




Outcomes of the Haigis-L formula for calculating intraocular lens power in extreme long axis eyes after myopic laser in situ keratomileusis

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Abstract

Purpose To evaluate the accuracy of refractive prediction by the Haigis-L formula compared to four other IOL power calculation formulas in eyes with extremely long axial lengths (AL > 29.0 mm) after LASIK.

Setting Shanghai Eye Disease and Prevention Treatment Center, Shanghai, China.

Design Retrospective case series.

Methods Twenty-nine eyes from 19 patients were available for analysis. The primary outcome measure was the arithmetic refractive prediction error (RPE), defined as the difference between the actual postoperative refractive error and the intended formula-derived refractive target. The main outcome measure was the median absolute refraction prediction error (MedAE). The accuracy of the Haigis-L was compared with Barrett True K No History, Shammas-PL, SRK/T_{corrected K}, and Holladay 2_{corrected K} methods to calculate IOL power.

Results The Haigis-L formula had a significantly larger MedAE than Shammas-PL and SRK/T_{corrected K} formulas ($P = 0.005$ and $P = 0.015$, respectively), a smaller percentage of eyes within ± 1.50 diopter (D) of predicted error in refraction compared with Shammas-PL and SRK/T_{corrected K} formulas ($P = 0.014$ and $P = 0.005$, respectively). The refractive prediction errors of 6 eyes with corneal keratometry of less than 35 D by Haigis-L all had more than 1.95 D of myopic overestimation, while none of the other four methods resulted in an absolute error over 1.95 D.

Conclusions The Haigis-L formula was relatively accurate in predicting extreme long axis (>29.0 mm) eyes after myopic LASIK surgery but less accurate for eyes with extremely flat corneas (<35 D). SRK/T_{corrected K} and Shammas-PL performed better than the other methods for refractive prediction in this type of eyes.

Synopsis Haigis-L performed worse than SRK/T_{corrected K} and Shammas-PL in predicting IOL power in extremely long axis (>29.0 mm) eyes after myopic LASIK, especially with extremely flat corneas ($K < 35$ D).

Introduction

In recent decades, there has been a significant increase in patients who have undergone laser refractive surgery and

later developed a cataract [1]. Cataract surgery has entered a new era in which minimizing postoperative refractive surprise is mandatory. Patients' expectations for perfect vision after surgery are increasing, especially in patients with previous laser refractive surgery, which typically have higher expectations because they have had exceptional results from the previous surgery. Unfortunately, calculation errors for IOLs occur more often in patients with previous laser refractive surgery [2, 3].

The sources of calculation errors for IOLs after laser refractive surgery have been divided into three categories: instrument error, index of refraction error, and formula error [4, 5]. A significant source of instrument error occurs because most keratometers measure the central corneal radius of curvature in a 2.5- to 3.2-mm zone and assume a spherocylindrical cornea that is no longer true after myopic

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laser refractive surgery [6, 7]. Modification of the anterior corneal surface changes the refractive index of the cornea and produces errors of measurements that are based on a refractive index of 1.3375 [8]. A third source of inaccuracy, formula error, occurs because the widely used third generation IOL power formulas (Holladay, Hoffer Q, Sanders-Retzlaff-Kraff (SRK)/T) use corneal power to predict the pseudophakic anterior chamber depth (ACD) [2]. Together, unless corrected, these sources of error combine to generate inadequate IOL power, resulting in a postoperative hyperopic surprise.

Two categories of formulas have been developed to more accurately calculate IOL power in this group of patients, that is, those requiring information from prior laser surgery (historical) and those that use only current biometry (non historical) [4]. Usually, the data before LASIK are not available or reliable, and the literature has shown that nonhistorical approaches are superior and are currently widely used in clinical practice. The nonhistorical methods evaluated were the Haigis-L, Shammas post-LASIK (Shammas-PL), and Barrett True-K (no history) methods [5, 9–11]. The American Society of Cataract and Refractive Surgery (ASCRS) online calculator was developed to facilitate this process.

The double-K SRK/T is one of the most accurate methods [12–14] for IOL power calculation in eyes that had previous myopic LASIK but can only be used when historical data are available. The ratio of corneal anterior and posterior surface curvature changes after LASIK, the K measured by keratometer or IOLmaster is not the true K, it is based on the condition of normal corneal B/F ratio. So we used the corrected keratometric value ($K_{\text{corrected}} = 1.114 \times (K_{\text{flattest}} + K_{\text{steepest}})/2 + K_{\text{posterior}}$), as the double-k value for the SRK/T formula [15]. As well for the widely used fourth-generation IOL power formulas Holladay 2, we used the corrected K too.

Moreover, in extremely long eyes, especially eyes with staphyloma and/or axial lengths (ALs) >28 mm, intraocular lens (IOL) power calculation remains very challenging, and patients sometimes end up with residual ametropia over 1.00 D, which can significantly affect uncorrected visual acuity [16–18].

Although numerous studies have proven the accuracy of these formulas, to the best of our knowledge, no article has evaluated the accuracy of refractive prediction for these formulas in extreme long axis eyes after LASIK.

The purpose of this study was to evaluate the accuracy of refractive prediction with the Haigis-L formula compared with another four nonhistorical IOL power calculation formulas (Barrett True K No History, Shammas-PL, SRK/T_{corrected K}, and Holladay 2_{corrected K}) in eyes with an AL >29.0 mm after LASIK.

Methods

Patients

Patients having undergone previous LASIK with ALs longer than 29.0 mm were consecutively enrolled in this prospective analysis. All eyes had uneventful cataract extraction by one surgeon (YLW) in Shanghai General Hospital from Feb 2015 to Jul 2019. All surgical procedures were performed using standard phacoemulsification techniques through a superior clear corneal incision (3 mm), and foldable one-piece IOLs (ZCB00, AMO, Inc.) were successfully implanted into the capsular bag in all eyes. The exclusion criteria were (1) complicated cataract surgery or coexisting conditions that may confound postoperative refraction, eyes with an AL of <29.0 mm, (2) previous ocular surgeries except myopic LASIK, combined surgery, intraoperative and postoperative complications, active ocular infection, systemic diseases affecting vision, and (3) a follow-up time <1 month. (4) corrected distance visual acuity of 20/50 or better at 1 month or later after cataract surgery.

The study was approved by the ethics committee of Shanghai General Hospital and conducted according to the tenets of the Declaration of Helsinki. Written consent forms were obtained from all patients.

Preoperative measurements

Biometric measurements including anterior corneal keratometry (flattest meridian (K_f), steepest meridian (K_s)), anterior chamber depth (ACD, epithelium to lens), white-to-white (WTW) values, and ALs were taken using an IOLMaster 700 (Carl Zeiss Jena, Germany). In addition, measurements, including the keratometry of the posterior corneal surface (K_p), were recorded using Scheimpflug imaging (Pentacam Oculus HR, version 70100). Macular morphology was examined using SS-OCT (Topcon DRI OCT Triton; Topcon Corp.).

Intraocular lens power calculations

Haigis-L + anterior K

The Haigis-L formula was designed for eyes that have undergone previous myopic LASIK/PRK [5]. With the Haigis-L formula, the K value measured with the IOLmaster 700 was modified and then used for IOL power calculation.

Barrett True K No-History + anterior K, Shammas-PL + anterior K

The IOL power was calculated according to the formulas (Barrett True-K No-History/Shammas No-History) using a

program available on the Asia-Pacific Association of Cataract and Refractive Surgeons (APACRS) website^A. With these formulas, the K value was measured with the IOLmaster 700.

SRK/T + corrected K, Holladay 2 + corrected K

The corneal power was calculated according to the formula:

$K_c = 1.114 \times (K_f + K_s)/2 + K_p$, where K_c is the corrected keratometric value.

K_f (corneal keratometry flattest meridian) and K_s (corneal keratometry steepest meridian) were measured by the IOLmaster 700, and K_p (keratometry of posterior corneal surface) was measured by Pentacam. This K_c was then entered into the SRK/T post-LASIK formula and Holladay 2 formula. The IOLmaster 700 was used to calculate the IOL power with these two formulas.

Refractive prediction error

IOL power was calculated with the formulas using optimized constants from the User Group for Laser Interference Biometry (ULIB)^B database. The refractive outcome at 1-month post operation was recorded for each patient, when stable refraction can be expected [19]. The refractive prediction error (RPE) associated with each formula was calculated by subtracting the predicted refraction from the implanted IOL determined by each formula from the spherical equivalent of the postoperative manifest refraction. A negative RPE indicated a postoperative refractive result that was more myopic than that predicted by the individual formula. The absolute error (AE) was defined as the absolute value of the RPE.

The mean absolute error (MAE) and median absolute error (MedAE) were calculated. The percentage of eyes with RPEs within ± 0.50 D, ± 1.00 D, ± 1.50 D, and ± 2.00 D were computed for each method.

Statistical analysis

The data distribution for normality was checked using the Kolmogorov–Smirnov test. Continuous variables (e.g., RPE) were expressed as means and standard deviations. Categorical variables (e.g., gender) were expressed as numbers and frequencies. The differences in the refractive errors between the Haigis-L and the other four formulas were assessed using a normality test followed by a paired *t* test and Wilcoxon signed-rank test, as appropriate. A chi-square test was performed to compare the number of eyes with RPEs within ± 0.5 D, ± 1.0 D, ± 1.5 D, and ± 2.0 D between the Haigis-L and the other four formulas.

Statistical analysis was performed using SPSS software (version 22.0, SPSS Inc., Chicago, USA), and a probability of $<5\%$ ($P < 0.05$) was considered statistically significant.

Table 1 Summary of demographic and biometric data.

Parameter	Mean \pm SD	Range
Age (y)	56.05 \pm 8.80	43, 66
Axial length (mm)	30.71 \pm 1.14	29.07, 33.59
Anterior chamber depth (mm)	3.31 \pm 0.35	2.65, 4.15
K_f	36.23 \pm 2.03	31.81, 40
K_s	36.85 \pm 1.91	32.89, 40.52
K_{aver}	36.54 \pm 1.96	32.35, 40
K_p	-6.16 \pm 0.23	-6.70, -5.80
K_c	34.43 \pm 2.20	30.04, 38.76
Spherical equivalent (D)		
Preoperative	-13.02 \pm 4.58	
Postoperative	-2.75 \pm 0.82	
IOL power implanted (D)	17.29 \pm 3.81	10.5, 24

K_f Corneal keratometry flattest meridian, K_s corneal keratometry steepest meridian, $K_{aver} = (K_f + K_s)/2$, K_p keratometry of posterior corneal surface, $K_c = K_{aver} \times 1.114 + K_p$, IOL intraocular lens.

Results

Patient characteristics

Table 1 shows patient demographic and biometric data. A total of 29 eyes from 19 patients with ALs longer than 29 mm were included. The ALs ranged from 29.07 to 33.59 mm with a mean value of 30.71 mm. The average K-reading ($K_{aver} = (K_f + K_s)/2$) was 36.54 ± 1.96 D (ranging from 32.35 to 40.00 D). The average corrected K-reading (K_c) was 34.43 ± 2.20 D (ranging from 30.04 to 38.76 D). The implanted IOL power ranged from 10.5 to 24 D with a mean value of 17.29 D.

Accuracy of the four formulas in refractive prediction

Table 2 compares the Haigis-L formula with the Barrett True K No History, Shammas-PL, SRK/T_{corrected K}, and Holladay 2_{corrected K} IOL calculation formulas. The MPE was significantly higher with the Haigis-L formula than with the Shammas-PL, SRK/T_{corrected K}, and Holladay 2_{corrected K} formulas, no statistically significant difference in the MPE between the Haigis-L and Barrett True K No History methods. The MAE was significantly higher with the Haigis-L than with the Barrett True K No History, Shammas-PL, SRK/T_{corrected K} and Holladay 2_{corrected K}. The MedAE was significantly higher with the Haigis-L formula than with the Shammas-PL, SRK/T_{corrected K}, ($P = 0.005$, $P = 0.015$, respectively), no statistically significant difference in the MPE between the Haigis-L and Barrett True K No History, Holladay 2_{corrected K}.

The overall predictability of achieving results within ± 0.50 D, ± 1.00 D, ± 1.50 D, and ± 2.00 D of the target were

Table 2 Comparison of IOL power calculation formulas.

Parameter	Haigis-L	Barrett True-K No history	<i>P</i> value ^a	Shammas-PL	<i>P</i> value ^b	SRK/T _{corrected K}	<i>P</i> value ^c	Holladay 2 _{corrected K}	<i>P</i> value ^d
MPE ± SD (D)	-1.15 ± 1.05	-0.80 ± 0.56	0.056	-0.46 ± 0.66	<0.001	0.27 ± 0.83	<0.001	0.09 ± 0.97	<0.001
MAE ± SD (D)	1.20 ± 0.98	0.82 ± 0.53	0.036	0.65 ± 0.47	0.003	0.70 ± 0.50	0.01	0.77 ± 0.58	0.042
MedAE (D)	0.80	0.75	0.112	0.53	0.005	0.59	0.015	0.56	0.057

Boldface values indicate a statistically significant difference (*P* < 0.05).

MPE mean numerical prediction error, *MAE* mean absolute error, *MedAE* median absolute error.

^aDifference between Haigis-L and Barrett True-K No history.

^bDifference between Haigis-L and Shammas-PL.

^cDifference between Haigis-L and SRK/T_{corrected K}.

^dDifference between Haigis-L and Holladay 2_{corrected K}.

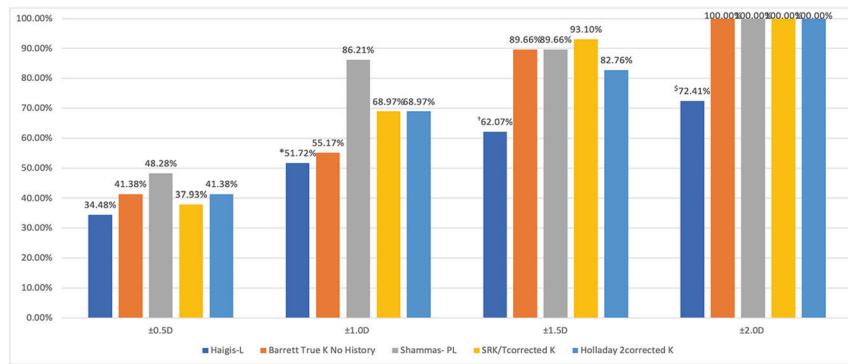


Fig. 1 Comparison of the percentage of eyes within certain ranges of prediction errors. *The Haigis-L had a significantly smaller percentage of eyes within ±1.0 D of RPE than did Shammas-PL (*P* = 0.005) and SRK/T_{corrected K} (*P* = 0.03), respectively. †The Haigis-L had a significantly smaller percentage of eyes within ±1.5 D of RPE than

did Barrett True-K No History (*P* = 0.014), Shammas-PL (*P* = 0.014), and SRK/T_{corrected K} (*P* = 0.005), respectively. ‡The Haigis-L had a significantly smaller percentage of eyes within ±2.0 D of RPE than did Barrett True-K No History, Shammas-PL, SRK/T_{corrected K}, (all *P* = 0.002) and Holladay 2_{corrected K} (*P* = 0.011).

34.48%, 51.72%, 62.07%, and 72.41%, respectively, for the Haigis-L formula (Fig. 1). There were significantly fewer eyes within ±2.0 D of the RPE with the Haigis-L than with the other four formulas (*P* = 0.002 (Barrett True K No History, Shammas-PL, and SRK/T_{corrected K} formulas), *P* = 0.011 (Holladay 2_{corrected K}), Fisher’s exact test). There were significantly fewer eyes within ±1.50 D of the RPE with the Haigis-L formula than with the Barrett True K No History, Shammas-PL, and SRK/T_{corrected K} formulas (*P* = 0.014, *P* = 0.033, and *P* = 0.01, respectively). There were significantly fewer eyes within ±1.00 D of the RPE with the Haigis-L formula than with the Shammas-PL and SRK/T_{corrected K} formulas (*P* = 0.005, *P* = 0.03, respectively).

In our series, six eyes had very flat post-LASIK K-readings (<35 D) (Table 3). In these cases, the refractive prediction errors by Haigis-L were all over 1.98 D with myopic overestimation (-1.98 D, -2.02 D, 2.22 D, -2.27 D, -3.17 D, and -3.30 D), while those obtained with the other two formulas using corrected K hyperopia overestimation were all <1.33 D. When the 6 eyes with very flat K values were excluded, there was no statistically significant

difference in the MAE or MedAE between the Haigis-L and Barrett True K No History, Shammas-PL, SRK/T_{corrected K}, and Holladay 2_{corrected K} formulas (Supplementary Table 1).

Discussion

Since its introduction in 2008, the Haigis-L method has been the easiest and most popular method [20], it is included in most optical measuring devices (e.g., IOLMaster) and also available in the ASCRS average method, which is easy for clinicians to directly obtain or refer to in first Impression. The calculated results are acceptable if the axial length is less than 28 mm and the corneal curvature is not too flat [9]. Hence, in extreme long axis eyes (AI > 29 mm) after LASIK, we compared the Haigis-L formula with another four nonhistorical IOL power calculation formulas (Barrett True K No History, Shammas-PL, SRK/T_{corrected K}, and Holladay 2_{corrected K}). We found that the Haigis-L formula was relatively accurate in predicting extreme long axis eyes after myopic LASIK surgery but less accurate for eyes

Table 3 Intraocular lens power calculation data of patients with $K < 35$ D.

Parameter	Case					
	1	2	3	4	5	6
Axial length (mm)	31.18	30.89	29.76	29.22	29.14	30.48
Anterior chamber depth (mm)	3.21	3.78	3.35	3.15	3.20	3.77
K_f value (D)	31.81	33.65	33.38	33.65	34.02	34.26
K_s value (D)	32.89	33.75	34.63	34.40	34.69	34.58
Average K -value (D, K_{aver})	32.35	33.70	34.00	34.02	34.32	34.42
K_p value (D)	-6.0	-5.9	-5.8	-6.2	-6.2	-5.9
K_c values (D)	30.04	31.64	32.08	31.70	32.08	32.44
IOL used (D)	23.0	19.5	21.5	24.0	23.5	19.5
PE (Haigis-L)	-3.30	-2.02	-2.27	-2.22	-1.98	-3.17
PE (Barrett True K)	-1.48	-0.95	-0.75	-0.36	-0.26	-1.52
PE (Shammas-PL)	-0.81	-0.45	-0.84	-0.8	-0.71	-1.79
PE (SRK/T _{corrected K})	+1.30	+1.29	+0.87	+0.93	+0.95	+1.33
PE (Holladay 2 _{corrected K})	+1.19	+1.07	+0.51	+0.46	+0.76	+0.03

K_f Corneal keratometry flattest meridian, K_s corneal keratometry steepest meridian, $K_{aver} = (K_f + K_s)/2$, K_p keratometry of posterior corneal surface, $K_c = K_{aver} \times 1.114 + K_p$, K_c corrected K -value, IOL intraocular lens, PE prediction error.

with extremely flat corneas (<35 D). SRK/T_{corrected K} and Shammas-PL performed better for refractive prediction in this set of eyes. To our knowledge, this is the first study to investigate the accuracy of refractive prediction with the Haigis-L formula compared with another four nonhistorical IOL power calculation formulas in eyes with an AL >29.0 mm after LASIK. Our findings will provide a reference for the selection of a formula for IOL power calculation for long axis eyes with a LASIK history, especially those patients with flat corneas.

Compared with the combinations of methods requiring clinical history, the Shammas-PL, Haigis-L, and Masket methods were less affected by axial length and had superior overall accuracy in both axial length subgroups (>27 and <27 mm) [21]. In view of the inherent limitations of the clinical history-based methods, we were particularly interested in methods that require only current measured values, such as the Haigis-L, Barrett True K No History, Shammas-PL, SRK/T_{corrected K}, and Holladay 2_{corrected K} methods.

In this study, the Haigis-L formula yielded a MedAE of 0.80 D, and 34.48% of eyes within ± 0.5 D of the RPE. In previous studies that investigated the accuracy of IOL power calculation formulas in eyes with prior myopia [11, 21–24], the Haigis-L formula produced MedAEs of 0.26 D to 0.62 D and 40.2 to 69.0% of eyes within ± 0.5 D of the RPE. Our results with the Haigis-L formula were slightly higher than the findings reported in the literature, the accuracy of Haigis-L formula for extreme long axis eyes

(especially for those with flatter corneal curvature (<35 D)) seems to be slightly worse than eyes with axis <29 mm. The Haigis-L formula had the lowest percentages with a RPE within ± 1.50 D (62.07%) compared with all other methods.

The Barrett True-K formula gave results better than or similar to those of various methods and formulas from the ASCRS online calculator with previous myopic LASIK or PRK correction [11]. In our study, with the Barrett True-K No History formula results were relatively balanced and had little correlation with corneal curvature (Supplementary Fig. 1).

McCarthy et al. [21] found that in very flat (<33.0 D) or very steep (>43.0 D) eyes, the keratometry was inconsistent with the expected refractive change or the axial length. In this study, the RPEs by Haigis-L were all over 1.95 D with myopic overestimation in the 6 eyes with keratometry <35.0 D, while the other two formulas using corrected K hyperopia overestimation all yielded RPEs <1.33 D. In our previous study [25] on the accuracy of the Haigis and SRK/T formulas in eyes longer than 29.0 mm, we found that SRK/T worked better for long eyes with flat corneas than did the Haigis formula. The SRK/T in particular is adversely affected by eyes that have flat or steep keratometry [26]. In our study, use of the corrected keratometric value ($K_c = 1.114 \times (K_f + K_s)/2 + K_p$) yielded accurate prediction results for extreme long axis eyes even with very flat corneas.

Our study has some limitations: (1) Because only eyes with ALs longer than 29 mm with previous LASIK surgery and subsequent cataract surgery were included, the functional vision was significantly improved in all patients after cataract surgery, the number of patients in this study was small. But on the other hand, we excluded eyes with poor corrected distance visual acuity after cataract surgery, because such eyes usually have larger measurement errors due to eccentric fixation. This ensured our study with high reference. (2) Postoperative refractive outcome was recorded at 1-month post operation in this study, which could be too early with a relatively large 3-mm corneal incision. Nevertheless, studies have shown that stable corneal curvature can be expected at 1 month after surgery with this kind of clear corneal incision [27, 28]. Moreover, longer time postoperatively may reflect different results in terms of IOL calculations, fibrotic changes of the capsule postoperatively may affect effective lens placement [19]. Future studies with longer follow-up times are needed to support our results.

In conclusion, our results show that for eyes with previous myopic LASIK correction, the Haigis-L formula was relatively accurate in predicting extreme long axis (>29 mm) eyes after myopic LASIK surgery but less accurate for eyes with extremely flat corneas (<35 D). However, the SRK/T_{corrected K} and Shammas-PL formulas performed better in refractive prediction in this set of eyes.

Future studies with large numbers should be completed to reinforce our findings.

Summary

What was known before

- It is difficult to predict accurate IOL power in eyes with previous corneal refract surgery, especially in extreme long axis eyes.
- The Haigis-L formula has been shown to be accurate in predicting IOL power in patients who had previous myopic laser refractive surgery.

What this study adds

- The Haigis-L formula was relatively accurate in predicting IOL power in the extremely long axis (\hat{a} 29.0 mm) eyes after myopic LASIK surgery, performed worse than SRK/T_{corrected K}, and Shammer-PL.
- In eyes with the extremely flat cornea (average $K < 35$ D), Haigis-L all had more than 1.95 D of myopic over-estimation, while none of the other four methods (Barrett True K No History, Shammass-PL, SRK/T_{corrected K}, and Holladay 2_{corrected K}) resulted in an AE over 1.95 D.

Author contributions Authors XLF, YLW, and XC conceived and designed the study. Authors XLF, SYB and YPD analysed and interpreted the data. Authors XLF, WWX, and YLW wrote the paper. All authors reviewed and provided critical feedback for the final paper.

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Compliance with ethical standards

Conflict of interest The author declares no competing interests.

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