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ORIGINAL RESEARCH

Comparing the Accuracy of the Kane, Barrett Universal II, Hill-Radial Basis Function, Emmetropia Verifying Optical, and Ladas Super Formula Intraocular Lens Power Calculation Formulas

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Purpose: To assess the accuracy of five new-generation intraocular lens (IOL) power formulas: Barrett Universal II (BUII), Emmetropia Verifying Optical (EVO) Formula, Hill-Radial Basis Function (Hill-RBF), Kane Formula, and Ladas Super Formula (LSF).

Patients and Methods: This is a retrospective single-surgeon study from a refractive clinic and clinical research center in Draper, UT, USA. The primary outcome measures were mean absolute error (MAE) and median absolute error (MedAE). Secondary outcome measures were the standard deviation (SD) of each formula's refractive prediction errors (RPE) and the percentage of eyes within ±0.50D. Refractive predictions were compared to the postoperative spherical equivalent to determine the RPE for each formula. RPEs were optimized, and MAE, MedAE, SD of the AME, and percent of eyes achieving RPEs within the specified ranges of ±0.125 D, ±0.25 D, ±0.50 D, ±0.75 D, ±1.0 D were calculated. Subgroup analysis between different axial lengths was attempted but yielded insufficient statistical power to draw meaningful conclusions.

Results: A total of 103 eyes of 103 patients were included in our study after applying inclusion and exclusion criteria to 606 eyes from 2019 to 2021. Formulas ranked in ascending order by MAE were Kane, EVO, BUII, Hill-RBF, and LSF. The ascending rankings of MedAE were Kane, BUII, Hill-RBF, EVO, Ladas. Kane had a significantly lower MAE than Hill-RBF ($p<0.001$). EVO had the lowest SD of AMEs and the highest percentage of eyes within ±0.50 D. According to heteroscedastic testing, EVO also had a statistically significant lower SD than Hill-RBF.

Conclusion: Kane was the most accurate formula in terms of MAE and MedAE. EVO and BUII achieved marginally higher MAEs than Kane, suggesting these three formulas are comparable in performance. With the exception EVO and Hill-RBF, the heteroscedastic test yielded no significant differences in SD between the formulas. Although there were multiple statistically significant differences between the formulas in terms of MAE, MedAE, and SD, these differences may not be appreciable clinically. Lastly, there were no statistically significant differences in the percent of eyes with RPEs within ±0.50 D, suggesting similar clinical performance between formulas.

Keywords: cataract surgery, refractive surgery, IOL power formulas, new generation IOL formulas, refractive lens exchange, clear lens extraction, RLE, CLE

Introduction

Estimates indicate that cataracts are the leading cause of remediable blindness globally.[1] The current treatment for a cataract involves removing the clouded lens and replacing it with an artificial intraocular lens (IOL). Determining the proper IOL power to achieve an optimal refractive outcome is complex and challenging. A study by Hill showed that less

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than 1% of surgeons attained a ±0.50 D accuracy in 92% of their cases or better and that most surgeons perform within ±0.50 D accuracy in 78% of their cases.[2] Significant improvement is still needed to achieve better outcomes for patients.

Optical biometry measurements and IOL power calculation formulas are used by surgeons to assist in accurately predicting postoperative refractive outcomes. Since the first theoretical IOL power calculation formula was created by Fedorov et al in 1967, many newer generation formulas have been developed.[3] These formulas have been categorized based on their derivation, which includes historical/refraction-based, regression, vergence, ray tracing, and artificial intelligence (AI).[4] Previous studies have compared different IOL formulas to determine which formula best predicts actual postoperative refractive results. Despite many studies addressing this topic, there is still considerable debate about the best formula. A study by Melles et al in 2018 indicated that Barrett Universal II (BUII) was the most accurate IOL formula compared to Haigis, Hoffer Q, Holladay 1, Holladay 2, Olsen, and SRK/T.[5] Newer formulas exist, including Emmetropia Verifying Optical (EVO) Formula, Hill-Radial Basis Function (Hill-RBF), Kane Formula, and Ladas Super Formula (LSF).

Although previous studies have compared the formulas mentioned above, they utilized multiple lens types, multiple surgeons, or a non-monofocal lens.[6–8] Protocols outlined by Hoffer et al state that it is preferable to utilize only one IOL model in studies that compare IOL formulas, as multiple IOL models can introduce bias that requires additional calculation and optimization to reduce.[9] Therefore, this study aims to compare the accuracy of five different IOL formulas: BUII, EVO, Hill-RBF, Kane, and LSF, in predicting the refractive outcome for cataract surgery in patients receiving a single monofocal IOL model with a single surgeon and a standardized surgical method in a refractive research center.

Materials and Methods

This retrospective study of 103 eyes of 103 patients using deidentified data is from a single private practice refractive clinical research center and a single surgeon performing a standardized cataract removal procedure. Full approval from the Biomedical Research Alliance of the New York Institutional Review Board (#A20-12-547-823) and the Hoopes Vision Ethics Board was obtained, and all participants provided written informed consent prior to participating in the study. The study adhered to the tenets of the Declaration of Helsinki.

Included in the study were patients who had undergone uneventful cataract surgery with implantation of a TECNIS® ZCB00 monofocal lens (Johnson & Johnson Surgical Vision, Irvine, CA) between January 2019 and December 2021. Exclusion criteria were prior refractive surgery, posterior capsule opacification, corrected distance visual acuity worse than 20/40, and a postoperative manifest refraction measurement taken less than 1 week after surgery. Prior refractive surgery modifies the corneal structure and geometry, which can cause inaccurate anterior keratometry measurement and keratometric index variation, ultimately resulting in IOL power calculation underestimation.[10,11] In regards to post-operative manifest refraction assessment, Hoffer and Savini indicate that measurements are generally considered stable at least 1 week after surgery, and measurements taken 2 months after surgery are also considered stable.[12] As this is a retrospective study, the timing of the follow up appointment to assess postoperative manifest refraction was not uniform among patients and was defined as any time greater than 1 week and up to 2 months after their surgery date. If both patient eyes met the inclusion criteria, only one eye was randomly selected and included to avoid compounding of data.

All biometry data were entered in an Excel (Microsoft, Redmond, Washington, USA) spreadsheet and deidentified. Sex and age were recorded for each patient (Table 1). All preoperative biometric measurements were made using the Zeiss IOLMaster® 700 version 1.90.12.05 (Carl Zeiss Meditec AG, Jana, Germany) and Lenstar® LS 900 version i9.6.3.0 (Haag-Streit, Koeniz, Switzerland). Both devices were included for use in our study because they are commonly used in clinical practice and have been historically validated in their performance. Multiple studies have found that both the IOLMaster® 700 and Lenstar® LS 900 yield biometry measurements that are in high agreement with one another and have no statistically significant differences in predicting refractive outcomes when used in IOL power calculations.[13–15] This lack of statistically significant differences suggests that both devices are capable of performing equivocally in IOL power calculations. All subjects had two sets of biometry measurements taken, one with IOLMaster® and one with Lenstar®. The biometric parameters were then averaged to create a composite set of biometric measurements for each patient and used in each IOL formula calculation. Follow-up distance testing using a Snellen visual acuity chart was

Table 1 Patient Demographics and Clinical Data (n=103)

Parameter	**Value or Mean ± SD (Range)**		
Age (years)	69.83 ± 8.97		
Sex	61 female / 42 male		
Eye (left / right)	47 / 56		
Implanted IOL Power (D)	19.66 ± 4.15 (8.00–27.50)		
Post-Op SE (D)	−0.46 ± 0.55 (−2.63–0.50)		
Myope (Post-Op SE < 0)	78		
Hyperope (Post-Op SE > 0)	10		
Biometer Parameter	**IOLM / LS Average**	**IOLM**	**LS**
AL (mm)	24.21 ± 1.56 (21.56–29.86)	24.18 ± 1.60 (21.55–29.83)	24.23 ± 1.56 (21.57–29.90)
K1 (D)	43.56 ± 1.38 (39.88–46.53)	43.72 ± 1.07 (41.56–46.53)	43.54 ± 1.35 (39.88–46.53)
K2 (D)	44.35 ± 1.45 (41.22–48.16)	44.51 ± 1.31 (42.42–47.27)	44.32 ± 1.44 (41.22–48.16)
K Mean (D)	43.96 ± 1.40 (40.69–47.09)	44.12 ± 1.12 (42.12–46.61)	43.93 ± 1.38 (40.69–47.09)
CCT (µm)	545.54 ± 31.87 (463.00–632.00)	546.42 ± 32.36 (464.00–635.00)	544.66 ± 32.01 (462.00–631.00)
ACD (mm)	4.60 ± 0.44 (3.56–5.67)	4.66 ± 0.42 (3.74–5.39)	4.58 ± 0.45 (3.38–5.67)
LT (mm)	12.05 ± 0.41 (10.97–13.53)	12.05 ± 0.34 (10.90–12.65)	12.08 ± 0.45 (11.04–14.15)
WTW (mm)	24.21 ± 1.56 (21.56–29.86)	24.18 ± 1.60 (21.55–29.83)	24.23 ± 1.56 (21.57–29.90)

Note: Biometry parameters are separated by device.
Abbreviations: SD, standard deviation; IOLM; IOL Master; LS, Lenstar; AL, axial length; CCT, central corneal thickness; AD, aqueous depth; ACD, anterior chamber depth; LT, lens thickness; WTW, white-to-white corneal diameter; IOL, intraocular lens; SE, spherical equivalent.

performed at 20 feet and the final postoperative manifest refractions according to distance testing were obtained by ophthalmic assistants and optometrists in the office or by the referring optometrist or ophthalmologist.

Surgical Procedure

A manual 2.75 mm clear corneal incision was created at the 180 degrees meridian in the temporal area. A Surgical Induced Astigmatism of 0.1 was used. The viscoelastic of choice was Duovisc (Alcon). A 5.0–5.5 mm continuous curvilinear capsulorhexis was performed and phacoemulsification was completed in a horizontal chop or divide-and-conquer fashion using the Infiniti Vision System (Alcon Laboratories, Inc., Fort Worth, TX). Manual clear corneal incisions were performed. No capsulotomy complications occurred, and all wounds were confirmed to be self-sealing.

Patients took a topical steroid four times daily and tapered weekly over one month following surgery. A topical NSAID eye drop was used twice daily for six weeks. Third- or fourth-generation fluoroquinolone antibiotic eye drops were used four times daily for one week.

Formulas

The formulas utilized in this study were accessed from their respective websites with the following versions: Barrett Universal II V1.05 (https://calc.apacrs.org/barrett_universal2105/; Accessed 2 Jun 2022), Emmetropia Verifying Optical Formula v2.0 (https://www.evoiolcalculator.com/; Accessed 2 Jun 2022), Hill-RBF Version 3.0 (https://rbfcalculator.com/online/index.html; Accessed 2 Jun 2022), Kane (https://www.iolformula.com/; Accessed 2 Jun 2022), and Ladas Super Formula v1.0b (https://www.iolcalc.com/home; Accessed 2 Jun 2022).

Formula Parameters

The recommended A-constant provided by each formula's website for the TECNIS® ZCB00 monofocal lens was utilized during calculations. If a formula required a K-index, a value of 1.3375 was used.

For EVO, Hill-RBF, Kane, the recommended A-constant values of 119.3, 119.34, 119.36, and were used, respectively, along with the following variables: axial length (AL), K1, K2, and anterior chamber depth (ACD). Lens thickness (LT) and central corneal thickness (CCT) are optional variables that were also included. For BUII, the recommended A-constant of 119.39 and lens factor of 2.09 were used, along with the following variables: AL, K1, K2, and optical ACD. LT and white-to-white (WTW) are optional variables that were also included. For LSF, AL, K1, K2, and optical ACD were used. LSF currently does not have a published set of recommended A-constants for the ZCB00 lens. In the absence of alternate recommendations, we utilized the recommended User Group for Laser Interference Biometry (ULIB) SRK/T A-constant of 119.3 for calculations (http://ocusoft.de/ulib/c1.htm; Accessed 2 Jun 2022). We chose this A-constant to remain consistent with EVO, which utilizes the same ULIB SRK/T A-constant for the ZCB00 lens.

Methods of Comparison and Adjustments

Our methods of comparison were adapted from suggestions by Wang et al Hoffer and Savini, and Holladay et al which provide general guidelines for comparing IOL formulas.[12,16,17] Initial data analysis was performed in Microsoft Excel. For each formula, the refractive prediction error (RPE) was calculated as the difference between the measured post-operative manifest refraction and each formula's predicted postoperative manifest refraction for each patient. The latest manifest refraction within a 1-week to 2-month postoperative window was used in these calculations. A negative RPE indicates a myopic result achieved for the formula, and a positive RPE indicates a hyperopic result. The arithmetic mean error (AME) and associated standard deviation (SD) were calculated for each formula by averaging the RPE for all patients across each formula. Lastly, the minimum, maximum, and range of each formula's RPEs were calculated.

Lens constant optimization is critical to studies that compare IOL formulas. Optimizing lens constants involves adjusting each formula's AME as close as possible to zero to eliminate existing systematic errors prior to statistical analysis. These errors, if uncorrected, may otherwise lead to inaccurately myopic or hyperopic tendencies in individual formulas. Previous studies have implemented different methods of lens constant optimization for use in older and newer generation IOL formulas, which include use of Excel's Goal Seek function, writing scripts in computer programming languages, or manual arithmetic adjustments of datasets to adjust the AME to zero.[7,8,12,16,18,19] While these methods differ in their approach, they all serve to minimize bias when comparing multiple IOL formulas. It should also be noted that lens constant optimization can serve to eliminate bias in studies that utilize multiple IOL models.[11]

For our study, lens constant optimization was accomplished by adjusting the RPE for each eye up or down by an amount equal to the AME to bring all AMEs as close to zero as possible, as suggested by Wang et al[16] These optimized AMEs were used in all subsequent calculations. Alternate methods of lens constant optimization were not possible for this study, as all five formulas are proprietary and are not publicly available.[12] Such methods would require advanced computer programming software, to which many ophthalmologists do not have access.[19]

To assess formula accuracy across different ALs, the study population was subdivided into three groups: short eyes (≤ 22.00 mm), medium eyes (> 22.00 mm and < 25.00 mm), and long eyes (≥ 25.00 mm). While other studies utilize similar values for each category, we selected these cutoffs given that mean adult values for AL tend to range between 22.00 mm and 25.00 mm.[20] The following calculations and statistical analysis were performed on all eyes, short eyes, medium, eyes, and long eyes. The mean absolute error (MAE) represents the mean absolute deviation from zero achieved by each formula and was calculated as the average of all optimized absolute AME values for each formula. Similarly, the median absolute error (MedAE) was calculated using the median of each formula's optimized absolute AME values. Because MAE does not follow a Gaussian distribution, IQR was utilized instead of SD to measure dispersion. MedAE was included to represent a central location of the absolute errors and account for any potential outlier effects on MAE. As recently suggested by Holladay et al, we performed a heteroscedastic test to compare the SD of each formula's AME as an assessment for formula performance.[17] Lastly, the number and percentage of total eyes with prediction errors within ±0.125D, ±0.25 D, ±0.5D, ±0.75D, and ±1.0D were calculated.

The primary outcome measures of our study were MAE and MedAE. The secondary outcome measures were the SD of each formula's AME, as dictated by the heteroscedastic method, and the percentage of eyes within ±0.50D of the target refraction, a commonly used endpoint for measuring refractive error in current literature.[21] While ±0.50D is the standard, we also included analysis at refractive error intervals up to ±0.125D to further assess marginal differences between formulas. While MedAE prevents outlier effects on the MAE, outliers are important in IOL studies as they can represent undesired outcomes in cataract surgeries and account for postoperative refraction surprise and unpredictability.[22]

Statistical Analysis

Statistical analysis was performed using SPSS Statistics version 28.0.1.1 (14) (IBM Inc., Armonk, NY) and The R Project for Statistical Computing version 2022.02.3+492 (R Foundation for Statistical Computing, Vienna, Austria). These methods primarily followed the guidelines for analyzing and comparing IOL formula outcomes recommended by Wang et al and Holladay et al[16,17] Normality of the RPE data was determined using the Kolmogorov–Smirnov test. RPE deviation from the mean was calculated using a one-sample *T*-test for formulas with normal distributions and a one-sample Wilcoxon signed rank test for formulas with non-normal distributions. Differences in MAE between formulas were analyzed using the Friedman Test and significance values were adjusted using the Bonferroni correction for multiple tests. Differences in the SD of each formula's RPEs were compared using the heteroscedastic method and significance values were adjusted using the Holm correction. Lastly, Cochran's Q-tests were used to compare the differences in the percent of eyes with prediction errors within the previously listed ranges. A p-value of less than 0.05 was considered significant for all tests. No further statistical analysis was performed on MedAE. Post-hoc statistical analysis was performed using G*Power (Version 3.1.9.6, Faul, Erdfelder, Lang, and Buchner, 2020. Available at https://www.gpower.hhu.de; Accessed 30 Jun 2023) to ensure our study was sufficiently powered to detect a small effect size (Cohen's f=0.07).

Results

A total of 103 eyes of 103 patients were included in the study after applying our exclusion criteria to the 606 eyes that underwent cataract surgery by a single surgeon between 2019 and 2021. Table 1 summarizes the characteristics of the eyes included in the study, including separated biometry measurements obtained by the IOLMaster and Lenstar. The average AL of the eyes included in the study was 24.21 ± 1.56 mm. The average age of patients included in the study was 69.83 ± 8.97 years, and the majority of patients included were female. Lastly, the mean number of postoperative days before follow-up manifest refraction was 36 ± 11.61 days.

Figure 1 illustrates the distribution of refractive prediction errors for each formula included in the study prior to optimization. Table 2 lists the outcomes for the 5 IOL formulas for all eyes included in the analysis and the minimum/maximum RPE values and RPE range for each formula prior to optimization. Our primary study outcomes included optimized MAE ± IQR, MedAE and our secondary outcomes included SD of each formula's AME, and percentage of eyes within the RPE of ±0.5 D. The formulas ranked by MAE ± IQR are as follows: Kane (0.238 ± 0.288 D), EVO (0.266 ± 0.293 D), BUII (0.274 ± 0.328), Hill-RBF (0.296 ± 0.338), and LSF (0.306 ± 0.320 D). In terms of MedAE, the rankings are as follows: Kane (0.151 D), BUII (0.184 D), Hill-RBF (0.212 D), EVO (0.221 D), and LSF (0.222 D). In terms of the heteroscedastic test, the SD rankings are as follows: EVO (0.392 D), Kane (0.409 D), LSF (0.422 D), BUII (0.424 D), and Hill-RBF (0.428 D).

There was a statistically significant difference in the MAE among the 5 formulas ($\chi^2[4] = 28.596$, p<0.001) for all eyes. Comparing the formulas pairwise, Kane achieved a statistically significant lower MAE than both Hill-RBF (p=0.005) and LSF (p<0.001). BUII also achieved a statistically significant lower MAE than LSF (p=0.003). With regards to the heteroscedastic test, EVO achieved a statistically significant lower SD than Hill-RBF (p=0.014). Otherwise, there were no statistically significant differences in the SD of each formula's AME. Table 3 summarizes the adjusted P values for the heteroscedastic test between each formula. There was no statistical significance among the 5 formulas for prediction errors within ±0.125 D, ±0.25 D, ±0.5 D, ±0.75 D, and ±1.00 D for all eyes. Kane had the highest percentage of eyes within ±0.125 D at 31.07% and Hill-RBF had the lowest at 27.18%. Hill-RBF, EVO, and LSF had the

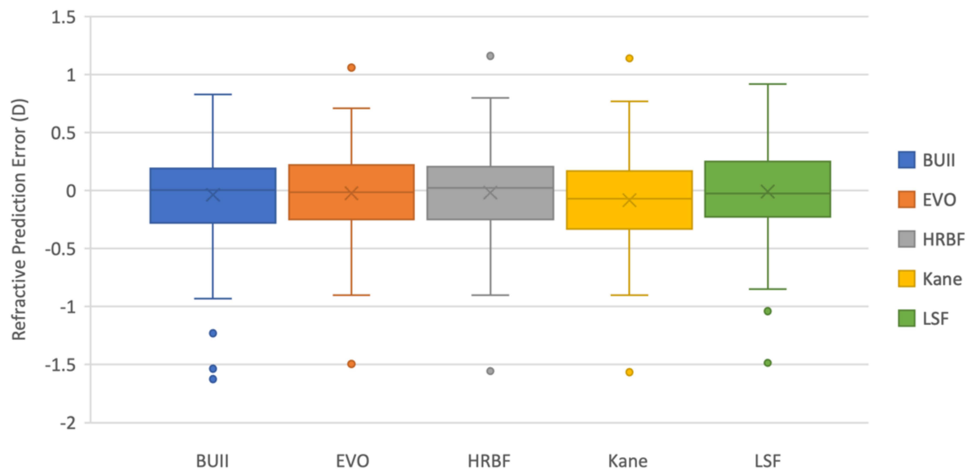

Figure 1 Box and whisker plot showing the initial distribution and outliers of each formula's refractive prediction errors prior to optimization (n=103).
Abbreviations: BUII, Barrett Universal II Formula; EVO, Emmetropia Verifying Optical Formula; HRBF, Hill-Radial Basis Function Formula; LSF, Ladas Super Formula.

highest percentage within ±0.25 D, all at 53.40% and Kane had the lowest at 51.46%. EVO had the highest percentage within ±0.5 D at 87.38% and Hill-RBF the lowest at 81.55%. EVO had the highest percentage within ±0.75 D at 96.12%, while BUII and LSF had the lowest at 93.20%. All eyes had the same percentage within ±1.00 D at 97.09% (Figure 2). Subgroup analysis between short eyes, medium eyes, and long eyes lacked the necessary sample size to yield results with sufficient statistical power. These results are summarized in Supplemental Table 1 for completeness.

Our post-hoc statistical analysis specifically evaluated the statistical power achieved in Friedman test when comparing the rank distribution of all five IOL formulas used in our study. We utilized our test statistic for Friedman test to calculate Kendall's W and estimate the effect size of our study as defined by Cohen's f. Our Cohen's f was calculated to be 0.07, which represents a small effect size when compared to the thresholds defined by Cohen. The correlation coefficients between each formula were calculated to range between 0.80 and 0.94 with a median correlation of 0.89. We

Table 2 Measures of Accuracy for the 5 Formulas in All Eyes (n=103)

Parameter	Kane	EVO	BUII	HRBF	LSF
Minimum RPE (D)	−1.565	−1.625	−1.555	−1.495	−1.485
Maximum RPE (D)	1.14	0.83	1.16	1.06	0.92
RPE Range (D)	2.705	2.455	2.715	2.555	2.405
Optimized AME ± SD (D)	−0.070 ± 0.352	−0.022 ± 0.374	−0.036 ± 0.398	−0.018 ± 0.416	−0.008 ± 0.415
MAE ± IQR (D)	0.238 ± 0.288	0.266 ± 0.293	0.274 ± 0.328	0.296 ± 0.338	0.306 ± 0.320
MedAE (D)	0.151	0.221	0.184	0.212	0.222
% ±0.125 D	31.07	30.1	29.13	27.18	30.1
% ±0.25 D	51.46	53.4	52.43	53.4	53.4
% ±0.50 D	82.52	87.38	82.52	81.55	83.5
% ±0.75 D	95.15	96.12	93.2	94.17	93.2
% ±1.00 D	97.09	97.09	97.09	97.09	97.09

Note: Formulas are organized by ascending MAE.
Abbreviations: RPE, refractive predictive error; AME, arithmetic mean error; SD, standard deviation; MAE, mean absolute error; IQR, interquartile range; MedAE, median absolute error; EVO, Emmetropia Verifying Optical Formula; BUII, Barrett Universal II Formula; HRBF, Hill-RBF Formula; LSF, Ladas Super Formula.

Table 3 Matrix of Paired Heteroscedastic Test Adjusted P values

Formula	SD	HC adj P	HC adj P	HC adj P	HC adj P	HC adj P
BUII	0.424	1				
EVO	0.392	0.952	1			
HRBF	0.428	0.952	0.014	1		
Kane	0.409	0.952	0.316	0.952	1	
LSF	0.422	0.952	0.198	0.952	0.952	1
		BUII	EVO	HRBF	Kane	LSF

Abbreviations: SD, standard deviation; HC, heteroscedastic; adj P, adjusted P value; BUII, Barrett Universal II Formula; EVO, Emmetropia Verifying Optical Formula; HRBF, Hill-Radial Basis Function Formula; LSF, Ladas Super Formula.

selected a conservative estimate of 0.85 for our final calculation. Lastly, given that Friedman test is nonparametric, we also reduced our sample size by 15% for our calculations, as suggested by Lehmann.[23] Our final post-hoc power for a sample size of 103, with conservative estimates in place, was calculated to be 0.88.

Discussion

This study compared the accuracy of five new-generation IOL formulas in predicting the refractive outcomes for cataract surgeries with monofocal IOL implantation. Our study is significant because it involves one surgeon using a standardized surgical procedure and a single monofocal IOL model in a refractive clinical research center.

Kane yielded the lowest overall MAE and MedAE and a statistically significant difference in MAE from Hill-RBF and LSF. Similarly, Pereira et al found that Kane performed most accurately compared with BUII, EVO, Hill-RBF 2.0, LSF, and six other formulas.[8] Additionally, the first study comparing Kane with other new-generation formulas found that Kane was most accurate compared with BUII, Hill-RBF 2.0, and six other formulas.[18] Darcy et al studied a large sample size of 10,930 eyes and found that Kane was the most accurate overall formula compared to BUII, Hill-RBF 2.0, and six other formulas.[24] Lastly, Maroun et al compared Kane, BUII, Hill-RBF 2.0, EVO, LSF, and four other IOL

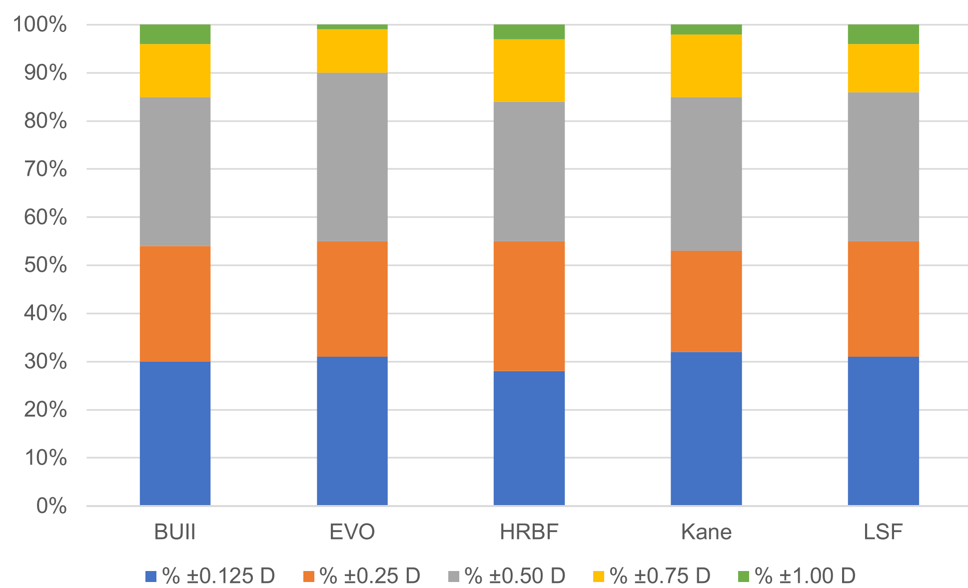

Figure 2 Percentage of eyes within prediction errors of ±0.125 D, ±0.25 D, ±0.5 D, ±0.75 D, ± 1.00 D (n=103).
Abbreviations: BUII, Barrett Universal II Formula; EVO, Emmetropia Verifying Optical Formula; HRBF, Hill-Radial Basis Function Formula; LSF, Ladas Super Formula.

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formulas using partial coherence interferometry measurements and found that Kane achieved the lowest MAE of all formulas and the highest percentage of eyes within ±0.50 D.[25]

In contrast, Rocha-de-Lossada et al found that EVO achieved the lowest MAE when compared to the same formulas as our study.[7] Additionally, Carmona-Gonzalez et al found that BUII achieved the lowest MAE compared to EVO, Hill-RBF, Kane, LSF, and six other formulas.[6] However, these studies included trifocal and toric lenses, which may explain these discrepancies with the results of this present study. Khatib et al compared BUII, EVO, and Hill-RBF and found that BUII achieved the lowest MAE of the three formulas, followed by EVO and Hill-RBF.[26] This study also included two monofocal IOL lenses instead of one, which could explain the difference in results. Lastly, Nemeth et al compared BUII with AI-based IOL formulas Hill-RBF 2.0, Kane, and PEARL-DGS, and found that Hill-RBF 2.0 had the lowest overall MAE and MedAE. Additionally, BUII performed similarly to Kane and PEARL-DGS.[27] Lastly, although Kane achieved the lowest MAE and MedAE, EVO had the lowest SD of the AME and the highest percentage of eyes within ±0.50 D out of all formulas.

The study was limited by several factors. Optimizing the lens constant for each formula to make the AME for all formulas equal to zero was not possible because the five formulas are not publicly available for individualized lens constant optimization methods.[19] In the absence of other options for lens constant optimization, we adjusted the RPE up or down for each eye to approximate an AME of zero using guidelines suggested by Wang et al[16] As a result, our optimized AME values were not exactly equal to zero, which may have adversely affected the accuracy of our MAE calculations. We utilized the recommended ZCB00 A-constants for each formula listed on each formula's respective website for our initial calculations. We also used the ULIB-recommended ZCB00 A-constant for LSF, as it currently does not have a recommended A-constant published for specific lens types, which may have affected its performance against the other formulas. Alternatively, some authors have suggested exclusively reporting the raw outcomes of IOL power calculations to reflect outcomes more generalizable to community ophthalmologists who do not have access to other optimization methods.[8,19] Lastly, De Bernardo et al recently derived a correction factor for preoperative AL measurements that could be used to eliminate systematic bias from IOL power calculation datasets without having to modify lens constants.[28] This may serve as another viable option for lens constant optimization when other methods may be unavailable. Future studies may benefit from utilizing SD as a primary outcome, by means of the heteroscedastic test, because of its ability to accurately assess formula performance given the heavy-tailed distributions of IOL formula RPE calculations.[17]

Additionally, although Hoffer and Savini state that postoperative manifest refraction can be stable at 1 week, they do recommend waiting at least 2 weeks to obtain these measurements to ensure the most stable measurement. In our study, five of our 103 included eyes had follow-up refraction data obtained less than 2 weeks postoperatively, which may have affected the reliability of some of our calculations.[12] Hill-RBF has also been optimized for use with Lenstar® measurements. Our study utilized averaged biometry data between Lenstar® and IOLMaster® devices, which may have adversely affected Hill-RBF results. Although studies have shown both devices to yield measurements in high agreement with one another when used in IOL power calculations, averaging biometric measurements from two separate instruments may have adversely affected the accuracy of the measurements collected.[13–15] The exclusion of the PEARL-DGS formula may have also limited the breadth of our analysis of new-generation IOL formulas. Postoperative manifest refractions were also measured by multiple ophthalmic technicians, which may have introduced a source of interobserver bias to our results. Lastly, our subgroup analysis lacked a sufficient sample size to be able to report meaningful conclusions from our data.

The emergence of new-generation IOL formulas has allowed for more accurate IOL power calculation and has significantly improved refractive surgery outcomes and patient satisfaction. However, the increasing number of available IOL formulas can be overwhelming, especially for newer clinicians seeking to identify a formula that will lead to the best possible patient outcomes. Although there were multiple statistically significant differences between the formulas in our study in terms of MAE, MedAE, and SD, these differences may not be appreciable clinically. Additionally, given that there were no statistically significant differences in terms of percentage of eyes with an RPE within ±0.50 D across all formulas, which ranged from 81.5% to 87.4%, the differences in clinical performance between the five formulas can be said to be marginal at the clinical level. Thus, clinicians seeking to identify the best formula for attaining successful outcomes in monofocal IOL cataract surgery may be validated in selecting any of the five formulas included in this study.

Conclusion

Kane was the best-performing formula in terms of MAE and MedAE, with a statistically significant difference from Hill-RBF and LSF. EVO performed best in terms of SD of the AME and the percentage of eyes achieving refractive prediction errors within ±0.50 D. Our results suggest that Kane is the most accurate of the five IOL formulas regarding MAE, especially compared to Hill-RBF and LSF. BUII and EVO achieved only marginally higher MAEs than Kane, suggesting these three formulas are comparable in performance. It should be noted that these differences in performance may not be apparent clinically, given the ±0.50 D cutoff for successful cataract surgeries and that all 5 formulas had MAEs and MedAEs less than 0.50 D. Additionally, with the exception of EVO and Hill-RBF, the heteroscedastic test revealed no statistically significant differences in SD between the other formulas, which also suggests most of the five formulas perform at a similar level clinically. Thus, ophthalmologists seeking to utilize the most accurate new-generation IOL formula for cataract surgery with monofocal IOL insertion may consider any of the five formulas for clinical practice and constantly analyze their outcomes.

Disclosure

The authors report no conflicts of interest in this work.

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