RESEARCH ARTICLE

Accuracy of Modern IOL Power Calculation Formulas in Eyes After Myopic Laser Vision Correction: A Stratified Axial Length Analysis

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ABSTRACT

PURPOSE: To evaluate the accuracy of modern intraocular lens (IOL) power calculation formulas in eyes with previous myopic laser vision correction (LVC), and to assess the impact of axial length (AL) on the formula performance.

METHODS: A total of 108 eyes were included, with 52 eyes in the AL less than 28 mm group and 56 eyes in the AL 28 mm or greater group. Refractive prediction errors (RPEs) were compared among nine post-LVC formulas: Haigis-TK, Haigis-TK_{CMAL} (incorporating Cooke-modified axial length [CMAL]), PEARL-DGS, Hoffer-QST TK, LISA TK, Barrett True-K TK, EVO TK, Haigis-L, and Shammas. Pearson correlation analysis was employed to evaluate the influence of AL and other biometric parameters on RPEs.

RESULTS: In the AL less than 28 mm group, no significant differences were observed between all formulas (all adjusted *P* > .05). However, in the AL 28 mm or greater group, Haigis-TK_{CMAL} demonstrated significantly lower root mean square absolute error (RMSAE) and mean absolute error (MAE) compared to the Hoffer-QST, Barrett True-K TK, Shammas, and Haigis-L (all adjusted *P* < .001). Similarly, the PEARL-DGS showed significantly lower RMSAE than the Barrett True-K TK, Shammas, and Haigis-L (both adjusted *P* < .001), and significantly lower MAE compared to the Barrett True-K TK and Haigis-L (both adjusted *P* < .001). The Haigis-TK_{CMAL} had the highest percentage of eyes with RPEs within ±0.50 diopters (D) (73.21%), whereas the PEARL-DGS had the highest percentage of eyes with RPEs within ±1.00 D (94.64%). A significant negative correlation between AL and RPE was found in most formulas, leading to a myopic shift in eyes with extremely long AL.

CONCLUSIONS: The performance of current post-LVC formulas was comparable in eyes with AL less than 28 mm, whereas the Haigis-TK_{CMAL} and PEARL-DGS demonstrated superior accuracy in eyes with AL 28 mm or greater. A notable myopic shift occurred in post-LVC eyes with extremely long AL, highlighting the need for careful formula selection in such cases.

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The calculation of intraocular lens (IOL) power in eyes that have undergone previous laser vision correction (LVC) has been a longstanding challenge.[1] One of the main reasons for IOL calculation inaccuracy is that LVC alters the ratio of the anterior-to-posterior corneal radius of curvature, leading to erroneous estimation of the corneal power and effective lens position (ELP).[2]

Advances in technology now allow for the measurement of posterior corneal curvature, facilitating a more accurate calculation of total corneal power.

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The total keratometry (TK), combining the telecentric keratometry and swept-source optical coherence tomography technology from the IOL Master700 (Carl Zeiss Meditec AG), is one of the latest technologies for measuring the total corneal power. The manufacturer asserts that TK is compatible with existing formulas and IOL constants. Promising results have been reported for TK-based IOL formulas in eyes with previous myopic LVC.[3-6] Despite improvements in corneal refractive power measurement accuracy, the prediction of ELP remains a great challenge.

In post-LVC eyes, although the corneal curvature is altered, the anterior segment anatomy remains unchanged, leading to increased errors in formulas that rely on corneal power for ELP calculation.[7] To address the ELP-related IOL prediction errors, Aramberri proposed the double-K method.[8] In the double-K formulas, pre-LVC corneal power is employed to estimate ELP, whereas post-LVC corneal power is used for IOL power calculation. However, the historical data required for the double-K method are not always available. An alternative strategy to reduce ELP-related errors is to avoid relying on corneal power to predict ELP, such as the Haigis-TK, PEARL-DGS, Haigis-L, and Shammas formulas.[4,9-11]

Another common source of error in IOL power calculations for eyes with previous myopic LVC arises from axial length (AL) measurements. It is well known that patients who undergo myopic LVC typically have longer AL. Previous research indicates that the optical biometry using the group refractive index tends to overestimate axial AL in long eyes, leading to IOL power underestimation and subsequent hyperopic errors.[12] Therefore, modern formulas have incorporated optimized algorithms, such as the Cooke-modified axial length (CMAL), to mitigate errors associated with AL.[11,13-15] However, most studies focus on eyes that have not undergone LVC, with limited data available on the performance of these formulas in post-LVC eyes with extremely long AL.

The purpose of this study was to evaluate the accuracy of modern IOL power calculation formulas in eyes with myopic LVC and to assess the impact of AL on the accuracy of these formulas.

PATIENTS AND METHODS

PATIENTS

This study was conducted in accordance with the principles of the Declaration of Helsinki and received approval from the ethics committee of Guangzhou Aier Eye Hospital. Patients were enrolled from Guangzhou Aier Eye Hospital, Changsha Aier Eye Hospital, and Wuhan Aier Eye Hospital. All patients underwent standard phacoemulsification by three experienced surgeons (ZW, Qiongyan Tang, YW) at these institutions.

Inclusion criteria were as follows: uneventful cataract surgery, previous myopic LVC (laser in situ keratomileusis/photorefractive keratectomy), postoperative manifest refraction at least 1 month postoperatively with corrected distance visual acuity (CDVA) of 20/40 or better, successful biometric measurements with the IOLMaster 700, and available TK data from the IOLMaster 700 before cataract surgery. Exclusion criteria included the presence of ocular surface disease, amblyopia, strabismus, intraoperative or postoperative complications, and retinal disorders or optic neuropathies resulting in postoperative CDVA worse than 20/40.

All patients underwent a comprehensive preoperative examination, including the assessments of CDVA, subjective refraction, slit-lamp examination, endothelial cell count, corneal topography, and dilated funduscopy. All biometric parameters were measured using the IOLMaster 700. Follow-up visits were scheduled at 1 day, 1 week, 2 weeks, and 1, 3, and 6 months postoperatively. Only patients with a minimum of 1 month of follow-up were included in this study. Postoperative subjective refraction was performed by experienced optometrists who were blinded to both patient information and the study protocol to prevent implementation bias.

Based on previous studies, an AL greater than 28 mm was defined as an extremely long eye.[16-18] Patients were further divided into two groups: AL less than 28 mm and AL 28 mm or greater.

IOL POWER CALCULATION METHODS

The PEARL-DGS (https://iolsolver.com/complex; accessed December 10, 2024), Hoffer-QST (https://hofferqst.com/; accessed December 10, 2024), LISA (http://lisa-iolcalculator.com/; accessed on March 2, 2024), Barrett True-K TK (https://calc.apacrs.org/Barrett_True_K_Universal_2105; accessed March 2, 2024), and EVO TK (https://www.evoiolcalculator.com/calculator.aspx; accessed on March 2, 2024) formulas were accessed using their respective online calculators. The myopic LVC versions of these formulas were used in this study. All optional variables, such as posterior keratometry (PK) and central corneal thickness, were entered into each calculator to assess each method at its full analytic capacity. The Haigis-TK formula, which combines the original Haigis formula with TK, was computed using Excel software (Microsoft Corporation). Because the original Haigis formula does not include an AL optimization algorithm, the Haigis-TK formula combined with CMAL was also evaluated and will be referred to as Haigis-TK_{CMAL}.[19,20]

TABLE 1

Patient Demographics

Parameter	Whole Sample Mean ± SD	Whole Sample Range	AL < 28 mm Mean ± SD	AL < 28 mm Range	AL ≥ 28 mm Mean ± SD	AL ≥ 28 mm Range
Age (year)	52 ± 8	34 to 70	50 ± 8	40 to 67	54 ± 8	34 to 70
AL (mm)	28.22 ± 2.30	23.72 to 33.1	26.17 ± 1.16	23.72 to 27.99	30.13 ± 1.19	28.03 to 33.1
Mean K (D)	38.42 ± 2.39	32.26 to 44.03	39.85 ± 2.00	34.94 to 44.03	37.10 ± 1.92	32.26 to 41.56
Mean TK (D)	37.83 ± 2.57	31.30 to 43.79	39.42 ± 2.11	34.16 to 43.79	36.36 ± 2.04	31.30 to 41.19
Mean PK (D)	5.74 ± 0.26	5.21 to 6.55	5.78 ± 0.25	5.21 to 6.25	5.71 ± 0.26	5.24 to 6.55
ACD (mm)	3.34 ± 0.36	2.64 to 4.62	3.35 ± 0.40	2.71 to 4.62	3.32 ± 0.32	2.64 to 3.88
LT (mm)	4.28 ± 0.46	3.14 to 5.68	4.22 ± 0.51	3.14 to 5.15	4.34 ± 0.42	3.59 to 5.68
CCT (μm)	485.91 ± 42.00	375 to 596	498.49 ± 44.77	412 to 596	474.22 ± 38.07	375 to 536
WTW (μm)	11.78 ± 0.43	10.70 to 13.20	11.89 ± 0.41	11.10 to 13.20	11.68 ± 0.43	10.70 to 12.70
IOL power implanted (D)	17.32 ± 3.66	8.50 to 24.50	19.68 ± 2.52	14.00 to 24.50	15.13 ± 3.16	8.50 to 22.50

ACD = anterior chamber depth; AL = axial length; CCT = central corneal thickness; D = diopters; IOL = intraocular lens; K = keratometry; LT = lens thickness; PK = posterior keratometry; SD = standard deviation; TK = total keratometry; WTW = white-to-white distance

The Haigis-L[9] and Shammas[10] formulas were also computed using Excel software.

For all formulas, the lens constants were obtained from the IOL Con website (https://iolcon.org/lensesTable.php; accessed on March 2, 2024).

Refractive Prediction Error (RPE)

The RPE was calculated by subtracting the predicted refraction from the actual postoperative refraction. A negative or positive RPE indicated a result that was more myopic or hyperopic than predicted by the individual formula. The root mean square absolute error (RMSAE), mean numerical error (MNE), mean absolute error (MAE), and median absolute error (MedAE) were calculated. The percentage of eyes with RPEs within ±0.50 and ±1.00 diopters (D) were computed for each method.

Statistical Analysis

Data analysis was performed using R statistical software (R Core Team, v 4.2.0). The normality of data distribution was evaluated by means of the Shapiro–Wilk test. The one-sample *t*-test was used to determine whether there was any significant deviation from zero in the MNE obtained with each formula. The non-parametric heteroscedastic analysis with Holm correction was used to compare the RMSAE, MedAE, and MAE between formulas.[21] The McNemar test with Holm correction was used to compare the percentage of eyes with RPEs within ±0.50 and ±1.00 D of the predicted refraction.[21] Correlation analyses were performed using Pearson and Spearman tests. A *P* value less than .05 was considered statistically significant.

RESULTS

Demographic Data

A total of 108 eyes from 81 patients were included in the study, with 52 eyes in the AL less than 28 mm group and 56 eyes in the AL 28 mm or greater group. **Table 1** presents the demographic and biometric data of the included patients. The types and constants of IOLs are summarized in **Table 2**.

Whole Group Analysis

Table 3 shows the results of IOL power calculation for all 108 eyes. Across the entire sample, the EVO TK and LISA TK formulas were the only two whose MNE (+0.01 D and +0.06 D, respectively) did not significantly deviate from zero (P = .852 and .358, respectively). Hyperopic errors were observed in the Hoffer-QST TK (+0.41 D), Haigis-TK (+0.41 D), Haigis-TK_{CMAL} (+0.14 D), and PEARL-DGS (+0.14 D) formulas, whereas myopic MNEs were noted in the Barrett True-K TK (-0.16 D), Haigis-L (-0.37 D), and Shammas (-0.40 D) formulas. The PEARL-DGS formula exhibited the lowest RMSAE (0.54 D), and the Haigis-TK_{CMAL} formula exhibited the lowest MAE (0.41 D) and MedAE (0.29 D). The non-parametric heteroscedastic analysis with Holm correction showed that the RMSAE of the PEARL-DGS and Haigis-TK_{CMAL} formulas was significantly lower than that of the Hoffer-QST TK and Haigis-L (both adjusted $P < .001$), The MAE of the Haigis-TK_{CMAL} formula was significantly lower than that of the Hoffer-QST TK and Haigis-L (both adjusted $P <$ .001) formulas. No significant differences in MedAE were observed among the formulas (all adjusted $P > .05$).

Table 3 also presents the percentage of eyes with RPEs within ±0.50 and ±1.00 D in the entire sample.

TABLE 2

Types and Constants of IOL Used in the Study

Manufacturer	Model	Design	No. of Implanted IOLs	A-Constant	Haigis Constant
Alcon	AcrySof SN60WF	Monofocal	22	119	a0 = -0.769, a1 = 0.234, a2 = 0.217
Alcon	Panoptix TFNT00	Diffractive multifocal	22	119.13	a0 = -0.036, a1 = 0.319, a2 = 0.175
Alcon	AcrySof SN6AD1	Diffractive multifocal	11	119	a0 = -0.385, a1 = 0.197, a2 = 0.204
Alcon	AcrySof Vivity DFT015	Wavefront-shaping EDOF	21	119.08	a0 = 1.476, a1 = 0.233, a2 = 0.122
Johnson & Johnson	ZXR00	Diffractive EDOF	24	119.056	a0 = -0.1886, a1 = 0.1716, a2 = 0.1977
Johnson & Johnson	ZCB00	Monofocal	8	119.3	a0 = -1.302, a1 = 0.21, a2 = 0.251

EDOF = extended depth-of-focus; IOL = intraocular lens

TABLE 3

Prediction Accuracy of the Formulas in the Whole Sample (N = 108)[a]

Parameter	MNE ± SD	RMSAE	MAE	MedAE	Max AE	% ±0.50 D	% ±1.00 D
PEARL-DGS	0.14 ± 0.52	0.54	0.43	0.38	1.48	63.89	94.44
Haigis-TKCMAL	0.14 ± 0.53	0.55	0.41	0.29	1.68	68.52	92.59
EVO TK	0.01 ± 0.61	0.61	0.48	0.43	1.68	56.48	92.59
LISA TK	0.06± 0.64	0.64	0.49	0.41	1.94	59.26	88.89
Haigis-TK	0.41 ± 0.52	0.66	0.53	0.49	1.87	53.70	88.89
Barrett True-K TK	-0.16 ± 0.68	0.70	0.55	0.46	2.05	55.56	87.96
Shammas	-0.40 ± 0.59	0.71	0.56	0.45	1.88	53.70	78.70
Hoffer-QST TK	0.41 ± 0.62	0.75	0.59	0.44	2.10	59.26	82.41
Haigis-L	-0.37 ± 0.70	0.79	0.61	0.50	2.88	50.00	82.41

CMAL = Cooke-modified axial length; D = diopters; Max AE = maximum absolute error; MAE = mean absolute error; MedAE = median absolute error; MNE = mean numerical error; RMSAE = root mean square absolute error; SD = standard deviation; TK = total keratometry
[a]Formulas are ranked by RMSAE.

The percentages of eyes with RPEs within ±0.50 and ±1.00 D ranged from 50.00% to 68.53% and from 78.70% to 94.44%, respectively. The McNemar test revealed a significant difference in the percentage of eyes with RPEs within ±1.00 D, but not within ±0.50 D. Specifically, the percentage of eyes with RPEs within ±1.00 D was significantly lower when using the Shammas compared to the PEARL-DGS (adjusted $P = .029$).

Stratified Analysis According to AL

Table 4 shows the prediction accuracy in the two subgroups classified by AL.

In the AL less than 28 mm group, hyperopic errors were observed for the Haigis-TK (+0.43 D), EVO TK (+0.30 D), Haigis-TK_{CMAL} (+0.28 D), Hoffer-QST TK (+0.26 D), LISA TK (+0.26 D), PEARL-DGS (+0.24 D), and Barrett True-K TK (+0.20 D), whereas myopic MNEs were noted in the Haigis-L (-0.22 D) and Shammas (-0.31 D). In the less than 28 mm group, no significant differences were observed in RMSAE, MAE, MedAE, and percentage of eyes with RPEs within ±0.50 and ±1.00 D (all adjusted $P > .05$).

In the AL 28 mm or greater group, the MNEs of the LISA TK (-0.14 D), PEARL-DGS (+0.05 D), and Haigis-TK_{CMAL} (+0.02 D) did not show a significant dif-

TABLE 4

Prediction Accuracy of the Formulas in the Subgroups Classified by AL[a]

Parameter	MNE ± SD	RMSAE	MAE	MedAE	Max AE	% ±0.50 D	% ±1.00 D
AL < 28 mm (n = 52)							
PEARL-DGS	0.24 ± 0.49	0.54	0.44	0.39	1.48	65.38	94.23
Barrett True-K TK	0.20 ± 0.53	0.56	0.43	0.37	1.62	61.54	96.15
EVO TK	0.30 ± 0.50	0.58	0.43	0.36	1.62	59.62	94.23
Haigis-TK_{CMAL}	0.28 ± 0.53	0.60	0.45	0.39	1.68	63.46	94.23
LISA TK	0.26 ± 0.57	0.62	0.50	0.38	1.60	53.85	90.38
Hoffer-QST TK	0.26 ± 0.57	0.62	0.50	0.40	1.63	65.38	90.38
Haigis-L	-0.22 ± 0.60	0.63	0.49	0.39	2.06	57.69	86.54
Shammas	-0.31 ± 0.57	0.64	0.51	0.37	1.51	57.69	82.69
Haigis-TK	0.43 ± 0.54	0.68	0.54	0.49	1.87	53.85	86.54
AL ≥ 28 mm (n = 56)							
Haigis-TK_{CMAL}	0.02 ± 0.51	0.50	0.38	0.27	1.46	73.21	91.07
PEARL-DGS	0.05 ± 0.53	0.53	0.43	0.36	1.40	62.50	94.64
EVO TK	-0.26 ± 0.58	0.63	0.51	0.47	1.59	53.57	91.07
Haigis-TK	0.40 ± 0.51	0.64	0.52	0.43	1.80	53.57	91.07
LISA TK	-0.14 ± 0.64	0.65	0.49	0.39	1.94	64.29	87.50
Shammas	-0.48 ± 0.60	0.76	0.61	0.49	1.88	50.00	75.00
Barrett True-K TK	-0.50 ± 0.65	0.81	0.66	0.50	2.05	50.00	80.36
Hoffer-QST TK	0.55 ± 0.64	0.84	0.66	0.47	2.10	53.57	75.00
Haigis-L	-0.51 ± 0.77	0.91	0.72	0.59	2.88	42.86	78.57

AL = axial length; CMAL = Cooke-modified axial length; D = diopters; MAE = mean absolute error; MedAE = median absolute error, Max AE = maximum absolute error; MNE = mean numerical error; RMSAE = root mean square absolute error; SD = standard deviation; TK = total keratometry
[a]*Formulas are ranked by RMSAE.*

ference from zero. Hyperopic errors were observed in the Hoffer-QST TK (+0.55 D) and Haigis-TK (+0.40 D) formulas, whereas myopic errors were noted in the Barrett True-K TK (-0.50 D), EVO TK (-0.26 D), Shammas (-0.48 D), and Haigis-L (-0.51 D) formulas. The Haigis-TK_{CMAL} formula exhibited the lowest RMSAE (0.50 D), MAE (0.38 D), and MedAE (0.27 D). The Haigis-TK_{CMAL} demonstrated significantly lower RMSAE than the Hoffer-QST TK, Barrett True-K TK, Shammas, and Haigis-L (both adjusted $P < .001$). Similarly, the PEARL-DGS showed significantly lower RMSAE compared to the Barrett True-K TK, Shammas, and Haigis-L (both adjusted $P < .001$). Additionally, the Haigis-TK_{CMAL} exhibited significantly lower MAE than the Barrett True-K TK, Shammas, and Haigis-L (both adjusted $P < .001$). Moreover, the PEARL-DGS had significantly lower MAE than the Barrett True-K TK and Haigis-L (both adjusted $P < .001$). Finally, the Haigis-TK_{CMAL} demonstrated significantly lower MedAE compared to the Barrett True-K TK and Haigis-L (both adjusted $P < .001$).

In the AL 28 mm or greater group, the Haigis-TK_{CMAL} showed the highest percentage of eyes with RPEs

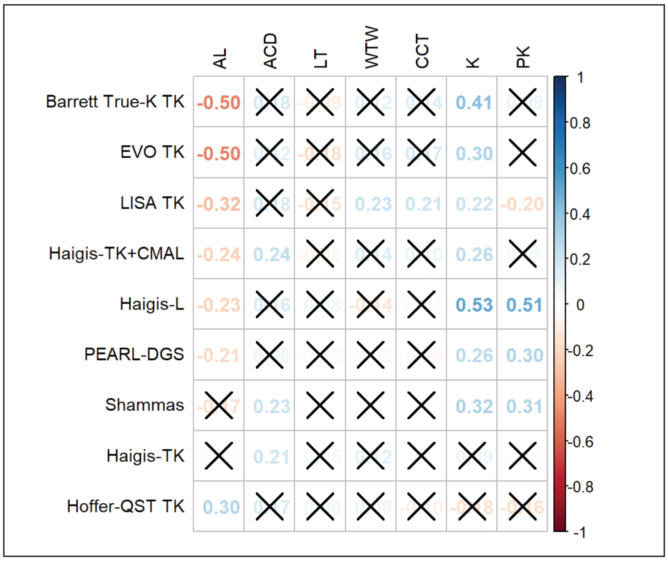

Figure 1. Correlation coefficients between the refractive prediction errors and biometric parameters across nine formulas. Statistical insignificance ($P > .05$) is indicated by an "X." ACD = anterior chamber depth; AL = axial length; CCT = central corneal thickness; CMAL = Cooke-modified axial length; K = keratometry; LT = lens thickness; MAE = mean absolute error; MNE = mean numerical error; PK = posterior keratometry; TK = total keratometry; WTW = white-to-white distance

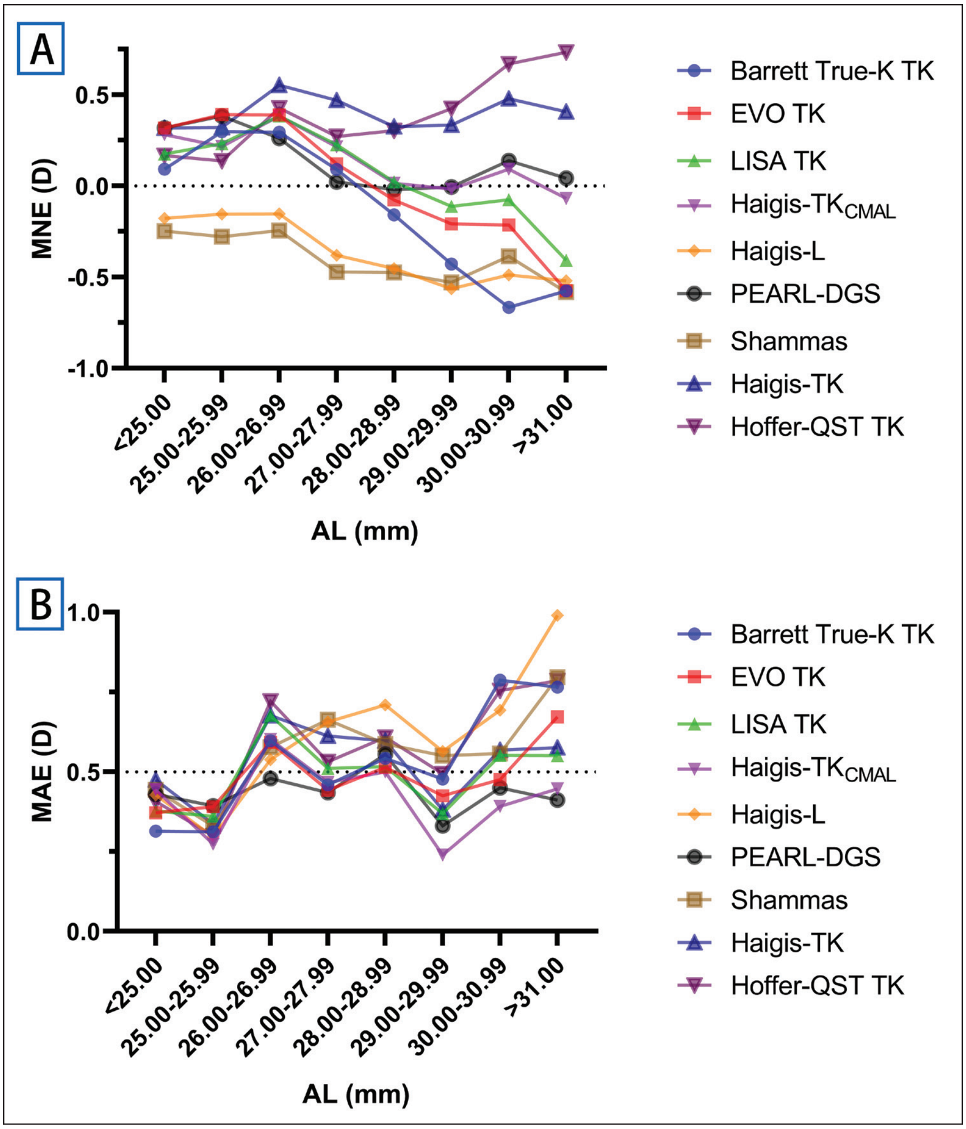

Figure 2. Smoothed line graphs of (A) mean numerical error and (B) mean absolute error for nine intraocular lens formulas versus axial length. AL = axial length; CMAL = Cooke-modified axial length; D = diopters; MAE = mean absolute error; MNE = mean numerical error; TK = total keratometry

within ±0.50 D (73.21%), and the PEARL-DGS exhibited the highest percentage of eyes with RPEs within ±1.00 D (94.64%). The McNemar test indicated that the Haigis-TK_{CMAL} formula achieved a significantly higher percentage of eyes with RPEs within ±0.50 D compared to the Haigis-L formula (adjusted $P = .049$). Regarding the percentage of eyes with RPEs within ±1.00 D, no significant differences were observed between formulas (all adjusted $P > .05$).

Correlation Between the RPEs and Biometric Parameters

Figure 1 displays the correlation between the RPEs and biometric parameters across the formulas. Significant negative correlations were observed between AL and the RPEs derived from the Barrett True-K TK, EVO TK, LISA TK, Haigis-TK_{CMAL}, Haigis-L and PEARL-DGS formulas (r = -0.50, -0.50, -0.32, -0.24, -0.23, and -0.11, respectively; all $P < .001$). Conversely, a significant positive correlation was found between AL and the RPEs derived from the Hoffer-QST formula (r = 0.30, P = 0.002). As for PK, significant positive correlations were observed with the RPEs derived from the Haigis-L, Shammas, and PEARL-DGS formulas (r = 0.51, 0.31, and 0.30, respectively; all $P < .05$), whereas a significant negative correlation was observed with the RPEs derived from the LISA formula (r = -0.20, P = .037). **Figure 2** depicts a smoothed line graph illustrating the MNE and MAE for each formula across AL.

DISCUSSION

Although LVC surgery produces excellent visual outcomes, it creates difficulties in the accurate calculation of IOL power.[1] In eyes that have undergone previous LVC, two primary reasons that contribute to challenges in IOL power calculation have been recognized for a long time: (1) inaccurate calculation of total corneal power and (2) problems in predicting the ELP.[2] However, it becomes even more daunting in eyes with a long AL, especially an extremely long AL.

Currently, the majority of optical biometers employ a group refractive index (1.3549) to convert the measured optical path length to AL, following the method described by Haigis.[9] Wang et al[12] found that using this group refractive index could overestimate the AL in long eyes, resulting in hyperopic errors in IOL calculations. As anticipated, the Haigis-TK formula yielded a hyperopic MNE of +0.41 D in our study, which is higher than the +0.19 D reported by Wang et al[4] and the +0.23 D reported by Lawless et al.[3] This discrepancy may be attributed to the considerably longer AL observed in our study (28.22 mm) compared to those reported by Wang et al (25.72 mm) and Lawless et al (26.01 mm).

The CMAL is an optimized AL correction algorithm that approximates the sum-of-segments AL, which considers different refractive indexes in each ocular segment.[19] It has been widely incorporated into modern IOL power calculation formulas, such as the EVO, LISA, and PEARL-DGS formulas.[11,14,15] Mo et al[22] found that combining the Haigis formula with CMAL achieved accuracy comparable to that of these new generation formulas in highly myopic virgin eyes. Encouragingly, the integration of the Haigis-TK with CMAL also significantly reduced hyperopic errors and demonstrated excellent accuracy in eyes with previous myopic LVC. Among all tested formulas, the Haigis-TK_{CMAL} formula exhibited the lowest overall MAE and MedAE of 0.41 and 0.29 D, respectively, and the highest proportion of RPEs within ±0.50 D (68.52%). In our study, Haigis-TK_{CMAL} also demonstrated superior accuracy in eyes with AL greater than 8 mm. These results highlight the significant potential of using the Haigis-TK combined with AL adjustment for IOL power calculation in post-myopic LVC eyes.

Our study found that the performance of current post-LVC formulas was comparable in the subgroup with AL less than 28 mm. However, significant differences emerged among the formulas when AL was 28 mm or greater. The Barrett True-K formula has long been recognized as one of the most accurate post-LVC formulas.[23-25] Indeed, when the AL was less than 28 mm, the Barrett True-K demonstrated excellent predictive outcomes, making it the preferred formula for these eyes. However, its accuracy declined when the AL exceeded 28 mm, consistent with the findings of Whang et al.[26] Despite incorporating measured posterior corneal power, the Barrett True-K TK still exhibited significantly lower accuracy compared to Haigis-TK_{CMAL} and PEARL-DGS in the extremely long AL subgroup.

The PEARL-DGS, EVO TK, and LISA TK formulas are recently developed thick lens formulas based on machine learning and CMAL correction.[11,14,15] Our results showed that the PEARL-DGS, EVO TK, and LISA TK formulas all performed well in calculating IOL power in eyes with previous LVC, achieving accuracy comparable to other modern LVC formulas. However, although no significant differences were observed between them, the PEARL-DGS consistently outperformed the EVO TK and LISA TK, whether in the overall cohort or in AL-stratified analyses. Given that all three formulas use the same AL correction, we believe that the superior performance of the PEARL-DGS is primarily due to its avoidance of using corneal power as a predictor of ELP. This may also explain why both the PEARL-DGS and Haigis-TK_{CMAL} were the best-performing formulas in our study. However, the current online version of the PEARL-DGS does not support compatibility with TK and it fails to consider the influence of the posterior corneal surface. As a result, a significant negative correlation was observed between PK and RPEs of the PEARL-DGS in this study. Nevertheless, despite incorporating measured posterior corneal power, the RPEs of the LISA formula still exhibited a negative correlation with PK. These results suggest that these formulas may introduce additional errors in eyes with extreme PK values.

The Hoffer-QST is the evolution of the Hoffer Q formula, using machine learning techniques to train an ELP prediction model based on data from 537 eyes.[27] An additional independent dataset, comprising 375 eyes with AL greater than 25 mm (mean AL = 26.37 ± 1.16 mm, range: 25.00 to 31.83 mm), is used to correct for AL correction. Recently, the Hoffer-QST introduced a post-LVC version that incorporates PK to calculate total corneal power. However, our study reveals that the accuracy of the Hoffer-QST TK in eyes with previous LVC is suboptimal, consistent with findings from prior research.[6,28] Specifically, in our cohort, the Hoffer-QST demonstrated significant hyperopic errors, particularly in eyes with AL 28 mm or greater, where the MNE reached +0.55 D. One possibility is that the training data for the Hoffer-QST in eyes with extremely long AL is still insufficient, resulting in overestimation of AL in such cases. We anticipate that future updates to the Hoffer-QST will include additional training data, which could improve its predictive accuracy.

In our study, the performance of the Shammas and Haigis-L formulas was inferior to that of the newer postmyopic LVC formulas. Specifically, the Shammas and Haigis-L demonstrated the lowest percentage of total eyes with RPEs within ±0.50 D (53.70% and 50.00%, respectively) and ±1.00 D (78.70% and 82.41%, respectively). Our results were consistent with previous studies.[6,29] Furthermore, it is noteworthy that the RPEs of the Shammas and Haigis-L formulas progressively shifted toward myopia with increasing PK. Therefore, the accuracy of these formulas may be further compromised in eyes with extremely steep PK.

Generally, the RPEs of formulas tend to exhibit a hyperopic shift as AL increases in virgin eyes.[12,30] However, contrary to our expectations, nearly all post-LVC formulas demonstrated a negative correlation between RPEs and AL, leading to a myopic shift in the subgroup with AL 28 mm or greater. We speculate on several reasons for this myopic shift phenomenon. One potential explanation is the prediction error associated with the ELP. The double-K formulas (eg, Barrett True-K TK and EVO TK) heavily rely on pre-LVC keratometry to predict ELP.[13,14] When historical data are unavailable, these formulas have to calculate the ELP using a hypothetical preoperative keratometry value (eg, 43.00 D). However, the keratometry value should vary with AL, which may contribute to the stronger negative correlation between RPEs and AL observed in the Barrett True-K TK and EVO TK compared to non-double-K formulas, such as the Haigis-TK, Haigis-L, Shammas, and PEARL-DGS. Additionally, spherical aberration may play a role in refractive changes. Bradley et al[31] found that the refraction changed by -0.36 D for every 1 µm increase in spherical aberration. LVC surgery for patients with high myopia often results in an increase in positive spherical aberration, which may lead to a myopic shift in post-LVC IOL power calculations.[32] The superior performance of the PEARL-DGS and Haigis-TK_{CMAL} in eyes with extremely long AL is likely attributable to the interaction of these two factors. Specifically, the reduction in ELP prediction errors and the compensatory effect of inherent hyperopic errors in eyes with extremely long AL may offset the myopic errors induced by other factors, such as spherical aberration.

This study has several limitations. First, due to the relatively small sample size, we included both eyes from the same patient in our analysis, which could introduce potential bias. Second, we included different types of IOLs, including monofocal, multifocal, and extended depth-of-focus IOLs. For multifocal and extended depth-of-focus IOLs, automated refraction may lead to more myopic refractive errors. Although we used subjective refraction to minimize the errors induced by automated refraction, we could not completely eliminate the potential systematic errors associated with these types of IOLs. Third, our follow-up period was relatively short. One month may be insufficient to achieve refractive stability in post-LVC eyes, which are more susceptible to refractive changes, such as corneal flattening. Fourth, we lacked historical data before LVC, which could have potentially improved the performance of the double-K formulas. Finally, the population in this study was limited to individuals of Chinese descent, and the generalizability of our findings to other ethnic groups requires further investigation. However, given the relatively small number of patients undergoing cataract surgery after LVC, numerous articles on this topic are also subject to these limitations. Future studies may wish to address these limitations.

CONCLUSION

The performance of current post-LVC formulas is comparable in the post-LVC eyes with AL less than 28 mm, whereas Haigis-TK_{CMAL} and PEARL-DGS demonstrated superior performance in eyes with AL 28 mm or greater. Surprisingly, a significant negative correlation was observed between AL and the RPEs derived from most existing post-LVC formulas, resulting in a myopic shift in eyes with extremely long AL following myopic LVC. Therefore, caution should be exercised when selecting IOL power calculation formulas in such cases.

AUTHOR CONTRIBUTIONS

Study concept and design (JL); data collection (JL, Qian Tan, ZW, YC, RJ, HC, Qiongyan Tang, YX, LX, DM, YW); analysis and interpretation of data (JL, Qian Tan, ZW, JO-U, DM, YW); writing the manuscript (JL); critical revision of the manuscript (Qian Tan, ZW, YC, RJ, HC, Qiongyan Tang, YX, LX, JO-U, DM, YW); statistical expertise (JL, Qian Tan, DM); administrative, technical, or material support (ZW, Qiongyan Tang, YW); supervision (ZW, YC, Qiongyan Tang, YW)

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