

Theoretical Accuracy of the Raytracing Method for Intraocular Calculation of Lens Power in Myopic Eyes after Small Incision Extraction of the Lenticule

Theoretische Genauigkeit der Raytracing-Methode zur intraokularen Berechnung der Linsenstärke bei myopen Augen nach einer Small Incision Lenticule Extraction



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ABSTRACT

Aim To evaluate the accuracy of the raytracing method for the calculation of intraocular lens (IOL) power in myopic eyes after small incision extraction of the lenticule (SMILE).

Methods Retrospective study. All patients undergoing surgery for myopic SMILE between May 1, 2020, and December 31, 2020, with Scheimpflug tomography optical biometry were eligible for inclusion. Manifest refraction was performed before and 6 months after refractive surgery. One eye from each patient was included in the final analysis. A theoretical model was invited to predict the accuracy of multiple methods of lens power calculation by comparing the IOL-induced refractive error at the corneal plane (IOL-Dif) and the SMILE-induced change of spherical equivalent (SMILE-Dif) before and after SMILE surgery. The prediction error (PE) was calculated as the difference between SMILE-Dif-IOL-Dif. IOL power calculations were performed using raytracing (Olsen Raytracing, Pentacam AXL, software version 1.22r05, Wetzlar, Germany) and other formulae with historical data (Barrett True-K, Double-K SRK/T, Masket, Modified Masket) and without historical data (Barrett True-K no history, Haigis-L, Hill Potvin Shammas PM, Shammas-PL) for the same IOL power and model. In addition, subgroup analysis was performed in different anterior chamber depths, axial lengths, back-to-front corneal radius ratio, keratometry, lens thickness, and preoperative spherical equivalents.

* These authors contributed equally to this work.

Results A total of 70 eyes of 70 patients were analyzed. The raytracing method had the smallest mean absolute PE (0.26 ± 0.24 D) and median absolute PE (0.16 D), and also had the largest percentage of eyes within a PE of ± 0.25 D (64.3%), ± 0.50 D (81.4%), ± 0.75 D (95.7%), and ± 1.00 D (100.0%). The raytracing method was significantly better than Double-K SRK/T, Haigis, Haigis-L, and Shammas-PL formulae in post-operative refraction prediction (all $p < 0.001$), but not better than the following formulae: Barrett True-K ($p = 0.314$), Barrett True-K no history ($p = 0.163$), Masket ($p = 1.0$), Modified Masket ($p = 0.806$), and Hill Potvin Shammas PM ($p = 0.286$). Subgroup analysis showed that refractive outcomes exhibited no statistically significant differences in the raytracing method (all $p < 0.05$).

Conclusion Raytracing was the most accurate method in predicting target refraction and had a good consistency in calculating IOL power for myopic eyes after SMILE.

ZUSAMMENFASSUNG

Ziel Das Ziel dieser Studie war es, die Genauigkeit der Raytracing-Methode zur Berechnung der Intraokularlinsenstärke (IOL-Stärke) bei myopen Augen nach der SMILE-Operation (Small Incision Lenticule Extraction) zu bewerten.

Methoden Es handelt sich um eine retrospektive Studie. Alle Patienten, die sich zwischen dem 1. Mai 2020 und dem 31. Dezember 2020 einer SMILE-Operation aufgrund von Myopie unterzogen haben und bei denen eine Scheimpflug-Tomografie-Optikbiometrie durchgeführt wurde, waren für die Studie geeignet. Eine Manifestrefraktion wurde vor und 6 Monate nach der refraktiven Chirurgie durchgeführt. Ein Auge jedes Patienten wurde in die abschließende Analyse einbezogen. Ein theoretisches Modell wurde verwendet, um die Genauigkeit mehrerer Methoden zur Berechnung der Linsenstärke vorherzusagen, indem der IOL-induzierte Refraktionsfehler in der Hornhautebene (IOL-Dif) und die SMILE-induzier-

te Änderung des sphärischen Äquivalents (SMILE-Dif) vor und nach der SMILE-Operation verglichen wurden. Der Vorhersagefehler (PE) wurde als Differenz zwischen SMILE-Dif und IOL-Dif berechnet. Die IOL-Berechnungen wurden unter Verwendung von Raytracing (Olsen Raytracing, Pentacam AXL, Softwareversion 1.22r05, Wetzlar, Deutschland) und anderen Formeln mit historischen Daten (Barrett True-K, Double-K SRK/T, Masket, Modified Masket) sowie ohne historische Daten (Barrett True-K ohne Historie, Haigis-L, Hill Potvin Shammas PM, Shammas-PL) für dieselbe IOL-Stärke und dasselbe Modell durchgeführt. Darüber hinaus wurde eine Untergruppenanalyse in Bezug auf verschiedene Vorderkammertiefen, Achslängen, Verhältnis von Rück- zu Vorderkornealradius, Keratometrie, Linsendicke und präoperative sphärische Äquivalente durchgeführt.

Ergebnisse Insgesamt wurden 70 Augen von 70 Patienten analysiert. Die Raytracing-Methode hatte den kleinsten durchschnittlichen absoluten PE ($0,26 \pm 0,24$ dpt) und den medianen absoluten PE (0,16 dpt) und hatte auch den größten Anteil an Augen mit einem PE von $\pm 0,25$ dpt (64,3%), $\pm 0,50$ dpt (81,4%), $\pm 0,75$ dpt (95,7%) und $\pm 1,00$ dpt (100,0%). Die Raytracing-Methode war signifikant besser als die Formeln Double-K SRK/T, Haigis, Haigis-L und Shammas-PL in der Vorhersage der postoperativen Refraktion (alle $p < 0,001$), aber nicht besser als die folgenden Formeln: Barrett True-K ($p = 0,314$), Barrett True-K ohne Historie ($p = 0,163$), Masket ($p = 1,0$), Modified Masket ($p = 0,806$) und Hill Potvin Shammas PM ($p = 0,286$). Die Untergruppenanalyse zeigte, dass die refraktiven Ergebnisse in der Raytracing-Methode keine statistisch signifikanten Unterschiede aufwiesen (alle $p < 0,05$).

Schlussfolgerung Raytracing war die genaueste Methode zur Vorhersage der Zielrefraktion und zeigte eine gute Konsistenz bei der Berechnung der IOL-Stärke für myope Augen nach SMILE.

Introduction

With the increasing number of patients with ametropia, more people choose corneal refractive surgery. Small incision lenticule extraction (SMILE) has been one of the most popular refractive correction surgeries all over the world. It is expected to offer better biomechanical stability than procedures that involve flap creation, such as laser *in situ* keratomileusis (LASIK) or photorefractive keratotomy (PRK). Patients who have had SMILE surgery still cannot avoid future cataract surgery with aging. However, studies have failed to compare the accuracy of intraocular lens (IOL) power calculation formulae in eyes after SMILE.

There are two main sources of error in calculating IOL power after refractive surgery, including corneal power measurement error [1,2] and effective lens position (ELP) error [3]. The error of corneal power is in itself a two-sided issue. First, corneal topographers do not consider the change of the back-to-front corneal radius ratio (B/F ratio) that occurs after excimer laser ablation of the

anterior cornea. Thus, an inappropriate refractive index is used for calculating corneal power. Second, most manual topographers do not authentically measure the curvature of the central cornea, which is the flattest area after myopic ablation. The second main error is the estimation error of ELP. Although this is challenging in virgin eyes as well, it imposes additional challenges after refractive surgery, especially in formulae that use corneal power to estimate ELP [4]. All these errors lead to the underestimation of IOL power in myopic ablation and the opposite in hyperopic ablation.

Over the past few decades, several formulae have been described to address the accuracy of the IOL power calculation in eyes after myopic LASIK/PRK surgery. These formulae are divided into two categories according to whether or not to use the historical data before refractive surgery [3]. The formulae with historical data would require knowledge of preoperative data and stable postoperative refractions [3]. For example, surgically induced refractive change at the corneal plane is needed in Barrett True-K, Masket, or Modified Masket method [5,6]. In addition, pre-refrac-

tive surgery keratometry is required in the Double-K or clinical history method (CHM) [7–9]. CHM was considered the gold standard to calculate IOL power for eyes with previous LASIK/PRK [8]. However, as the historical data are not available or not credible, the formulae with historical data were proven to be not as accurate as thought. Since then, several formulae that do not rely on historical data have been proposed, including Barrett True-K no history, Hill Potvin Shammass PM, Haigis-L, Shammass-PL, and others [5, 10–14]. However, most of them are derived based on empirical regression analysis, resulting in the accuracy of IOL power calculations for patients after excimer surgery being lower than that of the virgin eyes [15–17].

Theoretically, the optical raytracing method based on the Snell law is a better solution in calculating IOL power after refractive surgery [18]. The raytracing method relies on the true corneal curvature to calculate the corneal power, which is not subject to the corneal power error [19]. Moreover, unlike in the case of third-generation theoretical formulae, the raytracing method does not use the corneal power to evaluate ELP [20]. Thus, the ELP error could also be ignored. Previous studies indicated that the raytracing method had an encouraging outcome in calculating IOL power for eyes after myopic LASIK/PRK surgery [21–23]. The purpose of this study was to evaluate the accuracy of the raytracing method that was performed by a rotating Scheimpflug camera combined with a Placido disc corneal topographer in calculating IOL power for myopic eyes after SMILE surgery.

Patients and Methods

Ethical Approval

This study was performed in accordance with the ethical standards stated in the 2013 Declaration of Helsinki and was approved by the Tianjin Eye Hospital ethics committees. Informed written consent was obtained from all participants.

Study Participants

This was a retrospective study that comprised patients who had SMILE refractive surgery for treatment of myopic and/or myopic astigmatism between May 1, 2020, and December 31, 2020, at Tianjin Eye Hospital. Inclusion criteria were (1) age 18 years or older; (2) no complications during or after SMILE surgery; (3) manifest refraction was performed at least 6 months postoperatively; and (4) best-corrected distance visual acuity (BCVA) of 20/25 or better at 5 m distance. Exclusion criteria were (1) the presence of active ocular disease; (2) previous ocular trauma or ocular surgery; and (3) systemic diseases such as diabetes or connective tissue disorders.

Surgery and Measurement

The same surgeon performed all SMILE procedures using a femto-second laser platform (VisuMax, Carl Zeiss, AG, Jena, Germany) with a 500-kHz repetition rate. The parameters used included an optical zone of 6.5 to 7.0 mm, a cap diameter of 7.5 to 8.0 mm, a predetermined cap thickness of 120 μ m, and an energy of 125 to 160 nJ. The side cut was placed at the 12-o'clock position of the cornea with an angle of 90 degrees and a circumferential width

of 2.0 to 3.0 mm. Following removal of the lenticule, the incision was flushed with balanced salt solution (Alcon Laboratories, Inc., TX, USA). The optical measurement was performed by Scheimpflug tomography (Oculus, Pentacam AXL, Wetzlar, Germany) before and 6 months after SMILE surgery. Axial length was measured by a noncontact biometer (Lenstar LS-900; Haag-Streit, AG, Koeniz, Switzerland).

IOL Power Calculation and Optimization

The preoperative IOL power calculation was calculated by the raytracing method directly from Scheimpflug tomography (Pentacam AXL, Wetzlar, Germany), which utilized a C constant to predict the postoperative IOL position. The raytracing calculations were performed using Pentacam AXL software (version 1.22r05) over a 4.0-mm optical zone directly by the built-in calculation of “Olsen Raytracing”. The refractive prediction errors (PEs) and IOL powers after SMILE surgery of Double-K SRK/T, Hill-Potvin Shammass, Barrett True-K no history, and raytracing were also performed directly by using Pentacam. The following formulae were back-calculated in the American Society of Cataract and Refractive Surgery (ASCRS) calculator: Masket method, Modified Masket method, Barrett True-K, Haigis-L, and Shammass-PL formulae. Lens factors (constants) of each formula were optimized by zeroing out the mean arithmetic PE. Haigis constants (a_0 , a_1 , a_2) were obtained from the User Group for Laser Interference Biometry website.

Outcomes Measures

IOL power calculations were performed using the raytracing method before the SMILE procedure, and the IOL power corresponding to the minimum myopic refractive error was recorded. Six months after the SMILE surgery, the same IOL power was selected and the IOL-induced refractive error at the corneal plane was calculated using the raytracing method, formulae with historical data (Barrett True-K, Double-K SRK/T, Masket, Modified Masket), and formulae without historical data (Barrett True-K no history, Haigis-L, Hill Potvin Shammass PM, Shammass-PL). The difference between the IOL-induced refractive error at the corneal plane before and after the surgery was defined as IOL-Dif. In addition, the alteration of the spherical equivalent before and after the SMILE procedure was calculated in manifest refraction at the corneal plane (SMILE-Dif). The refractive PE was defined as the difference between the SMILE-Dif and IOL-Dif with different methods and formulae for the same IOL power and model (SN60WF, Alcon Laboratories, TX, USA) [24].

For example, if the patient's refraction was -6.00 D (spherical equivalent) before SMILE surgery, the IOL power corresponding to the -0.21 D was $+15$ D, then -0.21 D was recorded as the minimum myopic refractive error. Six months after the SMILE surgery, the same $+15$ D IOL power was selected and the IOL-induced refractive error at the corneal plane was $+6.76$ D. Then, the IOL-Dif can be calculated as $+6.76$ D $- (-0.21$ D), which was $+6.97$ D. In the meanwhile, the patient's refraction was also required post-operation, which in this case was $+0.50$ DS, and that made the SMILE-Dif 6.5 D. Taken together, the PE equaled 0.47 D.

The primary outcome was the mean arithmetic prediction error (ME). In order to eliminate the bias of the lens factor, the MEs

for each formula was made to equal zero by changing the constant individually for each formula [25]. The median absolute prediction error (MedAE) and mean absolute prediction error (MAE) were defined as the median and mean arithmetic value that turn all negative PEs into positive values, respectively. In addition, the percentages of eyes within PEs of ± 0.25 D, ± 0.50 D, ± 0.75 D, and ± 1.00 D were also calculated for different formulae. Subgroup analysis was performed according to different anterior chamber depths (cutoff value 3.5 mm), axial lengths (cutoff value 26 mm), B/F ratio (cutoff value 73%), keratometry (cutoff value 38 mm), lens thickness (cutoff value 3.5 mm), and preoperative refraction (cutoff value -6 D).

Statistical Analysis

The Kolmogorov-Smirnov test was used to check the data distribution for normality. Each group of statistics with a normal distribution was shown with a mean (standard deviation), while those with non-normal distribution were indicated with a median (lower quartiles, upper quartiles). For the analysis of MedAE and MAE differences, Friedman signed-rank or Student's t-test was used. Bonferroni correction was applied for multiple tests. The percentages of the targeting refraction within ± 0.25 D, ± 0.50 D, ± 0.75 D, and ± 1.00 D were compared using Cochran's Q test. Statistical analysis was performed using the Statistical Product and Service Solutions (SPSS, version 24 for Mac). A probability level of 0.05 was considered statistically significant.

Results

Baseline Data

A total of 70 eyes of 70 patients were eventually included in this study. The mean age was 21 ± 3 (18 ~ 32) years and 36 patients (51.4%) were female. All 70 eyes were from the same side of the patient and had available manifest refraction data before and

► **Table 1** Baseline characteristics.

Parameter	Values
Age (years)	21.00 ± 3 (18–32)
Sex (male:female)	34:36
Preoperative SE (D)	-5.67 ± 1.49 ($-9.50 \sim -2.125$)
Postoperative SE (D)	-0.23 ± 0.08 ($-0.75 \sim 0.25$)
Axial length (mm)	26.16 ± 0.88 (24.58 ~ 28.00)
Anterior chamber depth (mm)	3.80 ± 0.23 (3.31 ~ 4.25)
Preoperative K (D)	42.95 ± 1.25 (40.25 ~ 46.60)
Postoperative K (D)	38.56 ± 1.62 (34.55 ~ 42.05)
Lens thickness (mm)	3.50 ± 0.15 (3.10 ~ 3.84)
White-to-White (mm)	11.87 ± 1.43 (11.00 ~ 12.80)
B/F ratio (%)	73.59 ± 2.29 (69.10 ~ 79.80)
SE: spherical equivalent; D: diopter; K: keratometry; B/F ratio: back-to-front corneal radius ratio	

after 6-month SMILE. The mean preoperative spherical equivalent was -5.67 ± 1.49 D ($-9.50 \sim -2.125$ D). The mean IOL power before refractive surgery by the raytracing method was 14.67 ± 2.20 D (11.0 ~ 19.5 D) with a mean predicted spherical equivalent of -0.18 ± 0.09 D ($-0.33 \sim 0.02$ D) (all detailed data of IOL-Dif and SMILE-Dif data are listed in Supplementary Table 1). The baseline characteristics of this study cohort are summarized in

► **Table 1.**

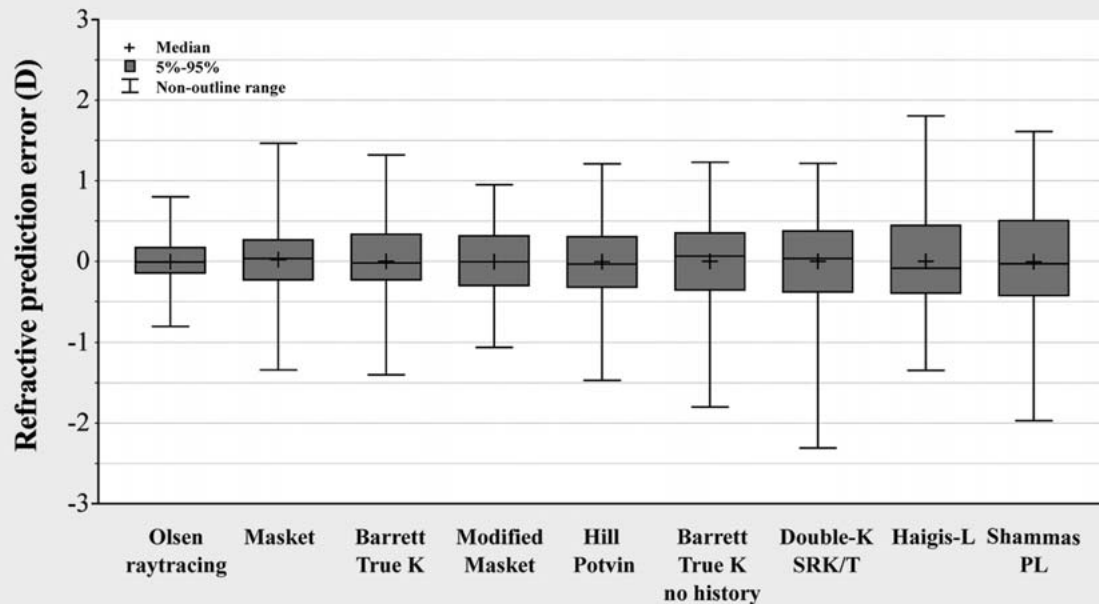
Outcomes of Different Formulae

► **Table 2** shows the outcomes of the including nine formulae. The raytracing method produced the lowest MAE (0.26 ± 0.24 D) and MedAE (0.16 D) in refractive prediction, which was lower than

► **Table 2** Refractive outcomes of different formulae (number = 70).

Formulae	Absolute prediction error (D)		Proportion of PE% (number)			
	Mean \pm SD	Median (Q1, Q3)	± 0.25 D	± 0.50 D	± 0.75 D	± 1.00 D
With history data						
Masket	0.36 ± 0.31	0.26 (0.14, 0.48)	50.0 (35)	77.1 (54)	88.6 (62)	95.7 (67)
Modified Masket	0.35 ± 0.26	0.31 (0.15, 0.50)	41.4 (29)	75.7 (53)	91.4 (64)	98.6 (69)
Barrett True-K	$0.40 \pm 0.34^*$	0.31 (0.12, 0.62)	47.1 (33)	67.1 (47)	81.4 (57)*	95.7 (67)
Double-K SRK/T	$0.48 \pm 0.39^*$	0.39 (0.18, 0.68)*	30.0 (21)*	62.9 (44)	77.1 (54)*	92.9 (65)
Without history data						
Olsen Raytracing	0.26 ± 0.24	0.16 (0.07, 0.48)	64.3 (45)	81.4 (57)	95.7 (67)	100.0 (70)
Hill Potvin Shammas PM	0.41 ± 0.31	0.32 (0.16, 0.55)	37.1 (26)*	65.7 (46)	87.1 (61)	92.9 (65)
Barrett True-K no history	0.43 ± 0.35	0.37 (0.16, 0.61)	41.4 (29)	67.1 (47)	87.1 (61)	91.4 (64)
Haigis-L	$0.52 \pm 0.43^*$	0.43 (0.16, 0.74)*	31.4 (22)*	60.0 (42)	75.7 (53)*	82.9 (58)*
Shammas-PL	$0.54 \pm 0.41^*$	0.45 (0.21, 0.75)*	30.0 (21)*	54.3 (38)*	75.7 (53)*	87.1 (61)*

*Significant difference compared with the Olsen Raytracing method after Bonferroni correction.



► **Fig. 1** Box diagram of the refractive prediction error of all formulae (sorted by the median absolute prediction error in ascending order).

Double-K SRK/T ($p = 0.004$ and $p < 0.001$), Shammas-PL (both $p < 0.001$), and Haigis-L (both $p < 0.001$) formulae. Raytracing also had a lower MAE than Barrett True-K no history formula ($p = 0.048$). Additionally, the Modified Masket method had a lower MAE than Shammas-PL ($p = 0.011$) and Haigis-L formulae ($p = 0.039$). The Masket method was better than the Shammas-PL formula in terms of MAE ($p = 0.030$) and MedAE ($p = 0.048$). Refractive PEs of all formulae are demonstrated in ► **Fig. 1**.

Moreover, Cochran's Q test showed that all nine formulae had significant statistical differences in percentages of eyes within a PE of ± 0.25 D ($p < 0.001$), ± 0.50 D ($p = 0.002$), ± 0.75 D ($p < 0.001$), and ± 1.00 D ($p < 0.001$). The raytracing method showed the highest percentages of eyes within a PE of ± 0.25 D (64.3%), ± 0.50 D (81.4%), ± 0.75 D (95.7%), and ± 1.00 D (100.0%). ► **Table 1** also showed the significant difference between the raytracing method and the others after Bonferroni correction. In pairwise comparison, Haigis-L had a significantly smaller percentage of eyes within a PE of ± 1.00 D than that of the Modified Masket method ($p = 0.001$), Masket method ($p = 0.014$), Barrett True-K no history ($p = 0.014$), and Shammas-PL ($p = 0.014$). The Masket method achieved a higher percentage of eyes within a PE of ± 0.50 D than Shammas-PL ($p = 0.04$). Stacked histogram showed the percentage of eyes within a given diopter range of predictive refraction outcome (► **Fig. 2**).

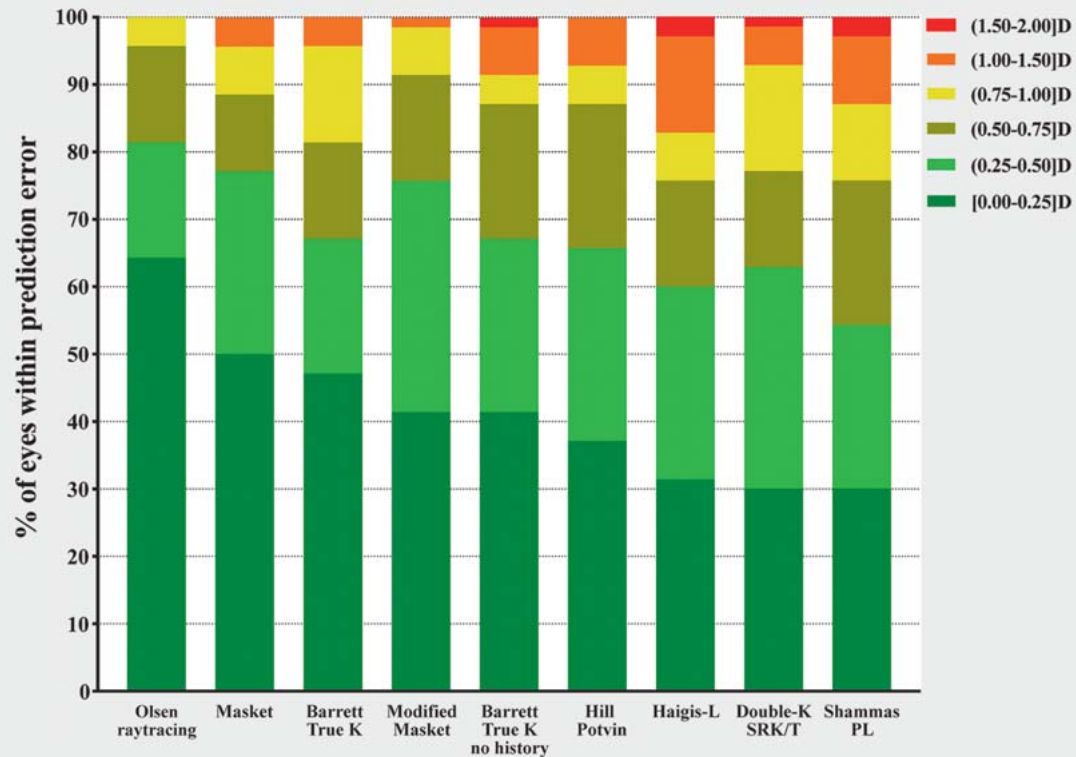
Subgroup Analysis

As the raytracing method considered multiple factors to calculate IOL power, including anterior chamber depth, lens thickness, and B/F ratio, we performed a subgroup analysis of these parameters. In addition, a subgroup analysis was also performed according to axial length, keratometry, and preoperative SE. ► **Table 3** shows the refractive outcomes from the subgroup analysis. There were

no statistically significant differences in terms of the MedAE or MAE in the different subgroups (all $p < 0.05$). Moreover, no difference was found in the percentage of eyes within a PE of ± 0.25 D, ± 0.50 D, ± 0.75 D, or ± 1.00 D as well (all $p < 0.05$). These results showed that raytracing had excellent consistency in calculating IOL power after myopic SMILE.

Discussion

Since the inception of SMILE almost 10 years ago, the procedure has been rapidly growing in popularity [26]. IOL power calculations in eyes after SMILE will inevitably become a challenging task for most ophthalmologists. Due to the limited number of patients who previously had myopic SMILE surgery and then had cataract surgery, it is difficult to compare the accuracy of different IOL power calculation formulae by directly calculating refractive PE. In this study, a theoretical model was adopted, that refractive PE could be indirectly obtained by calculating the difference between the residual spherical equivalent predicted by the standard method and the residual spherical equivalent predicted by the targeted formula for the same IOL power and model [17,24]. Olsen Raytracing was used as the standard and benchmark formula to calculate IOL power before refractive surgery, since it had the best outcomes in terms of accuracy for long eyes compared with Barrett Universal II, Haigis, or third-generation formulae [15]. Furthermore, the raytracing method has been proven to be highly effective in estimating the changes in corneal power and calculating IOL power after LASIK/PRK [18,27]. We evaluated the accuracy of IOL power calculations after SMILE using raytracing and compared the outcomes using formulae with historical data (Barrett True-K, Double-K SRK/T, Masket, Modified Masket) and without historical data (Barrett True-K no history, Haigis-L, Hill Potvin Shammas PM,



► **Fig. 2** Stacked histogram comparing the percentage of cases within a given diopter range of refractive prediction error (sorted by the percentage of eyes within a prediction error of ± 0.250 D in descending order).

► **Table 3** Refractive outcomes of Olsen Raytracing formula in different groups.

Different groups	Absolute prediction error (D)		Proportion of PE% (number)			
	Mean \pm SD	Median (Q1, Q3)	± 0.25 D	± 0.50 D	± 0.75 D	± 1.00 D
Pre-SE > -6 (42)	0.24 \pm 0.23	0.16 (0.05, 0.33)	69.0 (29)	83.3 (35)	95.2 (40)	100.0 (42)
Pre-SE \leq -6 (28)	0.30 \pm 0.26	0.18 (0.09, 0.50)	57.1 (16)	78.6 (22)	96.4 (27)	100.0 (28)
K < 38 mm (24)	0.26 \pm 0.24	0.17 (0.07, 0.49)	66.7 (16)	83.3 (20)	95.8 (23)	100.0 (24)
K \geq 38 mm (46)	0.26 \pm 0.24	0.16 (0.06, 0.44)	63.0 (29)	80.4 (37)	95.7 (44)	100.0 (46)
AL < 26 mm (32)	0.27 \pm 0.22	0.21 (0.10, 0.43)	62.5 (20)	81.3 (26)	96.9 (31)	100.0 (32)
AL \geq 26 mm (38)	0.25 \pm 0.26	0.16 (0.03, 0.49)	65.8 (25)	81.6 (31)	94.7 (36)	100.0 (38)
ACD < 3.5 mm (31)	0.27 \pm 0.24	0.20 (0.09, 0.49)	58.1 (18)	80.6 (25)	96.8 (30)	100.0 (31)
ACD \geq 3.5 mm (39)	0.25 \pm 0.25	0.16 (0.04, 0.48)	69.2 (27)	82.1 (32)	94.9 (37)	100.0 (39)
LT < 3.5 mm (35)	0.26 \pm 0.24	0.20 (0.06, 0.48)	62.9 (22)	82.9 (29)	97.1 (34)	100.0 (35)
LT \geq 3.5 mm (35)	0.26 \pm 0.25	0.16 (0.07, 0.49)	65.7 (23)	80.0 (28)	94.3 (33)	100.0 (35)
B/F ratio < 73% (28)	0.26 \pm 0.23	0.17 (0.07, 0.49)	60.7 (17)	85.7 (24)	96.4 (27)	100.0 (28)
B/F ratio \geq 73% (42)	0.26 \pm 0.25	0.16 (0.04, 0.44)	66.7 (28)	78.6 (33)	95.2 (40)	100.0 (42)

ACD: anterior chamber depth; AL: axial length; B/F ratio: back-to-front corneal radius ratio; D: diopter, K: keratometry; LT: lens thickness; Pre-SE: preoperative spherical equivalent

Shammas-PL). Our outcomes showed that raytracing is the most accurate method in predicting and achieving the target refraction in calculating IOL power for myopic eyes after SMILE, with good consistency in IOL power calculations of eyes with different axial lengths, anterior chamber depth, keratometry, lens thickness, B/F ratio, and preoperative refraction.

As mentioned above, formulae used to calculate IOL power after corneal refractive surgery can be divided into two categories, including with historical data and without. In this study, Barrett True-K, Double-K SRK/T, Masket, and Modified Masket require knowledge of preoperative refractive data. One previous study indicated that Barrett True-K had no significant differences with Masket and Modified Masket in calculating IOL power after excimer laser ablation [16], which was consistent with our results in eyes after SMILE. Although our study showed that raytracing had the lowest mean arithmetic PE among the four formulae with historical data, a significant difference was only found between raytracing and Double-K SRK/T. In addition, this study also enrolled formulae that did not require pre-refractive history data, including Barrett True-K no history. In the early years, Haigis-L and Shammas-PL formulae had good predictability of IOL power calculations when refractive historical data was unknown. With the introduction of Barrett True-K no history, its accuracy has been widely recognized in calculating IOL power in eyes after refractive surgery [28, 29]. However, a recent meta-analysis found that Barrett True-K no history had no significant difference from Haigis-L and Shammas-PL [30]. The same result was found in our study.

Unlike the third- and fourth-generation formulas, the raytracing method directly addresses the curvature of the corneal center, which truly reflects the change in total corneal power after refractive surgery [31]. The true net power (TNP; apex zone 4 mm) is calculated from the measurement of both corneal surfaces with the real ratio between the anterior and posterior corneal radius, which is much lower than the anterior simulated keratometry [12]. Our results showed that raytracing had a lower MedAE than Shammas-PL and Haigis-L, but not Barrett True-K no history and Hill Potvin Shammas PM. Similar results were found in eyes after myopic LASIK/PRK [32, 33]. Yet raytracing had a higher percentage of eyes within a PE of ± 0.25 D than Hill Potvin Shammas PM and within a PE of ± 0.75 D than Barrett True-K no history. These results demonstrated that it had a better outcome than all mentioned formulae without pre-refractive historical data in calculating IOL power after SMILE.

The raytracing method uses a special C constant to estimate ELP [21]. C constant is a constant based on preoperative anterior chamber depth, lens thickness, and IOL constant, and is no longer dependent on axial length or corneal curvature. Therefore, ELP errors could be prevented [34]. Moreover, the raytracing method uses measurements of both the anterior and posterior corneal radii rather than fictitiously assuming a constant ratio of anterior to posterior corneal curvature to determine total corneal power. Thus, it could also avoid the corneal power error in calculating IOL power after refractive surgery [34]. For eyes with an abnormal corneal curvature, raytracing displays its unique advantages compared with SRK/T and Haigis formulae [35]. Meanwhile, as the cornea is aspheric and pupil diameter is not fixed, it is not accurate to only consider the paraxial optical path, which would cause a large

aberration. The raytracing method considers several factors such as corneal irregularity, pupil diameter, and IOL thickness to minimize the aberration, which is also one of the advantages between the raytracing method and traditional formulae in calculating IOL power [36, 37]. Several studies have been devoted to comparing the accuracy of the raytracing method with traditional formulae for calculating IOL power after refractive surgery and demonstrated its superiority [38, 39].

These theoretical methodological advantages of the raytracing method have been previously proven in patients with a history of previous myopic laser vision correction who underwent cataract surgery and IOL implantation. For instance, in Savini's report [18], the percentage of eyes within a PE of ± 0.50 D (± 1.00 D) obtained by raytracing was 71.4% (85.7%), with the MedAE being $+0.25$ D. Gjerdrum et al. [40] yielded even better results. The Anterior-OKULIX calculations showed a higher percentage of eyes with PEs within ± 0.25 , ± 0.5 , and ± 0.75 (60%, 88%, and 100%, respectively). These results seem comparable to our findings in post-SMILE eyes. Lazaridis et al. [24] reported 81.9% of eyes within a PE of ± 0.50 D in a study of 204 eyes undergoing SMILE. Similar results were found in our study, in which the percentage of eyes within a PE of ± 0.50 D was 81.4%.

Our present data are also endorsed by the Lischke et al. study, which analyzed the first cohort of post-SMILE eyes undergoing cataract surgery and IOL implantation. Although the study is limited by its relatively small sample size, its result is highly coherent with our findings, in which raytracing showed the smallest mean absolute error (0.40 D) and yielded the largest percentage of eyes within $\pm 0.50/\pm 1.00$ D (82/91%) compared to other empirically optimized formulae available in the ASCRS post-keratorefractive surgery IOL power online calculator [41].

This study has several limitations. One limitation is the retrospective study design with a limited sample. Further prospective analysis should include more patients. Second, as SMILE has only been employed by clinicians since 2011, sufficient empirical data on IOL power prediction accuracy do not exist. Therefore, in this study, a theoretical model was used, which involved the virtual implantation of the same IOL before and after SMILE instead of actual implanting IOL in post-SMILE patients. It would be more ideal to gather and analyze a cohort of post-SMILE patients who have undergone cataract extraction with IOL implantation. Third, only formulae with a broad application were included in this study. The others, such as Atlas-, Galilei- or OCT-based corneal measurements, were not enrolled because of their limited application [10, 11]. Finally, since Olsen Raytracing was chosen as the standard method to calculate IOL power before refractive surgery, it may create potential bias that the postop values favored itself when comparing with other different approaches. However, the meaning of "bias" is complicated and vague. Zhu et al. conducted research comparing the stability of different formulae after SMILE surgery [42]. In their study, a concept of equivalent IOL power (EILD) was introduced, and a comparison of the same formula before and after SMILE surgery was made. Theoretically, if the formula is more stable, it could create more "bias" when chosen as the benchmark formula to calculate IOL power before refractive surgery, since it favors its own result. However, on the other hand, when choosing a standard formula before SMILE, the most stable

formula should be the first choice. For instance, in the above paper, the Barrett True-K formula was found to be more stable than SRK/T, Holladay 1, and Haigis and was recommended to calculate IOL power. Therefore, the “bias” may occur but can hardly be eliminated.

Conclusion

Previous studies indicated that the raytracing method provided great accuracy for IOL power calculations after myopic LASIK/PRK surgery. But its accuracy has not been described for eyes that underwent SMILE surgery, especially when raytracing was chosen as the standard method to calculate IOL power before SMILE. In this study, we have demonstrated that raytracing is the most accurate method in predicting and achieving the target refraction in calculating IOL power for myopic eyes after SMILE. It has a good consistency in IOL power calculations of eyes with different axial lengths, anterior chamber depths, keratometry, lens thickness, B/F ratio, and preoperative refraction.

Supporting Information

The IOL-Dif and SMILE-Dif of different formulae are presented in the **Supplementary Table 1**.

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Conflict of Interest

The authors declare that they have no conflict of interest.

References

- [1] Hoffer KJ. Intraocular lens power calculation after previous laser refractive surgery. *J Cataract Refract Surg* 2009; 35: 759–765. doi:10.1016/j.jcrs.2009.01.005
- [2] Langenbucher A, Haigis W, Seitz B. Difficult lens power calculations. *Curr Opin Ophthalmol* 2004; 15: 1–9. doi:10.1097/00055735-200402000-00002
- [3] Savini G, Hoffer KJ. Intraocular lens power calculation in eyes with previous corneal refractive surgery. *Eye Vis (Lond)* 2018; 5: 18. doi:10.1186/s40662-018-0110-5
- [4] Kang BS, Han JM, Oh JY et al. Intraocular Lens Power Calculation after Refractive Surgery: A Comparative Analysis of Accuracy and Predictability. *Korean J Ophthalmol* 2017; 31: 479–488. doi:10.3341/kjo.2016.0078
- [5] Abulafia A, Hill WE, Koch DD et al. Accuracy of the Barrett True-K formula for intraocular lens power prediction after laser *in situ* keratomileusis or photorefractive keratectomy for myopia. *J Cataract Refract Surg* 2016; 42: 363–369. doi:10.1016/j.jcrs.2015.11.039
- [6] Masket S, Masket SE. Simple regression formula for intraocular lens power adjustment in eyes requiring cataract surgery after excimer laser photoablation. *J Cataract Refract Surg* 2006; 32: 430–434. doi:10.1016/j.jcrs.2005.12.106
- [7] Aramberri J. Intraocular lens power calculation after corneal refractive surgery: double-K method. *J Cataract Refract Surg* 2003; 29: 2063–2068. doi:10.1016/s0886-3350(03)00957-x
- [8] Savini G, Barboni P, Zanini M. Intraocular lens power calculation after myopic refractive surgery: theoretical comparison of different methods. *Ophthalmology* 2006; 113: 1271–1282. doi:10.1016/j.ophtha.2006.03.024
- [9] Hoffer KJ. Intraocular lens power calculation for eyes after refractive keratotomy. *J Refract Surg* 1995; 11: 490–493. doi:10.3928/1081-597X-19951101-17
- [10] Tang M, Wang L, Koch DD et al. Intraocular lens power calculation after previous myopic laser vision correction based on corneal power measured by Fourier-domain optical coherence tomography. *J Cataract Refract Surg* 2012; 38: 589–594. doi:10.1016/j.jcrs.2011.11.025
- [11] Ianchulev T, Hoffer KJ, Yoo SH et al. Intraoperative refractive biometry for predicting intraocular lens power calculation after prior myopic refractive surgery. *Ophthalmology* 2014; 121: 56–60. doi:10.1016/j.ophtha.2013.08.041
- [12] Potvin R, Hill W. New algorithm for intraocular lens power calculations after myopic laser *in situ* keratomileusis based on rotating Scheimpflug camera data. *J Cataract Refract Surg* 2015; 41: 339–347. doi:10.1016/j.jcrs.2014.05.040
- [13] Haigis W. Intraocular lens calculation after refractive surgery for myopia: Haigis-L formula. *J Cataract Refract Surg* 2008; 34: 1658–1663. doi:10.1016/j.jcrs.2008.06.029
- [14] Shammas HJ, Shammas MC. No-history method of intraocular lens power calculation for cataract surgery after myopic laser *in situ* keratomileusis. *J Cataract Refract Surg* 2007; 33: 31–36. doi:10.1016/j.jcrs.2006.08.045
- [15] Melles RB, Holladay JT, Chang WJ. Accuracy of Intraocular Lens Calculation Formulas. *Ophthalmology* 2018; 125: 169–178. doi:10.1016/j.ophtha.2017.08.027
- [16] Wang L, Tang M, Huang D et al. Comparison of Newer Intraocular Lens Power Calculation Methods for Eyes after Corneal Refractive Surgery. *Ophthalmology* 2015; 122: 2443–2449. doi:10.1016/j.ophtha.2015.08.037
- [17] Fram NR, Masket S, Wang L. Comparison of Intraoperative Aberrometry, OCT-Based IOL Formula, Haigis-L, and Masket Formulae for IOL Power Calculation after Laser Vision Correction. *Ophthalmology* 2015; 122: 1096–1101. doi:10.1016/j.ophtha.2015.01.027
- [18] Savini G, Bedei A, Barboni P et al. Intraocular lens power calculation by ray-tracing after myopic excimer laser surgery. *Am J Ophthalmol* 2014; 157: 150–153.e1. doi:10.1016/j.ajo.2013.08.006
- [19] Saiki M, Negishi K, Kato N et al. Ray tracing software for intraocular lens power calculation after corneal excimer laser surgery. *Jpn J Ophthalmol* 2014; 58: 276–281. doi:10.1007/s10384-014-0304-x
- [20] 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. doi:10.1016/s0886-3350(13)80705-5
- [21] Olsen T, Hoffmann P. C constant: new concept for ray tracing-assisted intraocular lens power calculation. *J Cataract Refract Surg* 2014; 40: 764–773. doi:10.1016/j.jcrs.2013.10.037
- [22] Minami K, Kataoka Y, Matsunaga J et al. Ray-tracing intraocular lens power calculation using anterior segment optical coherence tomography measurements. *J Cataract Refract Surg* 2012; 38: 1758–1763. doi:10.1016/j.jcrs.2012.05.035
- [23] Rabsilber TM, Reuland AJ, Holzer MP et al. Intraocular lens power calculation using ray tracing following excimer laser surgery. *Eye (Lond)* 2007; 21: 697–701. doi:10.1038/sj.eye.6702300
- [24] Lazaridis A, Schraml F, Preussner PR et al. Predictability of intraocular lens power calculation after small-incision lenticule extraction for myopia. *J Cataract Refract Surg* 2021; 47: 304–310. doi:10.1097/j.jcrs.0000000000000405
- [25] Hoffer KJ, Aramberri J, Haigis W et al. Protocols for studies of intraocular lens formula accuracy. *Am J Ophthalmol* 2015; 160: 403–405.e1. doi:10.1016/j.ajo.2015.05.029

- [26] Ahmed AA, Hatch KM. Advantages of Small Incision Lenticule Extraction (SMILE) for Mass Eye and Ear Special Issue. *Semin Ophthalmol* 2020; 35: 224–231. doi:10.1080/08820538.2020.1807028
- [27] Savini G, Calossi A, Camellin M et al. Corneal ray tracing versus simulated keratometry for estimating corneal power changes after excimer laser surgery. *J Cataract Refract Surg* 2014; 40: 1109–1115. doi:10.1016/j.jcrs.2013.11.032
- [28] Leite de Pinho Tavares R, de Almeida Ferreira G, Ghanem VC et al. IOL Power Calculation After Radial Keratotomy Using the Haigis and Barrett True-K Formulas. *J Refract Surg* 2020; 36: 832–837. doi:10.3928/1081597X-20200930-02
- [29] Christopher KL, Patnaik JL, Miller DC et al. Accuracy of Intraoperative Aberrometry, Barrett True-K With and Without Posterior Cornea Measurements, Shammas-PL, and Haigis-L Formulas After Myopic Refractive Surgery. *J Refract Surg* 2021; 37: 60–68. doi:10.3928/1081597X-20201030-02
- [30] Li H, Nan L, Li J et al. Accuracy of intraocular lens power calculation formulae after laser refractive surgery in myopic eyes: a meta-analysis. *Eye Vis (Lond)* 2020; 7: 37. doi:10.1186/s40662-020-00188-1
- [31] Gonen T, Cosar CB, Sener B et al. Comparison of keratometric data obtained by automated keratometer, Dicon CT 200, Allegro Topolyzer, and Pentacam. *J Refract Surg* 2012; 28: 557–561. doi:10.3928/1081597X-20120723-04
- [32] Cho K, Lim DH, Yoo YS et al. New method for intraocular lens power calculation using a rotating Scheimpflug camera in eyes with corneal refractive surgery. *Sci Rep* 2020; 10: 8992. doi:10.1038/s41598-020-65827-y
- [33] Huang D, Tang M, Wang L et al. Optical coherence tomography-based corneal power measurement and intraocular lens power calculation following laser vision correction (an American Ophthalmological Society thesis). *Trans Am Ophthalmol Soc* 2013; 111: 34–45
- [34] Chang PJ, Zhang F, Wang JJ et al. Accuracy of Constant C for Ray Tracing: Assisted Intraocular Lens Power Calculation in Normal Ocular Axial Eyes. *Ophthalmic Res* 2021; 64: 85–90. doi:10.1159/000507963
- [35] Oh JH, Kim SH, Chuck RS et al. Evaluation of the Pentacam ray tracing method for the measurement of central corneal power after myopic photorefractive keratectomy. *Cornea* 2014; 33: 261–265. doi:10.1097/ICO.0000000000000034
- [36] Kim M, Eom Y, Lee H et al. Use of the Posterior/Anterior Corneal Curvature Radii Ratio to Improve the Accuracy of Intraocular Lens Power Calculation: Eom's Adjustment Method. *Invest Ophthalmol Vis Sci* 2018; 59: 1016–1024. doi:10.1167/jovs.17-22405
- [37] Ghoreyshi M, Khalilian A, Peyman M et al. Comparison of OKULIX ray-tracing software with SRK-T and Hoffer-Q formula in intraocular lens power calculation. *J Curr Ophthalmol* 2018; 30: 63–67. doi:10.1016/j.joco.2017.06.008
- [38] Olsen T, Funding M. Ray-tracing analysis of intraocular lens power *in situ*. *J Cataract Refract Surg* 2012; 38: 641–647. doi:10.1016/j.jcrs.2011.10.035
- [39] Canovas C, van der Mooren M, Rosen R et al. Effect of the equivalent refractive index on intraocular lens power prediction with ray tracing after myopic laser *in situ* keratomileusis. *J Cataract Refract Surg* 2015; 41: 1030–1037. doi:10.1016/j.jcrs.2014.07.044
- [40] Gjerdrum B, Gundersen KG, Lundmark PO et al. Refractive Precision of Ray Tracing IOL Calculations Based on OCT Data versus Traditional IOL Calculation Formulas Based on Reflectometry in Patients with a History of Laser Vision Correction for Myopia. *Clin Ophthalmol* 2021; 15: 845–857. doi:10.2147/OPHTH.S298007
- [41] Lischke R, Sekundo W, Wiltfang R et al. IOL Power Calculations and Cataract Surgery in Eyes with Previous Small Incision Lenticule Extraction. *J Clin Med* 2022; 11: 4418. doi:10.3390/jcm11154418
- [42] Zhu W, Zhang FJ, Li Y et al. Stability of the Barrett True-K formula for intraocular lens power calculation after SMILE in Chinese myopic eyes. *Int J Ophthalmol* 2020; 13: 560–566. doi:10.18240/ijo.2020.04.05