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Accuracy of Constant C for Ray Tracing: Assisted Intraocular Lens Power Calculation in Normal Ocular Axial Eyes

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Keywords
Ray tracing · Intraocular lens · Constant C

Abstract
Objective: To evaluate the effect of constant C for ray tracing-assisted intraocular lens (IOL) power calculation in patients with different refractive power, we compared the refractive outcome of the ray tracing method based on constant C and conventional IOL calculation. ***Methods:*** 215 eyes which underwent phacoemulsification and IOL implantation were enrolled in the study. According to the average corneal power, patients were divided into 3 groups: high corneal power (K >45 D) group, medium corneal power (43 ≤ K ≤ 45 D) group, and low corneal power (K <43 D) group. The predicted sphero-equivalent refractive outcome for the IOL power implanted at surgery was calculated using the ray tracing method, SRK/T, and Haigis formulas. ***Results:*** On the basis of the corneal refractive power, there were 65 eyes of K >45 D (30.23%), 96 eyes of 43 ≤ K ≤ 45 D (44.65%), and 54 eyes of K <43 D (25.12%). In general, the ray tracing group had the smallest value of mean absolute error (MAE) and mean error, and the proportions of eyes with absolute error (AE) <0.50 and <0.75 D were significantly higher than those of the other 2 formulas ($p = 0.010$). In each group, the value of MAE was smallest in the ray tracing group; for the proportions of AEs <0.50 and <0.75 D, the values in the ray tracing group were higher than those in the SRK/T and Haigis groups. Especially in the high and low corneal refractive groups, the proportion of AE <0.25 D was also obviously higher, but only in the low corneal refractive power group, and the difference was statistically significant ($p = 0.006$). ***Conclusions:*** Compared with the conventional formulas, C constant of the ray tracing-assisted IOL power calculation has more accuracy for the patients with different corneal refractive powers. Ray tracing could provide better guidance for IOL selection clinically.

Introduction

The accuracy of the prediction of the intraocular lens (IOL) power has been improved by the accurate biological measurement and the accurate selection of the power calculation formula. Biometric eye measurements include the measurement of axial length (AL), corneal curvature, and preoperative anterior chamber depth (ACD) [1, 2]. In the past few decades, with the application of coherent light technology of IOLMaster, the calculation of IOL has been improved from the first- to the fourth-generation formula [3]. From the linear regression formula at the very beginning, it has developed into the up-to-date formula using constant adjustments according to different ALs, corneal curvatures, ACDs, for example. For the prediction of effective lens position (ELP) after surgery,

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the SRK/T formula assumes ELP is related to the AL and corneal curvature, while the Haigis formula assumes that ELP is related to the AL and ACD. Therefore, in eyes with an abnormal AL, corneal curvature, and ACD, the predicted results will lead to a certain deviation.

Nowadays, ray tracing technology is widely used to analyze the optical properties of different optical systems [4–6]. For IOL power prediction based on the establishment of the model eye, the anterior and posterior surfaces of corneal and crystalline lenses are regarded as reflection plane; when we know the incident angle of the light and the refractive index medium, we can assess the light on the retina using the formula calculating the density scattergram; for IOL eyes with corneal curvature, ELP, ocular AL, and refractive medium data, such as the refractive index, the diameter of the pupil is indispensable to predict the degree of IOL [7].

Ray tracing is significantly different from the traditional IOL calculation formula [4]. The traditional formula is based on the assumption that the patients are standard. In the case of unusual corneal curvature, AL, and preoperative ACD, the assumed results will lead to deviations, thus the optimization of the constant of the formula is necessary. However, the ray tracing method is not based on this assumption. In ray tracing, constant C is a constant based on preoperative ACD, lens thickness, and IOL, and is no longer dependent on factors such as AL and corneal curvature. In addition, the ray tracing method takes the curvature of the anterior and posterior corneal surfaces and corneal thickness into account [8]. Meanwhile, the traditional IOL calculation formulas only consider the paraxial optical path. As the cornea is aspheric, the curvature is uneven; since pupil diameter is not fixed, the analysis of the optical path which based on the assumption that the axis is equivalent to the infinitesimal pupil is not accurate and will cause a large aberration. When using the ray tracing method for calculation, we will consider factors such as pupil diameter, corneal irregularity, and IOL thickness to minimize the aberration. This is also one of the significant differences between the optical ray tracing system and the traditional IOL calculation formulas [9–11].

The optical path tracing method based on constant C still needs the establishment of model eyes in the calculation of IOL [4]. Its accuracy is based on the accurate measurement, and its prediction of ELP is also obtained by assuming constant C, thus its results are still limited [12]. However, in general, compared with the traditional formulas, ray tracing takes more comprehensive factors for the calculation of IOL into account, thus providing a more reliable approach to IOL selection.

The purpose of this study is to analyze the influence of the corneal curvature on the accuracy of traditional formulas and ray tracing technology in the prediction of IOL in cataract patients with normal AL, in order to provide a better basis for the selection of IOL.

Methods

Participants

This study enrolled 215 eyes of 215 patients diagnosed with age-related cataract undergoing cataract micro-incision phacoemulsification and IOL implantation in the Eye Hospital of the Wenzhou Medical University (Hangzhou Branch) from September 2011 to 2018. To determine the number of patients, we used one-way analysis of variance (ANOVA) power analysis (online supplementary Table 1, for all online suppl. material, see www.karger.com/doi/10.1159/000507963). Patients who had best-corrected visual acuities ≥0.8 at 3 months postoperatively were included. Patients with an AL <22 or >26 mm were excluded. Patients with penetrating keratoplasty, refractive surgery, or postoperative complications were also excluded. If both eyes were eligible, only the right eye was included.

According to the corneal curvature power measured by IOLMaster before surgery, the patients were divided into 3 groups: high corneal diopter group (K >45 D), medium corneal diopter group (43 < K < 45 D), and low corneal diopter group (K <43 D).

Measurements

Every patient had standard eye parameters measured before surgery. AL and K with optical biometry were measured using the IOLMaster 500 (Carl Zeiss Meditech, Jena, Germany). According to the built-in software, different IOL powers were found using the different formulas, and the IOL power was chosen according to the ULIB user group (User Group for Laser Interference Biometry). Patients were followed up 1 week, and 1 and 3 months postoperatively. The uncorrected and best-corrected visual acuity of the patients' intraoperative eyes and the subjective refraction was examined, and the equivalent spherical equivalent value degree of the patients was calculated. PhacoOptics software was used as the ray tracing system based on constant C in this study. PhacoOptics has a database of commonly used IOLs, including the thickness of the specific IOL, the material and refractive index of the IOL, the front and back surface curvature of the IOL, and corrected spherical aberration. From these data, a constant of the postoperative ACD can be obtained, and the ELP can be inferred based on data such as AL and corneal curvature.

Statistical Analysis

The data were analyzed using the statistical software SPSS 21.0. Absolute errors (AE) were the difference between the spherical equivalent value after operation and the predicted refraction before operation. Mean errors (ME) and mean AEs (MAEs) were analyzed. MAEs and the proportions of cases with an AE <0.75, <0.5, and <0.25 D were calculated in each group, respectively. One-way ANOVA was performed on AE values of the 3 methods (SRK/T formula, Haigis formula, and ray tracing technology) in different groups. It was considered statistically significant when $p < 0.05$. All reported p values were 2 sided.

Table 1. Clinical characteristics of the eyes included in the present study

	n	Axial length, mm	Corneal refractive power (K)	Anterior chamber depth, mm
K >45 D	65	23.337±1.044	45.817±0.809	3.044±0.529
43 ≤ K ≤ 45 D	96	23.481±0.778	44.120±0.509	3.031±0.478
K <43 D	54	24.477±0.854	42.171±0.700	3.172±0.459

Table 2. Comparison of the 3 formulas in a population sample

	SRK/T	Haigis	Ray tracing
ME, D	0.126±0.392	0.038±0.454	0.002±0.357
MAE, D	0.325±0.252	0.355±0.284	0.293±0.202*
AE <0.75 D, %	92.56	88.37	97.67
AE <0.50 D, %	76.28	73.02	82.33
AE <0.25 D, %	46.98	46.51	46.51

MAE, mean absolute refractive error. * $p < 0.05$.

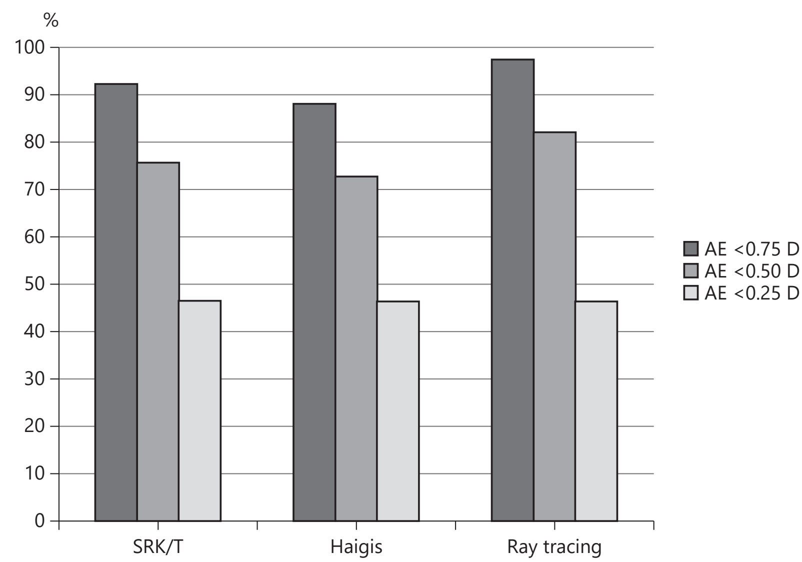

Fig. 1. Comparison of the percentage of cases within a given diopter range of predicted spherical equivalent refraction outcome.

Results

Altogether 215 eyes were qualified for inclusion. The main types of IOL were as follows: IQ-Toric (58 eyes), SN60WF (48 eyes), MI60 (40 eyes), and ZCB00 (25 eyes). The average AL of all samples was 23.674 mm, the average preoperative ACD was 3.071 mm, and the average corneal refractive power was 44.142 D. According to the corneal refractive power, the average refractive power of the cornea (K) was >45 D in 65 cases (30.23%), 43 ≤ K ≤ 45 D in 96 cases (44.65%), and K <43 D in 54 cases (25.12%) (Table 1).

ME, MAE, distribution of AE, and one-way ANOVA of AE were calculated for the 3 formulas. In the SRK/T group, the ME was 0.126 ± 0.392 D and MAE was 0.325 ± 0.252 D. In the Haigis group, the ME was 0.038 ± 0.454 D and MAE was 0.355 ± 0.284 D. In the ray tracing group, the ME was 0.002 ± 0.357 D, and MAE was 0.293 ± 0.202 D. In the samples with AE <0.50 and <0.75 D, the proportion of the ray tracing group was the largest, while in the samples with AE <0.25 D, there was no significant difference between the 3 methods. Univariate ANOVA was carried out for AE values of the 3 groups ($F = 4.629$, $p = 0.010$), showing significant statistical difference, that is, the accuracy of the optical tracing group was higher than that of the other 2 groups using traditional formulas in the overall sample (Table 2; Fig. 1).

High Corneal Refractive Power Group

The 65 samples with K >45 D were allocated to the high corneal refractive power group, and corresponding ME, MAE, and AE were calculated. In this group, the ME value of the SRK/T group was positive and higher than that of the other 2 groups, and the ME value of the ray tracing group was the lowest. MAE values of the SRK/T group and the Haigis group were close to each other, and

Table 3. Comparison of the 3 formulas in the different groups

	K >45 D			43 ≤ K ≤ 45 D			K <43 D		
	SRK/T	Haigis	ray tracing	SRK/T	Haigis	ray tracing	SRK/T	Haigis	ray tracing
ME, D	0.225±0.360	–0.155±0.393	–0.018±0.338	0.128±0.393	0.057±0.486	0.489±0.483	0.005±0.399	0.236±0.367	–0.051±0.269
MAE, D	0.331±0.264	0.326±0.266	0.278±0.189	0.327±0.251	0.356±0.250	0.320±0.214	0.315±0.242	0.356±0.250	0.219±0.162**
AE <0.75 D, %	90.77	92.30	94.86	92.71	85.42	96.84	94.44	88.89	100
AE <0.50 D, %	76.92	75.38	81.65	72.92	68.75	77.08	81.48	77.78	92.59
AE <0.25 D, %	44.62	47.69	52.31	48.96	47.92	40.63	46.30	40.74	59.26

MAE, mean absolute refractive error; K, mean corneal power.

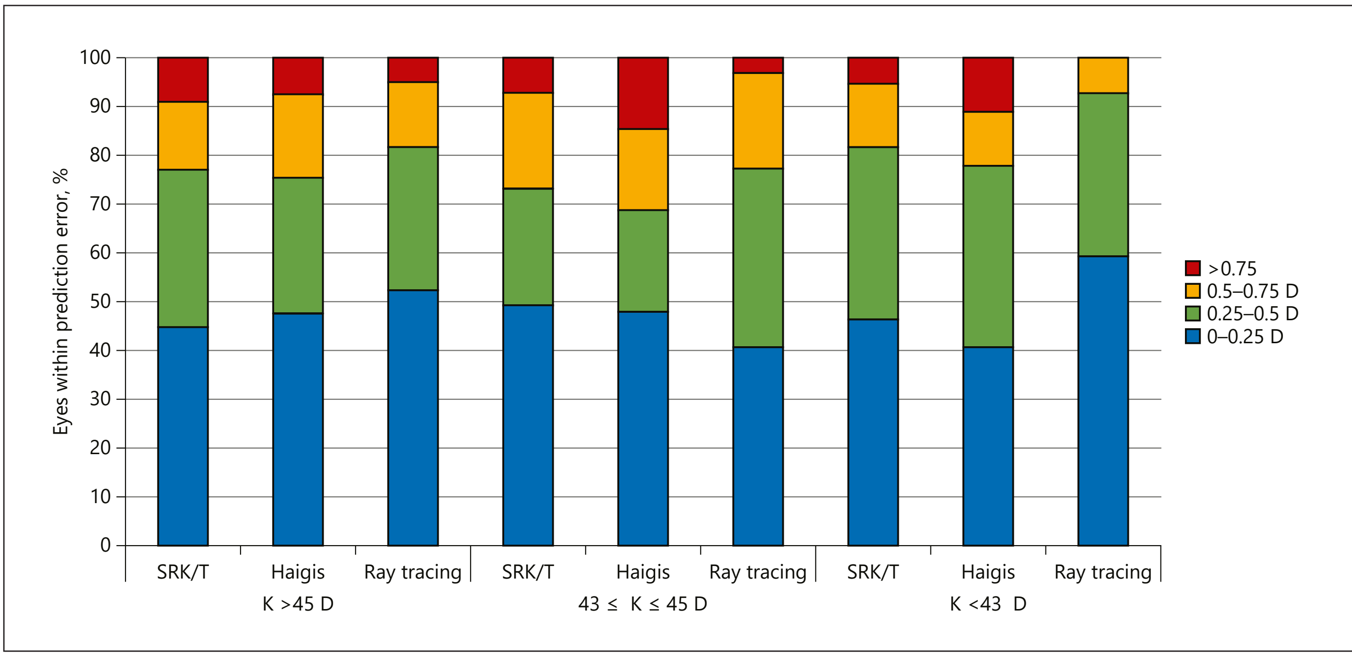

Fig. 2. Stacked histogram of the percentage of cases within a given diopter range of predicted spherical equivalent refraction outcome in 3 groups.

both were higher than those of the ray tracing group. In the samples with AE <0.50 and <0.75 D, the proportion of the ray tracing group was significantly higher than that of the other 2 groups, and there was no significant difference between the 3 groups with AE <0.25 D. However, one-way ANOVA was performed for the 3 groups (F = 0.953, p = 0.388), and the difference was not statistically significant (Table 3; Fig. 2).

Medium Corneal Refractive Power Group

The 96 samples with 43 ≤ K ≤ 45 D were assigned to the medium corneal refractive power group. The distribution of ME, MAE, and AE values were assessed. Among this group, ME was the smallest in the Haigis group and the largest in the ray tracing group. MAE values of the SRK/T group and ray tracing group were close to each other, and both were smaller than those of the Haigis group. In the samples with AE <0.50 and <0.75 D, the proportion of the ray tracing group was significantly higher than that of the other 2 groups, and there was no significant difference between the 3 groups with AE <0.25 D, and the AE value was not statistically significantly different among the 3 groups (F = 1.140, p = 0.388).

Low Corneal Refractive Power Group

Fifty-four examples with K <43 D were allocated to the low cornel refractive power group. In this group, ME was the largest in the Haigis group, and MAE was significantly lower in the ray tracing group than in the other 2 groups. In the samples with AE <0.25, <0.50, and

<0.75 D, the proportion of the ray tracing group was significantly higher than that of the other 2 groups. The difference among the 3 groups was statistically significant ($F = 5.362$, $p = 0.006$). In the low corneal refractive power group, the accuracy of the ray tracing group was higher than that of the SRK/T and the Haigis group.

Discussion

The traditional IOL calculation formula, based on gaussian optics, has experienced the development from the first generation to the fourth generation. For ELP, in different formulas, a linear or nonlinear relationship is established with different eye parameters [13]. The SRK/T formula, commonly used in clinical practice nowadays, is the third generation of the IOL calculation formula, in which constant A is introduced to improve the formula. The prediction of ELP is generally considered to be related to AL and corneal curvature. Constant A = IOL + (REF × RF) + 2.5 × L + 0.9 × K – C (REF refers to the actual postoperative diopter, RF refers to the corneal refractive index, L refers to the AL, K refers to the corneal curvature, and C refers to the adjustment factor used according to the AL of the second-generation IOL calculation formula) [5, 6]. Regarding the fourth-generation formula, the Haigis formula is different from the SRK/T formula in that it takes preoperative ACD rather than the corneal curvature into account [11, 14]. The prediction of ELP by the Haigis formula is as follows: ELP = a0 + a1 × ACD + a2 × L, in which L refers to the AL of the eye, a0 is the specific constant of IOL, a1 is affected by the preoperative measurement of ACD, and a2 is affected by the preoperative measurement of the AL of the eye [14].

Thomas Olsen introduced the concept of constant C for the prediction of ELP by optical ray tracing technology [6, 8]. Through continuous observation and study of ACD before and after surgery in 2,043 cataract patients, it was proposed that C = (postoperative ACD + 1/2 × TIOL – preoperative ACD)/preoperative LT, where preoperative LT is the preoperative lens thickness, and TIOL is the thickness of the IOL. That is, postoperative ELP was related to preoperative ACD and preoperative lens thickness. Because the surface design and material of each IOL are different, the value of C is not strictly a constant, but a value that changes with the type of IOL [8].

In this study, based on the analysis of the overall sample, the ME and MAE of the optical path tracing group were significantly lower than those of the 2 groups using the traditional IOL calculation formula ($p = 0.010$). Traditional IOL calculation formulas regard all planes in the eyes of the model as thin lenses and fail to take the IOL shape design into account. Even considering the IOL thickness, the aberration problem of the traditional formula is inevitable, which is now solved by the ray tracing method based on constant C. At present, many researchers have studied and confirmed the accuracy of ray tracing technology based on constant C in predicting the IOL diopter of eyes after corneal refractive surgery [5, 6]. The prediction of ELP based on the constant C theory is a significant advantage of the ray tracing technology, which reflects a huge difference from the traditional IOL calculation formula and provides a more reliable choice in the calculation of IOL.

Since the cornea accounts for the largest proportion of ocular refractive force [2], changes in the corneal curvature have a significant impact on the prediction of IOL. We found that in all high corneal refractive power groups (K >45 D) and low corneal refractive power groups (K < 43 D), both traditional calculation formulas showed no obvious difference, but the MAE and ME values of the ray tracing method are lower than in those traditional formulas. In addition, in the interval distribution of AE <0.75, 0.50, and 0.25 D, differences in the ray tracing method were significantly higher than in the other formulas, and in the low corneal refractive power group, the difference showed obvious statistical significance ($p = 0.006$). These differences can be explained by the formula principle. In the SRK/T formula, since the corneal curvature is directly related to the height of the cornea and thus affects the distance from the cornea to the IOL, namely ELP, the prediction of ELP is regarded as a nonlinear regression equation with the AL and the corneal curvature. However, in eyes with a normal AL, when the corneal curvature is too flat or steep, the accuracy of the SRK/T formula will be reduced, so constant A needs to be optimized to adapt to all kinds of abnormal eyes. For example, when the predicted error results are biased towards myopia, a smaller constant A is often needed. Studies have also shown that the Haigis formula predicts hyperopia in the eyes of steeper corneas [15]. The prediction of ELP by ray tracing technology based on constant C does not depend on corneal refractive power but considers the change in ACD before and after surgery through constant C. For the eyes with an abnormal corneal refractive power, the ray tracing method based on constant C shows its unique advantages compared with the SRK/T and Haigis formulas [16].

We are also aware that this study has some limitations. First, the method to determine the postoperative equivalent diopter of patients is subjective refraction. It requires good cooperation between the examinee and the patient.

Although patients with best-corrected visual acuity >0.8 were selected, errors still might exist due to poor cooperation. Second, the grouping of the corneal curvature in this experiment was based on the 3-mm corneal refractive force measured by IOLMaster in the central area of the anterior corneal surface, which is different from the curvature measured by Pentacam on the anterior and posterior surface of the whole cornea. Thirdly, this study did not take the types of IOL into account. In the future, detailed experimental analysis could be carried out for a specific type of IOL [17–19].

In summary, compared with the traditional IOL calculation formula, the ray tracing technology avoids the problem of making assumptions about different optical planes, showing its unique advantages and better accuracy. For patients with different corneal refractive powers, the ray tracing technology has more accurate prediction ability, which thus clinically provides a better guide for the choice of IOL and helps the cataract patients to attain a better postoperative refractive status. For the prediction of IOL in patients with a normal AL, we still need to conduct further studies with larger samples in the future to obtain more reliable results.

Statement of Ethics

The study was approved by the review board of the Eye Hospital of the Wenzhou Medical University and adhered to the tenets of the Declaration of Helsinki. Written informed consent was obtained from each subject.

Disclosure Statement

The authors declare that they have no competing interests.

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Author Contributions

P.C. drafted this manuscript, designed this study, and analyzed the data. F.Z. critically revised the manuscript and analyzed the data. J.W. collected the data. Y.Z. was involved in the supervision and critical revision of manuscript, and gave final approval.

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