulas.

Conclusion

To summarize, the spherical equivalent performance of EVO, Barrett, Kane, and Castrop was better than that of the other formulas. However, in astigmatic performance, the Hoffer QST, EVO, Kane, Abulafia Koch combined with Hill-RBF, and Barrett formulas performed well in comparison to Castrop formula. Since for IOL power calculations, a single formula is generally used to calculate the spherical equivalent and toric IOL power, the results of the present study demonstrate that EVO, Barrett, and Kane formulas performed comparably for the spherical equivalent and astigmatic performance in eyes implanted with enVista toric IOL.

Overall, these findings reinforce the critical role of formula selection in optimizing refractive outcomes in toric IOL implantation. The results of the study may aid surgeons' decision-making to achieve superior refractive outcomes for their patients.

Abbreviations

IOLs, Intraocular lenses; ACD, anterior chamber depth; AL, axial length; OCT, Optical coherence tomography; ELP, Effective lens position; ETDRS, Early Treatment Diabetic Retinopathy Study; PE, Prediction error; SEQ-PE, Spherical equivalent prediction error; RA-PE, Residual astigmatism prediction error; SD, Standard deviation; MAE, Mean absolute error; RMSAE, Root mean square absolute error; PCA, posterior corneal astigmatism.

Data Sharing Statement

The data that support the findings of this study are available from the corresponding author (FJCA), upon reasonable request.

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Disclosure

FJCA and MP are consultants to Bausch + Lomb, Inc (B+L). FJCA also reports honoraria from Alcon, B+L; meeting/travel support from Medicontur, Alcon, B+L, J&J; data safety/advisory board participation for Alcon and B+L, outside the submitted work. MJC reports honoraria from GSLS, Boston Sight, outside the submitted work. RHV and SMM report no conflicts of interest in this work.

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