Open

ARTICLE

Accuracy of newer intraocular lens power formulas in short and long eyes using sum-of-segments biometry

H. John Shammas, MD, Leonardo Taroni, MD, Marco Pellegrini, MD, Maya C. Shammas, MD, Renu V. Jivrajka, MD

Purpose: To analyze the accuracy of newer intraocular lens power formulas in long and short eyes measured using the sum-of-segments biometry.

Setting: Private practice, Lynwood, California.

Design: Retrospective observational study.

Methods: 595 patients scheduled for cataract surgery had their eyes measured using the sum-of-segments biometry. The expected residual refractions were calculated using Barrett Universal II (B II), Barrett True Axial Length (BTAL), Emmetropia Verifying Optical (EVO), Hill-RBF, Hoffer QST, Holladay 2, Holladay 2-NLR, K6, Kane, Olsen, PEARL-DGS, T2, and VRF formulas and compared with the traditional Haigis, Hoffer Q, Holladay 1, and SRK/T formulas.

Results: In the 102 long eyes, all new formulas had a mean absolute error (MAE) equal or lower than the traditional formulas, ranging from 0.29 to 0.32 diopter (D). In the 78 short eyes, BTAL, EVO, Hoffer QST, K6, Olsen, and PEARL-DGS formulas had the lowest MAE (0.33 D, 0.33 D, 0.31 D, 0.36 D, 0.32 D, and 0.32 D, respectively), whereas all traditional formulas exceeded 0.36 D.

Conclusions: All new formulas performed equal or better than the traditional formulas with the sum-of-segments biometry. The best overall results in the short and long eyes as well as in the very short and very long eyes were noted with the BTAL, EVO, Hoffer QST, K6, Olsen, and PEARL-DGS formulas, closely followed by the B II and Kane formulas.

J Cataract Refract Surg 2022; 48:1113–1120 Copyright © 2022 The Author(s). Published by Wolters Kluwer Health, Inc. on behalf of ASCRS and ESCRS

For over 20 years, optical biometry has been the standard of care for axial length (AL) measurement and intraocular lens (IOL) power calculation in cataract surgery. The IOLMaster 500 (Carl Zeiss Meditec AG) uses partial coherence interferometry (PCI) with a 780 nm laser diode infrared light to measure the entire eye's optical path length (OPL).[1] The OPL is then converted to a geometrical path length (GPL) using a single variable regression equation, thus allowing the PCI biometer's AL output to match the same AL measured with immersion ultrasound.[2] The Lenstar LS900 (Haag-Streit AG) uses optical low-coherence reflectometry (OLCR) with an 820 nm superluminescent diode to also measure the entire eye's OPL; the OPL is then converted to a GPL using a single-group refractive function for the entire eye.[3,4] By contrast, the Argos (Movu, Inc.) swept-source optical coherence tomographer (SS-OCT) uses a 1060 nm wavelength and a 20 nm bandwidth swept-source technology to collect 2-dimensional OCT data of the full eye.[5,6] More importantly, it measures the OPL of each segment of the eye and uses a specific refractive index for each of these segments (cornea, aqueous depth, lens, and vitreous). As such, when there are variations in the relative lengths of these components, the AL calculation is appropriately adjusted. In 3 recent studies, the refractive accuracy of most commonly used formulas was higher in eyes measured with a specific refractive index for each segment of the eye than in eyes measured with a single-group refractive function for the entire eye; in all 3 studies, this increase in the formulas' refractive accuracy was more evident in the short and long eyes when the sum-of-segments (S-O-S) measurement is used.[4,7,8]

Newer formulas, some of which are based on artificial intelligence or machine learning, are quickly gaining in popularity. These include the Barrett Universal II (B II) formula currently programmed in the SS-OCT biometer, the Barrett True Axial Length (BTAL), Emmetropia

Submitted: November 6, 2021 | Final revision submitted: April 9, 2022 | Accepted: April 19, 2022

From the Department of Ophthalmology, Keck School of Medicine of USC, Los Angeles, California (H.J. Shammas); Shammas Eye Medical Center, Lynwood, California (H.J. Shammas, M.C. Shammas, Jivrajka); Eye Clinic, S. Orsola-Malpighi University Hospital, University of Bologna, Bologna, Italy (Taroni, Pellegrini); Ophthalmology Unit, Santa Maria delle Croci Hospital, Ravena, Italy (Taroni).

The study was supported by a grant from Alcon Laboratories, Inc. (ITT# 69523705).

Corresponding author: H. John Shammas, MD, Shammas Eye Medical Center, 3510 Martin Luther King Jr. Blvd, Lynwood, CA 90262. Email: hshammas@shammaseye.com.

0886-3350/$ - see frontmatter
https://doi.org/10.1097/j.jcrs.0000000000000958

Verifying Optical (EVO), Hill-RBF, Hoffer QST, Holladay 2, Holladay 2-NLR, K6, Kane, Olsen, PEARL-DGS, T2, and VRF formulas.[9–14] The refractive outcomes of these newer formulas using the S-O-S biometry measurements remain unknown, especially in the long and the short eyes. The purpose of this retrospective study is to analyze the accuracy of the newer IOL power formulas in the long and short eyes and to compare them with the commonly used traditional Haigis, Hoffer Q, Holladay 1, and SRK/T formulas.[15–18]

METHODS

This study conformed to the ethics code based on the tenets of the Declaration of Helsinki. It is a comparative noninterventional study comprising a retrospective chart review of patients with a history of cataract surgery at 1 center. The study was approved by the Milkie-Shammas Surgery Center Institutional Review Board (Lynwood, California). A waiver of informed consent was granted to allow the use of deidentified patient data.

Eligible charts were those from patients who have had previous uneventful cataract surgery where the biometry was performed with the Argos SS-OCT device. To reduce variability related to the IOL implanted, only eyes receiving the AcrySof SN60WF aspheric monofocal IOL (Alcon Laboratories, Inc.) were included. Eyes with clinically significant ocular pathology other than residual refractive error (eg, macular degeneration or advanced glaucoma) were excluded. Eyes with suboptimal surgical outcomes that were not related to the treatment plan (eg, capsular tear, cystoid macular edema, and wound leaks necessitating corneal suturing) were also excluded. In addition, the corrected distance visual acuity in the eye had to be 20/40 or better to reduce the likelihood of variability in the postoperative refraction. If both eyes of a patient were eligible to be included in the study, only the first operated eye was included.

Both manual and electronic data records were used to identify a consecutive series of eyes that fit the inclusion and exclusion criteria above. Deidentified data from the preoperative examination and the 6- to 8-week postoperative examination were collected, including age, sex, postoperative refraction, and corrected distance visual acuity. The biometric data retrieved from the Argos OCT biometer included the displayed AL, the central corneal thickness, the aqueous depth, the anterior chamber depth, the lens thickness, the corneal diameter, and the keratometric readings in the flattest and steepest meridians. The displayed AL on the Argos biometer uses the following indices of refraction: 1.375 for the cornea, 1.336 for the aqueous depth and for the vitreous, and 1.41 for the lens.[5] The K readings are not the result of a direct measurement of that power; instead, the integrated keratometer measures the anterior corneal radius in millimeters and converted to power values (K in diopters) according to the laws of Gaussian optics using the following formula: $K = 1000\ (n - 1)/r$, where n is the standard refractive index of 1.3375. The surgical treatment data, IOL power calculations, and power of the IOL implanted were also recorded.

With all biometry measurements kept the same for each eye, the expected residual refractions based on the newer IOL formulas were calculated in each eye. These formulas included:

The B II formula: The expected residual refractive errors using the B II formula available on the biometer were noted.[9]

The BTAL formula: This is an updated version of the B II formula, designed for those measurements that use the sum-of-segment methodology.[9] The formula will soon be available on the Asia-Pacific Association of Cataract and Refractive Surgeons website (G. Barrett, personal communication, July 17, 2021). Constant optimization and data analysis were performed by Graham Barrett, MD.

The EVO formula, v. 2.0, available at: www.evoiolcalculator.com (accessed on May 17, 2021): It stands for Emmetropia Verifying Optical formula that generates an emmetropia factor for each eye. In this study, we used the Argos version of the formula available at its own website, flagging the specific icon. Constant optimization and data analysis were performed by one of the authors (L.T.).

The Hill-RBF formula, v. 3.0, available at: https://rbfcalculator.com/ (accessed on August 4, 2021): The formula is based on radial basis function using pattern recognition and sophisticated data interpolation. Eleven eyes (4 long and 7 short) were out of bounds of the pattern recognition grid and were not included in the calculations. Constant optimization and data analysis were performed by Warren Hill, MD.

The Hoffer Q/Savini/Taroni formula (Hoffer QST) is an updated Hoffer Q formula by means of new algorithms and machine learning process.[16] It is available at www.hofferqst.com (accessed on May 18, 2021). Constant optimization and data analysis were performed by one of the authors (L.T.).

The Holladay 2 formula was used with the Holladay IOL Consultant (v. 2014.0607, Holladay consulting. Accessed on August 8, 2021). Constant optimization and data analysis were performed by David Cooke, MD.

The Holladay 2 formula with NLR (Holladay 2-NLR) (accessed on December 18, 2021): This newer version of the software modifies the AL using a nonlinear regression (NLR) equation that affects eyes exceeding 24.0 mm. Constant optimization and data analysis were performed by David Cooke, MD.

The K6 formula, available at: www.CookeFormula.com (accessed on August 8, 2021): The formula transforms the optical biometer's AL to be the distance from the anterior cornea to the retinal pigment epithelium. It also uses a proprietary estimated lens position calculation based on postoperative measurement of 245 eyes. Constant optimization and data analysis were performed by David Cooke, MD.

The Kane formula, available at: www.iolformula.com (accessed on May 18, 2021): The formula uses regression equations and artificial intelligence components to improve predictions.[10] Constant optimization and data analysis were performed by one of the authors (L.T.).

The Olsen formula, available at: www.phacoOptics.net (accessed on August 8, 2021): The formula is based on exact ray tracing, and it uses the C-constant concept to predict the IOL position inside the eye.[11] Constant optimization and data analysis were performed by David Cooke, MD.

The PEARL-DGS formula, available at: www.iolsolver.com (accessed on August 8, 2021): It stands for Postoperative spherical Equivalent prediction using ARtificial intelligence and Linear algorithms, developed by Debellemanière, Gatinel, and Saad.[12] This formula is a thick lens version of the Haigis formula, trained using a perfect back-calculated lens position with artificial intelligence and a linear algorithms formula. The Cooke-modified AL (CMAL) function needed to correct the AL from a traditional one to a sum-of-segments one was replaced by the S-O-S measurement obtained by the SS-OCT biometer. Constant optimization and data analysis were performed by Guillaume Debellemanière, MD.

The T2 formula, using the T2 formula calculator: The formula is an improvement on the SRK/T formula by replacing the steps in the SRK/T formula used to estimate corneal height with a regression formula derived from a large collection of patient data.[13,18] Constant optimization and data analysis were performed by David Cooke, MD.

The VRF formula: The formula uses a special algorithm to determine the postoperative position of the IOL.[14] Constant optimization and data analysis were performed by David Cooke, MD.

Postoperative refractive evaluation was performed at 6 to 8 weeks from surgery. The operated eye is first checked objectively using an Auto Refractometer/keratometer (model ARK-1 from Nidek Co., Ltd.) followed by a subjective refraction performed by a licensed optometrist and checking the vision at 20 feet. To calculate the refractive prediction error (PE), the predicted refraction (based on the IOL power implanted) was subtracted from the postoperative refraction according to each formula. Therefore, a negative PE value reveals that the result achieved was more myopic than the predicted refraction, whereas a positive PE value

Table 1. Demographic and biometric data

Parameter	Entire series (N = 595)	Short eyes (n = 78)	Long eyes (n = 102)
Age (y)	71 ± 9 (23, 92)	72 ± 10 (23, 91)	68 ± 10 (27, 84)
Sex (M/F)	250 (42)/345 (58)	15 (19)/63 (81)	55 (54)/47 (46)
Eye involved (R/L)	297 (50)/298 (50)	42 (54)/36 (46)	51 (50)/51 (50)
Axial length (mm)	23.58 ± 1.07 (20.75, 29.65)	22.00 ± 0.38 (20.75, 22.49)	25.27 ± 0.76 (24.51, 29.65)
Corneal thickness (mm)	0.53 ± 0.03 (0.43, 0.64)	0.53 ± 0.03 (0.45, 0.60)	0.53 ± 0.03 (0.46, 0.63)
Aqueous depth (mm)	2.68 ± 0.37 (1.75, 4.06)	2.42 ± 0.33 (1.81, 3.38)	2.92 ± 0.37 (2.10, 4.06)
Phakic ACD (mm)	3.21 ± 0.37 (2.28, 4.60)	2.95 ± 0.34 (2.31, 3.92)	3.45 ± 0.36 (2.61, 4.60)
Corneal diameter (mm)	12.16 ± 0.57 (10.47, 13.90)	11.61 ± 0.46 (10.50, 12.81)	12.69 ± 0.50 (11.33, 13.90)
Flat K (D)	43.36 ± 1.66 (37.50, 50.06)	45.23 ± 1.68 (41.65, 49.88)	42.16 ± 1.61 (37.50, 47.22)
Steep K (D)	44.28 ± 1.70 (38.92, 51.68)	46.15 ± 1.62 (42.84, 50.90)	43.23 ± 1.79 (38.92, 48.57)
Average K (D)	43.82 ± 1.65 (38.56, 50.87)	45.69 ± 1.62 (42.39, 50.39)	42.69 ± 1.65 (38.56, 47.8)

ACD = anterior chamber depth; K = keratometry
Data are presented as n (%) or mean ± SD (range)

represents a more hyperopic result. The mean PE and its SD, the median absolute error (MedAE), the mean absolute error (MAE), and the percentage of eyes with a PE within ±0.25 diopter (D), ±0.50 D, ±0.75 D, and ±1.00 D were calculated for each formula. Lens constant optimization for each formula was achieved by bringing each mean PE to zero in the entire series. We analyzed the results of all these formulas in 78 short eyes (AL <22.50 mm) and 102 long eyes (AL >24.50 mm).[19] We further analyzed the results in 42 very short eyes (AL of 22.0 mm and shorter) and 53 very long eyes (AL of 25.0 mm and longer).[19]

Statistical Analysis

For patients who had undergone surgery in both eyes, only the first eye was considered for analysis. Statistical calculations were conducted using R (v. 4.0.0) and RStudio (v. 1.2.5042) software. Because of the non-normal distribution of data, the variances of PEs were compared using the heteroscedastic method proposed by Holladay et al.[20,21]

Sample size calculations suggested a minimum of 388 eyes to be included in the dataset. A post hoc analysis (G*Power 3.1) of the whole dataset with N = 595, highest SD = 0.396, and lowest SD = 0.358 and 2 tails yields a power of 0.700 for an alpha level of 0.05.

RESULTS

In this study, we enrolled 595 eyes of 595 patients. The demographic and biometric data are noted in Table 1. Patients with short eyes tended to be slightly older at the time of surgery than patients with long eyes (72 ± 10 years vs 68 ± 10 years), with a higher percentage of females (81% vs 46%). Compared with the long eyes, the short eyes had a shallower phakic anterior chamber depth (2.95 ± 0.34 mm

Table 2. Optimized constants and refractive outcomes of the study population (N = 595)

Formula	Optimized constant	MPE ± SD (D)	MedAE (D)	MAE (D)	MaxAE (D)	PE (%) < 0.25 D	0.50 D	0.75 D	1.00 D
New formulas									
B II	2.00	0.00 ± 0.378	0.27	0.31	1.10	45.9	80.5	96.5	99.5
BTAL	1.97	−0.01 ± 0.370	0.26	0.30	1.00	48.4	80.3	97.0	100.0
EVO	119.12	0.00 ± 0.364	0.27	0.30	0.98	47.4	81.5	97.3	100.0
Hill-RBF[a]	119.22	0.01 ± 0.380	0.28	0.31	1.48	44.4	81.5	97.0	99.5
Hoffer QST	5.72	0.00 ± 0.371	0.28	0.31	1.12	46.4	80.7	97.3	99.8
HOL2	5.65	0.00 ± 0.396	0.29	0.32	1.09	44.7	76.6	95.3	99.5
HOL2-NLR	5.64	0.00 ± 0.390	0.28	0.32	1.15	44.7	77.8	95.3	99.5
K6	119.22	0.00 ± 0.364	0.26	0.29	1.31	48.2	81.3	97.7	99.5
Kane	119.19	0.00 ± 0.373	0.27	0.30	1.38	47.2	80.3	97.1	99.7
Olsen	4.74	−0.01 ± 0.377	0.26	0.30	1.64	47.7	80.5	96.1	99.5
P-DGS	118.60	0.00 ± 0.358	0.26	0.29	1.23	48.4	81.7	98.0	99.8
T2	119.24	0.00 ± 0.386	0.29	0.32	0.98	44.4	78.8	96.0	100.0
VRF	5.70	0.00 ± 0.388	0.28	0.32	1.40	46.1	77.8	96.8	99.5
Traditional formulas									
Haigis	[b]	0.00 ± 0.397	0.29	0.32	1.10	45.8	77.4	94.2	99.8
Hoffer Q	5.75	0.00 ± 0.410	0.29	0.33	1.11	45.8	74.8	93.1	99.3
Holladay 1	1.98	0.00 ± 0.388	0.28	0.32	1.10	45.8	77.4	94.2	99.8
SRK/T	119.25	0.00 ± 0.408	0.30	0.34	1.03	42.5	75.0	94.6	99.6

B II = Barrett Universal II; BTAL = Barrett True Axial Length; EVO = Emmetropia Verifying Optical; HOL2 = Holladay 2; HOL2-NLR = Holladay 2 with the nonlinear regression; MAE = mean absolute error; MaxAE = maximal absolute error; MedAE = median absolute error; MPE = mean prediction error; P-DGS = PEARL-DGS; PE = prediction error
[a]Only 584 eyes were measured, with 11 eyes out of bounds of the pattern recognition grid
[b]Haigis constants (a0 = 0.623, a1 = 0.323, and a2 = 0.149)

Table 3. Refractive outcomes in the short eyes (n = 78)

Formula	Optimized constant	MPE ± SD (D)	MedAE (D)	MAE (D)	MaxAE (D)	PE (%) <			
						0.25 D	0.50 D	0.75 D	1.00 D
New formulas									
B II	2.00	0.09 ± 0.418	0.31	0.35	1.01	38.5	70.5	93.6	98.7
BTAL	1.97	−0.07 ± 0.396	0.30	0.33	0.86	42.3	71.8	97.4	100.0
EVO	119.12	−0.11 ± 0.383	0.28	0.33	0.87	41.0	76.9	97.4	100.0
Hill-RBF[a]	119.22	0.18 ± 0.418	0.32	0.38	1.14	34.6	71.8	92.3	97.4
Hoffer QST	5.72	−0.00 ± 0.411	0.34	0.36	0.95	41.0	74.4	96.2	100.0
HOL2	5.65	−0.15 ± 0.437	0.36	0.38	1.09	34.6	68.0	92.3	97.4
HOL2-NLR	5.64	−0.11 ± 0.437	0.35	0.38	1.13	30.8	70.5	94.9	97.4
K6	119.22	0.09 ± 0.376	0.26	0.31	1.02	47.4	79.5	96.2	98.7
Kane	119.19	0.02 ± 0.422	0.35	0.36	1.03	37.2	69.2	96.2	98.7
Olsen	4.74	0.04 ± 0.383	0.28	0.32	0.88	42.3	79.5	94.9	100.0
P-DGS	118.60	−0.04 ± 0.377	0.27	0.32	0.86	47.4	80.8	97.4	100.0
T2	119.24	−0.02 ± 0.428	0.34	0.36	0.92	35.9	71.8	93.6	100.0
VRF	5.70	−0.06 ± 0.428	0.33	0.36	1.04	37.2	73.1	94.9	98.7
Traditional formulas									
Haigis	[b]	0.05 ± 0.462	0.36	0.38	1.10	38.5	66.7	91.0	98.7
Hoffer Q	5.75	−0.08 ± 0.461	0.37	0.38	0.94	38.5	66.7	85.9	100.0
Holladay 1	1.98	0.02 ± 0.434	0.33	0.37	0.93	35.9	71.7	94.9	100.0
SRK/T	119.25	−0.02 ± 0.453	0.31	0.37	1.02	39.7	70.5	88.5	98.7

B II = Barrett Universal II; BTAL = Barrett True Axial Length; EVO = Emmetropia Verifying Optical; HOL2 = Holladay 2; HOL2-NLR = Holladay 2 with the nonlinear regression; MAE = mean absolute error; MaxAE = maximal absolute error; MedAE = median absolute error; MPE = mean prediction error; P-DGS = PEARL-DGS; PE = prediction error

[a]Only 71 eyes were measured, with 7 eyes out of bounds of the pattern recognition grid

[b]Haigis constants (a0 = 0.623, a1 = 0.323, and a2 = 0.149)

vs 3.45 ± 0.36 mm), a smaller corneal diameter (11.61 ± 0.46 mm vs 12.69 ± 0.50 mm), and steeper Ks (average of 45.69 ± 1.62 D vs 42.69 ± 1.65 D).

Table 2 shows the refractive outcomes in the entire series, and the results were used to determine the optimized constants in our cohort by bringing each MPE closest to 0. All new formulas had a MAE equal or lower than the traditional formulas, with over 76% of the eyes achieving a refraction within ±0.50 D from the predicted one, with the B II, BTAL, EVO, Hill-RBF, Hoffer QST, K6, Kane, Olsen, and PEARL-DGS formulas exceeding 80%.

Table 3 shows the refractive outcomes in the 78 short eyes, keeping the same optimized constants. BTAL, EVO, K6, Olsen, and PEARL-DGS formulas had the lowest MAE (0.33 D, 0.33 D, 0.31 D, 0.32 D, and 0.32 D, respectively), whereas all 4 traditional formulas recorded a MAE exceeding 0.36 D. The percentage of eyes achieving a refraction within ±0.50 D from the predicted one with the noted formulas was 71.8%, 76.9%, 79.5%, 79.5%, and 80.8%, respectively. In the very short eyes, all 5 of the previously mentioned formulas had a low MAE (0.36 D, 0.35 D, 0.33 D, 0.35 D, and 0.33 D, respectively), and the percentage of eyes achieving a refraction within ±0.50 D from the predicted one was 72.4%, 76.1%, 76.2%, 73.8%, and 76.2%, respectively (Table 4). Equally good results were noted with the Hoffer QST and VRF formulas, with the percentage of eyes achieving a refraction within ±0.50 D from the predicted one was 76.2%.

Table 5 shows the refractive outcomes in the 102 long eyes, keeping the same optimized constants. All new formulas had a MAE equal or lower than the traditional formulas. BTAL, EVO, Hoffer QST, Kane, and PEARL-DGS formulas had the lowest MAE of 0.29 D; the percentage of eyes achieving a refraction within ±0.50 D from the predicted one with these formulas was 82.4%, 78.0%, 80.4%, 79.4%, and 80.4%, respectively. In the very long eyes, all 5 of the previously mentioned formulas had a low MAE (0.26 D, 0.28 D, 0.27 D, 0.27 D, and 0.27 D, respectively), and the percentage of eyes achieving a refraction within ±0.50 D from the predicted one was 90.6%, 81.1%, 86.8%, 84.9%, and 83.0%, respectively (Table 6). Equally good results were noted with the B II, Hill-RBF, Holladay 2-NLR, K6, Olsen, and T2 formulas, with the percentage of eyes achieving a refraction within ±0.50 D from the predicted one was 91.2%, 86.8%, 88.7%, 88.7%, 84.9%, and 90.6%, respectively.

Supplemental Tables A, B, C, D, and E (http://links.lww.com/JRS/A591, http://links.lww.com/JRS/A592, http://links.lww.com/JRS/A593, http://links.lww.com/JRS/A594, http://links.lww.com/JRS/A595) represent the matrices of SDs of PEs in the entire series, short eyes, very short eyes, long eyes, and very long eyes, respectively; the *P* values were computed using the heteroscedastic method.

DISCUSSION

The S-O-S methodology used in the Argos SS-OCT biometer measures each segment of the eye at its correct velocity just like A-scan biometry. Wang et al. calculated the segmented AL of 4992 eyes measured by an OLCR biometer by adding all geometrical ocular segments converted from the respective OPL in each medium.[4] On

Table 4. Refractive outcomes in the very short eyes, 22.0 mm and shorter (n = 42)

Formula	Optimized constant	MPE ± SD (D)	MedAE (D)	MAE (D)	MaxAE (D)	PE (%) < 0.25 D	0.50 D	0.75 D	1.00 D
New formulas									
B II	2.00	0.08 ± 0.443	0.35	0.38	1.02	39.5	72.1	93.0	97.7
BTAL	1.97	−0.09 ± 0.419	0.32	0.36	0.86	38.1	72.4	95.2	100.0
EVO	119.12	−0.13 ± 0.400	0.33	0.35	0.87	38.1	76.1	95.2	100.0
Hill-RBF[a]	119.22	0.24 ± 0.430	0.32	0.40	1.14	33.3	69.1	88.1	95.2
Hoffer QST	5.72	−0.02 ± 0.420	0.36	0.36	0.95	33.3	76.2	95.2	100.0
HOL2	5.65	−0.13 ± 0.452	0.37	0.41	1.09	30.9	66.7	92.9	97.6
HOL2-NLR	5.64	−0.10 ± 0.452	0.36	0.40	1.13	23.8	71.4	97.6	97.6
K6	119.22	0.13 ± 0.401	0.26	0.33	1.02	47.6	76.2	95.2	97.6
Kane	119.19	0.04 ± 0.429	0.36	0.36	1.03	35.7	69.1	95.2	97.6
Olsen	4.74	0.04 ± 0.422	0.34	0.35	0.88	40.5	73.8	92.9	100.0
P-DGS	118.60	−0.04 ± 0.331	0.27	0.33	0.86	45.2	76.2	95.2	100.0
T2	119.24	0.03 ± 0.439	0.35	0.36	0.92	33.3	73.8	90.5	100.0
VRF	5.70	−0.04 ± 0.434	0.35	0.37	1.04	28.6	76.2	95.2	97.6
Traditional formulas									
Haigis	[b]	0.06 ± 0.479	0.38	0.40	1.10	34.9	69.8	88.4	97.7
Hoffer Q	5.75	−0.07 ± 0.474	0.42	0.40	0.81	25.6	67.4	86.0	100.0
Holladay 1	1.98	0.06 ± 0.444	0.39	0.38	0.93	27.9	76.7	93.0	100.0
SRK/T	119.25	−0.03 ± 0.443	0.26	0.36	0.98	46.5	72.1	90.7	98.7

B II = Barrett Universal II; BTAL = Barrett True Axial Length; EVO = Emmetropia Verifying Optical; HOL2 = Holladay 2; HOL2-NLR = Holladay 2 with the nonlinear regression; MAE = mean absolute error; MaxAE = maximal absolute error; MedAE = median absolute error; MPE = mean prediction error; P-DGS = PEARL-DGS; PE = prediction error

[a]Only 71 eyes were measured, with 7 eyes out of bounds of the pattern recognition grid

[b]Haigis constants (a0 = 0.623, a1 = 0.323, and a2 = 0.149)

average, the segmented ALs were longer in short eyes and shorter in long eyes compared with the displayed ALs calculated with a single-group refractive index for the entire eye. Furthermore, the refractive accuracy with segmented ALs was improved in short eyes with the Hoffer Q and Holladay 1 formulas and in long eyes with the B II, Haigis,

Table 5. Refractive outcomes in the long eyes, over 24.5 mm (n = 102)

Formula	Optimized constant	MPE ± SD (D)	MedAE (D)	MAE (D)	MaxAE (D)	PE (%) < 0.25 D	0.50 D	0.75 D	1.00 D
New formulas									
B II	2.00	−0.08 ± 0.372	0.25	0.30	1.10	49.0	83.3	95.1	99.0
BTAL	1.97	−0.06 ± 0.357	0.23	0.29	0.86	52.0	82.4	96.1	100.0
EVO	119.12	0.06 ± 0.360	0.24	0.29	0.85	52.9	78.0	98.0	100.0
Hill-RBF[a]	119.22	−0.15 ± 0.368	0.29	0.32	1.48	45.1	82.4	96.1	99.0
Hoffer QST	5.72	−0.03 ± 0.361	0.25	0.29	1.12	50.0	80.4	99.0	99.0
HOL2	5.65	0.13 ± 0.375	0.28	0.32	0.79	46.1	73.5	96.1	100.0
HOL2-NLR	5.64	0.00 ± 0.374	0.24	0.30	1.15	52.0	80.4	96.1	99.0
K6	119.22	−0.13 ± 0.361	0.25	0.30	1.31	50.0	80.4	96.1	99.0
Kane	119.19	−0.03 ± 0.376	0.25	0.29	1.38	50.0	79.4	97.1	99.0
Olsen	4.74	−0.11 ± 0.376	0.27	0.31	1.22	49.0	78.4	95.1	99.0
P-DGS	118.60	0.00 ± 0.362	0.25	0.29	0.96	51.0	80.4	98.0	100.0
T2	119.24	−0.04 ± 0.375	0.27	0.31	0.89	45.1	81.4	95.1	100.0
VRF	5.70	0.02 ± 0.392	0.21	0.30	1.40	52.9	76.5	97.1	99.0
Traditional formulas									
Haigis	[b]	−0.02 ± 0.394	0.25	0.32	0.88	50.0	75.5	94.1	100.0
Hoffer Q	5.75	0.06 ± 0.423	0.27	0.34	1.01	47.1	73.5	88.2	99.0
Holladay 1	1.98	−0.01 ± 0.391	0.27	0.32	1.09	49.0	73.5	96.1	98.2
SRK/T	119.25	0.02 ± 0.412	0.27	0.33	0.93	46.1	72.6	96.1	100.0

B II = Barrett Universal II; BTAL = Barrett True Axial Length; EVO = Emmetropia Verifying Optical; HOL2 = Holladay 2; HOL2-NLR = Holladay 2 with the nonlinear regression; MAE = mean absolute error; MaxAE = maximal absolute error; MedAE = median absolute error; MPE = mean prediction error; P-DGS = PEARL-DGS; PE = prediction error

[a]Only 98 eyes were measured, with 4 long eyes out of bounds of the pattern recognition grid

[b]Haigis constants (a0 = 0.623, a1 = 0.323, and a2 = 0.149)

Table 6. Refractive outcomes in the very long eyes, 25.0 mm and longer (n = 53)

Formula	Optimized constant	MPE ± SD (D)	MedAE (D)	MAE (D)	MaxAE (D)	PE (%) < 0.25 D	0.50 D	0.75 D	1.00 D
New formulas									
B II	2.00	−0.09 ± 0.332	0.23	0.27	1.09	56.1	91.2	96.5	98.2
BTAL	1.97	−0.05 ± 0.327	0.24	0.26	0.86	50.9	90.6	96.2	100.0
EVO	119.12	0.08 ± 0.343	0.22	0.28	0.85	56.6	81.1	98.1	100.0
Hill-RBF[a]	119.22	−0.18 ± 0.348	0.28	0.29	1.48	49.1	86.8	94.3	98.1
Hoffer QST	5.72	−0.06 ± 0.339	0.19	0.27	1.12	54.7	86.8	98.1	98.1
HOL2	5.65	0.17 ± 0.347	0.27	0.31	0.79	49.1	75.5	94.3	100.0
HOL2-NLR	5.64	−0.01 ± 0.351	0.24	0.28	1.15	54.7	88.7	96.2	98.1
K6	119.22	−0.14 ± 0.343	0.18	0.27	1.31	56.6	88.7	94.3	98.1
Kane	119.19	−0.03 ± 0.369	0.22	0.27	1.38	54.7	84.9	94.3	98.1
Olsen	4.74	−0.10 ± 0.365	0.23	0.29	1.22	50.9	84.9	96.2	98.1
P-DGS	118.60	0.03 ± 0.342	0.25	0.27	0.96	49.1	83.0	98.1	100.0
T2	119.24	−0.06 ± 0.341	0.27	0.28	0.89	43.4	90.6	96.2	100.0
VRF	5.70	0.05 ± 0.392	0.19	0.29	1.40	60.4	77.4	96.2	98.1
Traditional formulas									
Haigis	[b]	0.03 ± 0.372	0.20	0.29	0.83	56.1	78.9	94.7	100.0
Hoffer Q	5.75	0.11 ± 0.409	0.25	0.33	1.01	50.9	71.9	89.5	98.2
Holladay 1	1.98	−0.09 ± 0.332	0.23	0.27	1.09	56.1	91.2	96.5	98.2
SRK/T	119.25	0.01 ± 0.376	0.19	0.29	0.93	52.6	80.7	96.5	100.0

B II = Barrett Universal II; BTAL = Barrett True Axial Length; EVO = Emmetropia Verifying Optical; HOL2 = Holladay 2; HOL2-NLR = Holladay 2 with the nonlinear regression; MAE = mean absolute error; MaxAE = maximal absolute error; MedAE = median absolute error; MPE = mean prediction error; P-DGS = PEARL-DGS; PE = prediction error
[a]Only 98 eyes were measured, with 4 long eyes out of bounds of the pattern recognition grid
[b]Haigis constants (a0 = 0.623, a1 = 0.323, and a2 = 0.149)

Hoffer Q, Holladay 1, and SRK/T formulas. Cooke and Cooke reviewed 215 eyes measured with an OLCR biometer and developed the CMAL that closely approximates the S-O-S AL.[7] Reviewing the clinical results in 1442-eye validation set, the CMAL produced more accurate predictions in the Hoffer Q, Holladay 1, SRK/T, and Holladay 2 IOL formulas; the improvement was mainly noted in the short and long eyes. Shammas et al. compared the AL as measured by the Argos SS-OCT biometer using the S-O-S methodology to a measurement that simulates an AL measured with a single refractive index in 595 eligible eyes.[8] On average, the simulated measurements were shorter than the Argos measurements in the short eyes and longer in the long eyes, with a higher MAE with the B II, Holladay 1, Haigis, Hoffer Q, and SRK/T formulas. The drawback of these 3 studies is that the refractive index of an individual cataractous lens is unknown, and the conversion from the OPL to GPL uses a fixed assumed value of 1.41. In a recent study, Yang et al. evaluated 146 eyes measured by the Argos SS-OCT biometer that uses the S-O-S methodology, by the IOLMaster 700 SS-OCT, and the IOLMaster v. 5.4 PCI biometer.[22] In this study, the AL measured by Argos showed a significant difference compared with the measurements from the 2 IOLMaster biometers. The postoperative MAE was reported to be 0.41 ± 0.31 D, 0.42 ± 0.32 D, and 0.35 ± 0.30 D for the IOLMaster v. 5.4, IOLMaster 700, and Argos, respectively.

In this study, we analyzed the refractive outcomes of 13 new formulas using measurements from the Argos OCT biometer, and we compared them with the traditional Haigis, Hoffer Q, Holladay 1, and SRK/T formulas.[15–18] The selected new formulas are currently among the most studied and available options for IOL power calculation. In our cohort of 595 eyes, all new formulas had a MAE equal or lower than the traditional formulas, with over 76% (452/595) of the eyes achieving a refraction within ±0.50 D from the predicted one, with the B II, BTAL, EVO, Hill-RBF, Hoffer QST, K6, Kane, Olsen, and PEARL-DGS formulas exceeding 80% (476/595).

The BTAL, EVO, and PEARL-DGS formulas adjust for measurements made with the S-O-S biometry. All other formulas were the original ones with no modifications. The Hill-RBF, v. 3.0, is the only formula that does not require an estimated lens position or a vergence formula; instead, it uses artificial intelligence for pattern recognition using only data collected from the Lenstar OLCR biometer. The formula performed extremely well with 81.5% (585/595) within ±0.50 D in the entire study population and 82.4% (84/102) in the long eyes. However, the measurement differences between the traditional method of the Lenstar and the S-O-S method of the Argos appear to mainly affect the IOL prediction in the short eyes, with only 71.8% (56/78) of the eyes within ±0.50 D. Furthermore, in our series, we encountered difficulties in calculating the IOL power in 4 long and 7 short eyes that were out of bounds of the pattern recognition grid, and these cases were not included in the study. The Hoffer QST performed better with the S-O-S biometry than its predecessor, the Hoffer Q formula, and increased the percentage of eyes within ±0.50 D from 67.4% to 76.2% in the very short eyes and from

71.9% to 86.8% in the very long eyes. On the other hand, the Holladay 2 and the Holladay 2-NLR did not perform better than the Holladay 1 with the S-O-S biometry and achieved a lower percentage of eyes within ±0.50 D in the very short eyes (66.7% and 71.4% vs 76.7%, respectively) and in the very long eyes (75.5% and 88.7% vs 96.5%, respectively).

The benchmark standards for refractive outcomes after cataract surgery settled in 2009 by the National Health Service of the United Kingdom reported that 55% of eyes had to show a PE within ±0.50 D.[23] This target was based on measurements of the IOLMaster 500 or the Lenstar LS900. Large variations in the MAE and the percentage of postoperative eyes within ±0.50 D still exist. In 2008, Norrby identified 3 main parameters that contribute to the sources of errors in the refractive outcome of cataract surgery.[24] These included the preoperative estimation of the postoperative IOL position (35%), the postoperative refraction determination (27%), and the preoperative AL measurement (17%) with a MAE of 0.6 D for an eye of average dimensions. The advent of swept-source OCT biometry and the use of aspheric IOLs and of newer formulas capable of better predicting the postoperative lens position have markedly decreased the MAE and increased the number of eyes within ±0.50 D. The quality of refraction becomes primordial in achieving more accurate results.

In this study, we evaluated the use of the newer IOL power formulas with the S-O-S AL measurements; the overall percentage of eyes with a PE within ±0.50 D was higher than 80% (476/595) with the B II, BTAL, EVO, Hill-RBF, Hoffer QST, K6, Kane, Olsen, and PEARL-DGS formulas (Table 2). Tables 3–6 show that the newer formulas have raised that benchmark standard to almost 75% in short (AL <22.50 mm) and very short eyes (AL of 22.0 mm and shorter) and exceeding 80% in the long eyes (AL >24.50 mm) and very long eyes (25.0 mm and longer). Although there is a lot of controversy in the literature on what AL value constitutes a short eye or a long eye, we followed the recommendations of Shammas and Jabre who used the e-norms methodology to determine the normative values of biometric measurements and placed the normal AL measurement between 22.5 mm and 24.5 mm.[19]

Our study confirms the findings of Melles et al. who noted the Kane, Olsen, B II, and EVO formulas achieving a PE within ±0.50 D in over 80% of the 13 301 operated eyes with an SN60WF IOL and 5200 with an SA60AT IOL.[25] In their recent evaluation of 939 eyes, Debellemanière et al. also noted results exceeding 80% of eyes within ±0.50 D with the PEARL-DGS, K6, Olsen, and B II formulas.[12]

To the authors' knowledge, this is the first article that compares the newer formulas with the Argos SS-OCT biometer and its S-O-S AL measurements. The main limitation of this study is the relatively small number of very short and very long eyes that are the subgroups where, theoretically, the S-O-S AL methodology would increase accuracy over the single refractive index biometry. The study also does not include extremely short or extremely long eyes; the IOL power ranged between 6 and 30 D with no eyes shorter than 20.75 mm or longer than 29.65 mm.

In conclusion, all new formulas performed equal or better than the traditional formulas with the sum-of-segments biometry. The best overall results in the short and long eyes and in the very short and very long eyes were noted with the BTAL, EVO, Hoffer QST, K6, Olsen, and PEARL-DGS formulas, closely followed by the B II and Kane formulas.

WHAT WAS KNOWN

- Biometers using the sum-of-segments technology measure the optical path length of each segment of the eye and use a specific refractive index for each of these segments (cornea, aqueous depth, lens, and vitreous). As such, when there are variations in the relative lengths of these components, the axial length calculation is appropriately adjusted.
- The Haigis, Hoffer Q, Holladay 1, and SRK/T formulas are considered to be the traditional ones and are commonly used for IOL power calculation.
- Newer formulas, some of which are based on artificial intelligence or machine learning, are quickly gaining in popularity. These include the Barrett Universal II (B II), Barrett True Axial Length (BTAL), Emmetropia Verifying Optical (EVO), Hill-RBF, Hoffer QST, Holladay 2, Holladay 2-NLR, K6, Kane, Olsen, PEARL-DGS, T2, and VRF formulas.

WHAT THIS PAPER ADDS

- All new formulas performed relatively well with the sum-of-segments biometry.
- The best overall results in the short and long eyes and in the very short and very long eyes were noted with the BTAL, EVO, Hoffer QST, K6, Olsen, and PEARL-DGS formulas, closely followed by the B II and Kane formulas.

REFERENCES

1. Shammas HJ, Chan S. Precision of IOLMaster measurements. J Cataract Refract Surg 2010;36:1474–1478
2. Haigis W, Lege B, Miller N, Schneider B. Comparison of immersion ultrasound biometry and partial coherence interferometry for intraocular lens calculation according to Haigis. Graefes Arch Clin Exp Ophthalmol 2000;93:807–810
3. Shammas HJ, Hoffer KJ. Repeatability and reproducibility of biometry and keratometry measurements using a non-contact optical low-coherence reflectometer and keratometer. Am J Ophthalmol 2012;153:55–61
4. Wang L, Cao D, Weikert MP, Koch DD. Calculation of axial length using a single group refractive index versus using different refractive indices for each ocular segment: theoretical study and refractive outcomes. Ophthalmology 2019;126:663–670
5. Shammas HJ, Ortiz S, Shammas MC, Kim SH, Chong C. Biometry measurements using a new large-coherence-length swept-source optical coherence tomographer. J Cataract Refract Surg 2016;42:50–61
6. Omoto MK, Torii H, Masui S, Ayaki M, Tsubota K, Negishi K. Ocular biometry and refractive outcomes using two swept-source optical coherence tomography-based biometers with segmental or equivalent refractive indices. Sci Rep 2019;9:6557
7. Cooke DL, Cooke TL. Approximating sum-of-segments axial length from a traditional optical low-coherence reflectometry measurement. J Cataract Refract Surg 2019;45:351–354
8. Shammas HJ, Shammas MC, Jivrajka RV, Cooke DL, Potvin R. Effects on IOL power calculation and expected clinical outcomes of axial length measurements based on multiple vs single refractive indices. Clin Ophthalmol 2020;14:1511–1519
9. Barrett GD. An improved universal theoretical formula for intraocular lens implants. J Cataract Refract Surg 1993;19:713–720
10. Kane JX, Van Herdeen A, Atik A, Petsoglou C. Intraocular lens power formula accuracy: comparison of 7 formulas. J Cataract Refract Surg 2016; 42:1490–1500
11. Olsen T, Hoffman P. New concept for ray tracing-assisted intraocular lens power calculation. J Cataract Refract Surg 2014;40:764–773

12. Debellemanière G, Dubois M, Gauvin M, Wallerstein A, Luis FB, Radhika R, Saad A, Gatinel D. The PEARL-DGS formula: the development of an open-source machine learning-based thick IOL calculation formula. Am J Ophthalmol 2021;232:58–69
13. Sheard RM, Smith GT, Cooke DL. Improving the prediction accuracy of the SRK/T formula: the T2 formula. J Cataract Refract Surg 2010;36: 1829–1834
14. Voytsekhivskyy OV. Development and clinical accuracy of a new intraocular lens power formula (VRF) compared to other formulas. Am J Ophthalmol 2018;185:56–67
15. Haigis W. The Haigis formula. In: Shammas HJ, ed. Intraocular Lens Power Calculations. Thorofare, NJ: Slack, Inc.; 2004:41–57
16. Hoffer KJ. The Hoffer Q formula: a comparison of theoretic and regression formulas. J Cataract Refract Surg 1993;19:700–712; errata 1994;20:677 and 2007;33:2–3
17. Holladay JT, Praeger TC, Chandler TY, Musgrove KH, Lewis JW, Ruiz RS. A three-part system for refining intraocular lens power calculations. J Cataract Refract Surg 1988;14:17–24
18. Retzlaff JA, Sanders DR, Kraff MC. Development of the SRK/T intraocular lens implant power calculation formula. J Cataract Refract Surg 1990;16: 333–340; correction 528
19. Shammas HJ, Jabre JF. Validating e-norms methodology in ophthalmic biometry. BMJ Open Ophthalmol 2020;5:e000500
20. Holladay JT, Wilcox RR, Koch DD, Wang L. Review and recommendations for univariate statistical analysis of spherical equivalent prediction error for intraocular lens power calculations. J Cataract Refract Surg 2021;47:65–77
21. Wilcox RR. Comparing the variances of two dependent variables. J Stat Distrib Appl 2015;2:7
22. Yang CM, Lim DH, Kim HJ, Chung TY. Comparison of two swept source optical coherence tomography biometers and a partial coherence interferometer. PLoS One 2019;14:e0223114
23. Gale RP, Saldana M, Johnston RL, Zuberbuhler B, McKibbin M. Benchmark standards for refractive outcomes after NHS cataract surgery. Eye (Lond) 2009;23:149–152
24. Norrby S. Sources of error in intraocular lens power calculation. J Cataract Refract Surg 2008;34:368–376
25. Melles RB, Kane JX, Olsen T, Chang WJ. Update on intraocular lens calculation formulas. Ophthalmology 2019;126:1334–1335

Disclosures: *H.J. Shammas is a consultant for Alcon Laboratories, Inc. and receives licensing fees from various biometry companies for the Shammas post-LASIK formulas license. The other authors report no further conflict of interest.*

First author:
H. John Shammas, MD

Department of Ophthalmology, Keck School of Medicine of USC, Los Angeles, California