• Clinical Research •

Accuracy of eight intraocular lens power calculation formulas for segmented multifocal intraocular lens

Jing Zhao, Liang–Ping Liu, Huan–Huan Cheng, Jian–Bing Li, Xiao–Tong Han, Yu Liu, Ming–Xing Wu

State Key Laboratory of Ophthalmology, Zhongshan Ophthalmic Center, Sun Yat-sen University, Guangzhou 510060, Guangdong Province, China

Co-first authors: Jing Zhao and Liang-Ping Liu

Correspondence to: Ming-Xing Wu. No.54 South Xianlie Road, Guangzhou 510060, Guangdong Province, China. wumingx@mail.sysu.edu.cn

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Abstract

● **AIM:** To evaluate the accuracy of eight different intraocular lens (IOL) power calculation formulas for a segmented multifocal IOL.

● **METHODS:** A total of 53 eyes of 41 adult cataract patients who underwent phacoemulsification and implantation with the SBL-3 segmented multifocal IOL between January 1, 2017 and January 31, 2019 were included in this retrospective study. Preoperative biometry measurements were obtained using an IOL Master. Manifest refraction was performed at least 4wk postoperatively. Accuracy of the eight formulas [Barrett Universal II, Emmetropia Verifying Optical (EVO), Haigis, Hill-RBF 2.0, Hoffer Q, Holladay 1, Kane, and SRK/T] was analyzed.

● **RESULTS:** Using current lens constants, all formulas exhibited errors of slight myopic shift in refractive prediction. The Barrett Universal II formula had a significantly lower median absolute error (MedAE) than did Holladay 1 (P=0.02), Kane (P=0.001) and Hill-RBF 2.0 (P<0.001) formulas. The Haigis formula had a lower MedAE value than did the Hill-RBF 2.0 formula (P=0.005). Differences in MedAE values among SRK/T, EVO and Hoffer Q formulas were not significant. After optimizing lens constants, the MedAE values of all formulas were reduced; significant changes were noted for EVO (P=0.022), Haigis (P=0.048), Hill-RBF 2.0 (P=0.014), Holladay 1 (P=0.045) and Kane (P=0.022) formulas. All formulas performed equally well after optimization of lens constants (P=0.203).

● **CONCLUSION:** All eight formulas tend to result in a myopic shift when using current lens constants. Optimized lens constants improve the accuracy of these formulas among adult Chinese patients.

● **KEYWORDS:** accuracy; intraocular lens formulas; lens constants; segmented multifocal intraocular lens

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INTRODUCTION

Cataract surgery is among the most commonly performed ocular surgeries in the world and in China there is a high prevalence of cataracts among senior citizens[1]. The rate of cataract surgery is increasing each year[2]. Surgery aims not only to restore optical media transparency but also to improve refractive status, as patients seek better postoperative vision without the need for spectacles. To achieve this goal, much effort has been made to increase the accuracy of biometric measurement, formulaic calculation and intraocular lens (IOL) design[3-4]. One of the main complaints regarding traditional monofocal lens implantation is presbyopia. Multifocal IOL use has been met with great success in clinical practice, as it allows for clear vision at different focal distances and provides better near vision than does pseudophakic monovision[5].

Traditionally, multifocal IOL design has incorporated concentric rings that form different foci and has not been as effective as segmented multifocal IOL (SMIOL) function pertaining to improvement in contrast sensitivity and reduction of dysphotopsias[6]. The SBL-3 (Lenstec, Inc., USA), a novel SMIOL, possesses a rotationally asymmetric design. The combination of superior distance vision and inferior surface-embedded near vision sections in this lens provides a good range of distance, optimize near vision and minimizes light loss[7-8]. This type of SMIOL is produced at 0.25 diopter (D) intervals, and has been demonstrated to have better refractive outcomes as compared to lenses with 0.50 D intervals[9]. The SBL-3 lens also allows better near vision and is associated with fewer nocturnal visual optical disturbances as compared to the similarly designed LENTIS™ MPlus, making it a particularly good choice for improving near vision[7,10]. Selecting the most appropriate IOL power is critical in optimizing postoperative vision. Precise IOL power calculation, likewise, is crucial for good postoperative refractive outcomes. The accuracy of IOL power calculation was greatly improved with advances in biometry measurement using partial coherence interferometry (PCI) and the introduction of new IOL power calculation formulas[11-12]. Third- and fourth-generation representative formulas, including SRK/T, Holladay 1, Hoffer Q, Haigis and Barrett Universal II formulas, are widely used in clinical practice. A recent study by Melles *et al*[13] reported that new formulas, including the Hill-RBF 2.0, Emmetropia Verifying Optical (EVO) and Kane formulas, also had good accuracy in predicting postoperative refraction. Here, we assess the performance of these formulas in relation to the SBL-3 SMIOL in Chinese population, where the largest number of cataract patients resides. Whether the currently used A-constant or lens factor, as recommended by the manufacturer, will result in anticipated postoperative refractive status in Chinese patients remains questionable. The purpose of this study was to evaluate the performance of five traditional and three new IOL power calculation formulas using current lens constants among adult patients and improve their accuracy by optimizing lens constants of each formula.

SUBJECTS AND METHODS

Ethical Approval This study was approved by the Institutional Review Boards of Zhongshan Ophthalmic Center, Sun Yat-sen University and conformed to the tenets of the Declaration of Helsinki. Informed consent was obtained before surgery.

Patients Patients who underwent uncomplicated cataract surgery and SBL-3 SMIOL implantation from January 1, 2017 and January 31, 2019 were enrolled. Patients with previous corneal disease, ocular trauma, intraocular surgery, unavailable postoperative refraction data or corrected distance visual acuity of less than 20/40 were excluded. Age and gender of each patient were obtained from medical records. Ocular biometric data, including axial length (AL), anterior chamber depth (ACD) and keratometry (K) were measured preoperatively using the PCI platform (IOL Master, Carl Zeiss Meditec, Inc., Germany). Standardized phacoemulsification cataract surgery was performed *via* clear cornea temporal incision by one experienced surgeon. The power of the IOL was selected according to the SRK/T formula. Postoperative refraction status was examined at 4wk postoperatively.

Evaluation of the Prediction Accuracy The performance of eight IOL power calculation formulas (Barrett Universal II, EVO, Haigis, Hill-RBF 2.0, Hoffer Q, Holladay 1, Kane and SRK/T) using current lens constants was evaluated. Primary outcomes were calculated using current lens constants (Table 1). The IOL Master had licensed versions of Haigis, Hoffer Q, Holladay 1 and SRK/T formulas. Barrett Universal II formula analysis was performed at https://www.apacrs.org/barrett_universal2/; the Hill-RBF calculator version 2.0 was available at https://rbfcalculator.com/online/index.html; the Kane formula was analyzed on https://www.iolformula.com/. The EVO formula was analyzed at https://www.evoiolcalculator.com/calculator.aspx. Refractive prediction errors were calculated as the difference between the postoperative spherical equivalent and the predicted refraction errors as determined by the formulas. Numerical errors (NE) were obtained by subtracting predicted from postoperative refraction using each formula, while absolute errors (AE) represented absolute NE values. Mean and median NE values were used to assess hyperopic or myopic shifts in postoperative refraction. Mean AE (MAE) and median AE (MedAE) values were used to assess formula prediction accuracy. Comparisons between formulas were performed by nonparametric method since AE values did not follow a Gaussian distribution[14]. The benchmark standard of 55% of eyes within 0.50 D and 85% of eyes within 1.00 D were used to judge formula performance with a particular lens constant[15].

Table 1 Current and optimized lens constants

Formulas	Current lens constant	Optimized lens constant
Barrett Universal II		
Lens factor	1.41	1.11
EVO		
A constant	118.43	117.82
Haigis		
a_0	0.537	0.270
a_1	0.333	0.333
a_2	0.126	0.126
Hill-RBF 2.0		
A constant	118.35	117.63
Hoffer Q		
pACD	5.22	4.94
Holladay 1		
Surgeon factor	1.47	1.12
Kane		
A constant	118.43	117.75
SRK/T		
A constant	118.43	117.83

Optimized lens constants were calculated with clinical data from patients while minimizing systematic errors due to biometric measurement, surgical procedure and/or the formula. The A constant for SRK/T, Surgeon factor for Holladay 1, pACD for Hoffer Q and a_0 for Haigis formulas were optimized after the formulas were inputted to Microsoft Excel program. The lens factor for the Barrett Universal II formula as well as the A constants for EVO, Kane and Hill-RBF 2.0 formulas were optimized by trial and error, varying the adjusted lens constants in 0.01 steps to seek for the most suited value.

Adjustments were made to minimize mean NE for each formula.

Statistical Analysis The one-sample *t* test was used to determine whether mean numerical refraction prediction errors by the formulas significantly differed from zero. Multiple comparisons of formulas were conducted using the Friedman test, evaluating absolute prediction errors (SPSS version 23, IBM Inc., USA). A *P* value of less than 0.05 was considered statistically significant; Bonferroni correction was applied for multiple comparisons between formulas.

RESULTS

Demographics Patient demographic characteristics are shown in Table 2. A total of 53 eyes (right, 27; left, 26) from 41 patients (20 females, 21 males) were included in this study. Mean patient age was 54.3±12.8y (ranging from 19-79y). AL and K findings of most eyes undergoing SBL-3 implantation fell within the medium range, at 77.4% and 92.5%, respectively.

Accuracy with Current Lens Constants Refractive prediction errors resulting from the eight formulas are displayed in Table 3. All formulas yielded negative mean and median NE values, indicating a myopic shift. The mean NE in all formulas significantly differed from zero (all *P*<0.05). MAE and MedAE values significantly differed among formulas (*P*<0.05). The Barrett Universal II formula had a significantly lower MedAE than did the Holladay 1 (*P*=0.020), Kane (*P*=0.001) and Hill-RBF 2.0 (*P*<0.001) formulas after Bonferroni correction. The Haigis formula was found to have a significantly lower MedAE as compared to the Hill-RBF 2.0 formula (*P*=0.005). Differences among SRK/T, EVO, and Hoffer Q formulas were not statistically significant (Table 4). With current lens constants, Barrett Universal II, EVO, and Haigis formulas reached the standard of 55% of eyes within 0.50 D. None of the formulas achieved the goal of 85% of eyes with a refractive prediction error less than 1.00 D (Table 5).

Accuracy with Optimization of Lens Constants Optimized lens constants were calculated for the eight formulas, as shown in Table 1. MAE and MedAE values of all formulas were reduced with optimized constants as compared to current constants. The AE values were significantly reduced for EVO (*P*=0.022), Haigis (*P*=0.048), Hill-RBF 2.0 (*P*=0.014), Holladay 1 (*P*=0.045) and Kane (*P*=0.022) formulas, but not significantly so for Barrett Universal II, SRK/T, or Hoffer Q formulas. All formulas performed similarly when comparing AE values using the Friedman test (*P*=0.203). The reduction in AE indicates improvement in formula accuracy. All the eight formulas reached the benchmark standards of 55% of eyes within 0.50 D and 85% of eyes within 1.00 D (Table 5).

Performance of Formulas in Patients of Different Axial Length Groups We divided all eyes into normal AL (shorter than 25 mm) and long AL (equal to or longer than 25 mm) groups. Among patients in the normal AL group, significant differences in MedAE between formulas were noted (*P*<0.001). The Hill RBF 2.0 formula had a significantly higher MedAE than most other formulas, including the Barrett Universal II, EVO, Haigis, Holladay 1 and SRK/T formulas (all *P*<0.05). Nevertheless, all formulas exhibited similar accuracy regarding MedAE values using optimized lens constants (*P*=0.539). Among patients in the long AL group, no significant differences in MedAE values were noted between formulas using current (*P*=0.333) or optimized (*P*=0.574) lens constants. Optimized lens constants resulted in reduced MedAE for most formulas (all *P*<0.05) except the Barrett Universal II (*P*=0.099) in the normal AL group; no significant improvement in MedAE in the long AL group was noted (all *P*>0.05).

Table 2 Patient demographics (*n*=53)

Parameters	Mean±SD	Range
Age (y)	54.3±12.8	19, 79
AL (mm)	23.93±1.22	20.91, 27.16
ACD (mm)	3.36±0.36	2.34, 4.09
K (D)	43.92±1.16	41.82, 47.24
Preoperative corneal astigmatism (D)	-0.64±0.32	-1.42, -0.11
IOL power (D)	18.92±3.21	10, 25.5
Postoperative SE (D)	-0.46±0.58	-1.88, 0.50

AL: Axial length; ACD: Anterior chamber depth; K: Keratometry; IOL: Intraocular lens.

DISCUSSION

Selecting appropriate IOL power is of critical importance for cataract patients, especially to individuals who are to undergo multifocal IOL implantation. Formula calculation accuracy is greatly influenced by lens constants based on IOL type, surgical procedure and the population in question. Here, we evaluated prediction errors of eight formulas in adult Chinese patients who were implanted with an SBL-3 SMIOL after cataract surgery. We observed a slight myopic shift in these patients which could be adjusted by optimizing lens constants. After lens constant optimization, the percentage of eyes within 0.50 and 1.00 D increased, implying reduced dependency on spectacle correction. Results additionally suggested that currently used lens constants, recommended by the manufacturers, were not optimal for Chinese patients. Lens constants adjustment was needed when calculating IOL power for this population.

Average ocular parameters were reported to vary among different ethnic populations. Wang *et al*[16] found significant differences in lens position (LP) among four major ethnic groups. The LP was defined as the ACD +1/2 of lens thickness (LT). Asians and Hispanics were found to have relatively smaller LP values than did Whites, after adjusting for AL.

Table 3 NE and AE with current or optimized lens constants

Formulas	Current lens constants (D)		Optimized lens constants (D)		*P*
	NE	AE	NE	AE	
Barrett Universal II					0.115
Mean±SD	-0.37±0.60	0.51±0.49	0.00±0.61	0.44±0.42	
Median	-0.34	0.39	0.05	0.31	
Range	-2.08, 0.74	0.00, 2.08	-1.69, 1.13	0.00, 1.69	
EVO					0.022[a]
Mean±SD	-0.44±0.60	0.56±0.50	0.00±0.60	0.43±0.41	
Median	-0.36	0.46	0.05	0.30	
Range	-2.08, 0.68	0.01, 2.08	-1.61, 1.15	0.00, 1.61	
Haigis					0.048[a]
Mean±SD	-0.35±0.60	0.53±0.45	0.00±0.60	0.45±0.40	
Median	-0.31	0.38	0.11	0.33	
Range	-1.97, 0.87	0.03, 1.97	-1.62, 1.23	0.00, 1.62	
Hill-RBF 2.0					0.014[a]
Mean±SD	-0.51±0.61	0.61±0.50	0.00±0.61	0.46±0.39	
Median	-0.47	0.55	0.06	0.36	
Range	-2.20, 0.64	0.01, 2.20	-1.72, 1.14	0.03, 1.72	
Hoffer Q					0.065
Mean±SD	-0.36±0.62	0.56±0.45	0.00±0.61	0.47±0.38	
Median	-0.33	0.45	0.03	0.36	
Range	-1.93, 0.80	0.00, 1.93	-1.56, 1.18	0.01, 1.56	
Holladay 1					0.045[a]
Mean±SD	-0.43±0.62	0.57±0.49	0.00±0.62	0.46±0.40	
Median	-0.39	0.52	0.03	0.38	
Range	-2.04, 0.68	0.02, 2.04	-1.59, 1.14	0.02, 1.59	
Kane					0.022[a]
Mean±SD	-0.50±0.60	0.58±0.52	0.00±0.61	0.45±0.40	
Median	-0.40	0.45	0.11	0.31	
Range	-2.18, 0.60	0.01, 2.18	-1.64, 1.15	0.01, 1.64	
SRK/T					0.062
Mean±SD	-0.46±0.62	0.57±0.51	0.00±0.62	0.46±0.41	
Median	-0.44	0.50	0.02	0.40	
Range	-2.13, 0.60	0.01, 2.13	-1.65, 1.07	0.00, 1.65	

NE: Numerical errors; AE: Absolute errors. *P* value: The difference between the MedAE of each formula prior to and after IOL constant optimization ([a]$P<0.05$).

Smaller LP values may, in turn, lead to smaller postoperative ACD, causing the effective LP to move slightly anteriorly, and requiring lower power to reach emmetropia[17-18]. Excessive IOL power was thus likely responsible for observed postoperative myopic shift. Therefore, an adjustment of lens constants was made. For each of the eight formulas, MAE and MedAE values as well as standard deviation were all reduced, indicating improved accuracy and stability. Myopic shift correction was evaluated by a decrement in the percentage of myopic prediction errors as well as an increase in the percentage of eyes within 1.00 and 0.50 D.

Estimating ELP has always been a key concern in the development of formulas for IOL power calculation. As has been previously reported, the prediction of postoperative ACD is among the largest sources of error in postoperative refractive outcomes[19-20]. In the bifocal era, refractive results affect distance vision and near focal distance as well as add power in the spectacle plane[21-22]. Improving formula accuracy is therefore critical for allowing multifocal IOL implants to provide both good near and distant vision. Multiple linear regression analysis has previously emphasized the close correlation between preoperative ACD and postoperative effective ACD[17]. The Haigis formula includes preoperative ACD in the regression formula of ACD prediction[17,23-24]. In comparison with third generation formulas, the Haigis formula is more preferable for eyes longer than 24.5 mm

Table 4 Comparisons of AE between formulas with current lens constants after Bonferroni correction

Formulas	Barrett Universal II	EVO	Haigis	Hill-RBF 2.0	Hoffer Q	Holladay 1	Kane	SRK/T
Barrett Universal II	-	-	-	-	-	-	-	-
EVO	0.185	-	-	-	-	-	-	-
Haigis	1.000	1.000	-	-	-	-	-	-
Hill-RBF 2.0	0.000[c]	0.154	0.005[b]	-	-	-	-	-
Hoffer Q	0.072	1.000	1.000	0.370	-	-	-	-
Holladay 1	0.020[a]	1.000	1.000	0.997	1.000	-	-	-
Kane	0.001[b]	1.000	0.570	1.000	1.000	1.000	-	-
SRK/T	0.248	1.000	1.000	0.113	1.000	1.000	1.000	-

AE: Absolute errors. [a]$P<0.05$; [b]$P<0.01$; [c]$P<0.001$.

Table 5 Percentage of eyes within a given range of predictive errors according to formula %

Formulas	Current lens constants (D)					Optimized lens constants (D)				
	±0.25	±0.50	±0.75	±1.00	±2.00	±0.25	±0.50	±0.75	±1.00	±2.00
Barrett Universal II	39.6	64.2	81.1	83.0	98.1	41.5	67.9	79.2	88.7	100.0
EVO	32.1	60.4	79.2	83.0	98.1	45.3	69.8	79.2	88.7	100.0
Haigis	30.2	62.3	79.2	83.0	100.0	43.4	66.0	77.4	90.6	100.0
Hill-RBF 2.0	24.5	47.2	73.6	81.1	98.1	43.4	62.3	77.4	90.6	100.0
Hoffer Q	32.1	52.8	77.4	83.0	100.0	30.2	60.4	75.5	86.8	100.0
Holladay 1	30.2	49.1	81.1	81.1	98.1	39.6	67.9	75.5	90.6	100.0
Kane	28.3	52.8	75.5	83.0	98.1	37.7	67.9	83.0	88.7	100.0
SRK/T	32.1	50.9	81.1	81.1	98.1	43.4	64.2	79.2	90.6	100.0

and with an ACD over 3.5 mm[25]. The Barrett Universal II formula incorporates LT and white-to-white (WTW) values as determined by paraxial ray tracing; this formula exhibits superior accuracy for eyes with long, medium, and short AL[26]. In our retrospective study, LT and WTW values were not available as patients were examined previously with an IOL Master 500. Reitblat *et al*[3] reported that the role of LT in the Barrett Universal II formula was minor and that this factor minorly impacted prediction results.

Advances in artificial intelligence (AI) have helped further refine the accuracy of formula prediction. The Hill-RBF formula, entirely based on data from a certain patient group, employs AI in its prediction of postoperative refraction. Hill-RBF formula biometric data was collected using Lenstar LS 900 while implanted IOL type was mainly SN60WF[14]. Though this method has been reported to be free from calculation bias, the results would be affected by a certain number of eyes of similar dimensions, biometric measurement methods and IOL design differences. The Kane formula incorporates regression and AI components based on theoretical optics, taking gender into consideration in addition to optical biometry data. According to a recent study by Connell and Kane[27], the Kane formula yields the lowest MAE and MedAE values among existing formulas. The EVO formula aims to make predictions based on the theory of emmetropization[13]. In our study, these three novel formulas were similar in accuracy to older formulas, consistent with prior studies[13,27]. After lens constant optimization, these formulas were found to work well in the setting of SBL-3 SMIOL implantation. Though no significant difference was observed, the EVO formula was found to have the lowest MedAE while the Barrett Universal II and Kane formulas were found to have second-lowest MedAE values. The SRK/T formula was found to have the highest MedAE. We used MedAE instead of MAE values formula accuracy as the latter is less affected by extreme values.

Formula performance has long been established to be crucially affected by eye AL[26]. Most formulas have been reported to provide excellent results for eyes with AL values of between 22.0 and 25.0 mm[26,28-29]. In our study, 77.4% of AL values fell within this range. We analyzed refractive outcome after dividing eyes into different groups according to AL. After optimizing lens constants, MedAE values were greatly reduced for most formulas in the normal AL group. Although no significant improvement in MedAE was noted in eyes with AL values of greater than 25 mm, further studies evaluating larger sample sizes are required for confirmation. The varying of lens constants according to AL, however, seems beneficial.

Our study was not without limitations. First, the optimization of all three constants (a_0, a_1, a_2) as described by Haighs requires at least 200 eyes[23]. Since the required number of eyes was not available for optimization modeling, only a_0 was optimized for the Haigis formula. Second, our relatively small sample size may not have represented whole-population status. Optimized lens constants are currently not recommended to be used in clinical practice. Further evaluation of a larger number of eyes is required in future research. Finally, in this study, preoperative assessment was conducted *via* IOL Master 500. The lack of greater number of variables (LT, WTW, *etc.*) limited evaluation of other widely-used formulas (such as Holladay 2 and Olsen formulas). However, basic requirements for IOL power calculation were met with measurement of AL, ACD, and K. In most areas of China, preoperative ocular biometric measurement remains highly dependent on IOL Master 500 use. Surgeons will thus find our study helpful to their clinical practice.

Overall, both established and novel formulas tended to result in a postoperative myopic refractive shift with current lens constants. Optimized lens constants were found to improve formula performance among adult Chinese patients. Further research is required to formulate better prognostic models for patients who undergo SBL-3 SMIOL implantation.

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