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Algorithmic intraocular lens power calculation formula selection by keratometry, anterior chamber depth and axial length

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ABSTRACT.

Purpose: **To compare the prediction accuracy of algorithmic intraocular lens (IOL) power calculation formula selection method using conventional formulas (Haigis, Hoffer Q, Holladay 1, SRK/T and/or Barrett Universal II) based on keratometry (K), anterior chamber depth (ACD) and axial length (AL).**

Methods: **A total of 1653 patients (1653 eyes) implanted with Tecnis ZCB00 IOL during cataract surgery were enrolled in this study. Intraocular lens (IOL) power calculation formulas with a small absolute value in the sum of the area under the curve measured by K, ACD and AL subgroup were selected to calculate IOL power in the relevant biometry subgroup. The median absolute error (MedAE) calculated by the Haigis, Hoffer Q, Holladay 1, SRK/T and Barrett Universal II formulas individually was compared to that calculated by the algorithmic selection method using four formulas, Haigis, Hoffer Q, Holladay 1 and SRK/T, or five formulas when Barrett is included.**

Results: **The MedAE was 0.27 D in the Haigis, 0.30 D in the Hoffer Q, 0.27 D in the Holladay 1, 0.29 D in the SRK/T and 0.26 D in the Barrett Universal II formulas. The MedAEs determined by the algorithmic selection method using four (019 D) and five (0.21 D) formulas were significantly lower than those by the conventional IOL power calculation formulas.**

Conclusions: **The IOL power calculation formula selection method by biometry subgroup combined with biometric parameters K, ACD and AL may offer a more superior postoperative refractive error prediction in cataract surgery.**

Key words: anterior chamber depth – axial length – intraocular lens – keratometry – power

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Introduction

An accurate intraocular lens (IOL) power calculation and IOL implantation could offer patients an optimal postoperative refractive state following cataract surgery (Olsen 2007). In particular, the minimization of refractive errors by an accurate IOL power calculation improves the postoperative satisfaction of patients implanted with premium IOLs such as multifocal IOL (Kim et al. 2020). In this regard, ophthalmologists and researchers have developed a variety of formulas for more accurate IOL power calculation and have reported comparisons between the formulas (Olsen 2007; Roh et al. 2011; Cooke & Cooke 2016; Melles et al. 2018).

Previous studies have revealed that in eyes with average biometric values, such as axial length (AL) and keratometry (K), there is not much difference in the accuracy of the postoperative refractive error prediction between IOL power calculation formulas (Melles et al. 2018; Fernández et al. 2020). Conversely, for eyes with biometric values that deviate from the average, accuracy can vary depending on the formulas (Gavin & Hammond 2008; Eom et al. 2013a; Eom et al. 2014; Melles et al. 2018; Kane & Melles 2020). Thus, to improve the accuracy of the postoperative refractive error prediction, there have been efforts to select IOL power calculation formulas by a subgroup composed of the biometric parameters of eyes to be operated (Gavin & Hammond 2008; Eom et al. 2014; Hoffer & Savini 2017). Traditionally, there is a method of selection by using AL, such as the Ladas Super Formula, with its proven advantages and effectiveness (Ladas et al. 2015; Hoffer & Savini 2017; Wang et al. 2018a; Wang et al. 2018b). For eyes with short AL, the accuracy between the formulas is altered depending on the anterior chamber depth (ACD) because the change in effective lens position (ELP) has an increased effect on IOL power (Eom et al. 2014). A recent study reported that the IOL power calculation formula selected by the ratio of AL and K was evaluated to be more accurate than that by AL subgroup alone (Omoto et al. 2020).

Melles et al. (2018) explored 13 301 eyes and reported the tendency of refractive prediction error in the diversity of IOL power calculation formulas according to K, ACD and AL. Based on the refractive prediction error tendency proposed by Melles et al. (2018), this study suggests a method to select the optimal IOL power calculation formula from conventional formulas (Haigis, Hoffer Q, Holladay 1, SRK/T and Barrett Universal II) using K, ACD and AL and assessed the accuracy of the calculations.

Materials and Methods

Study population

This retrospective consecutive case study included 1653 eyes of 1653 cataract patients who underwent uncomplicated phacoemulsification with implantation of a Tecnis ZCB00 (Johnson & Johnson Vision Care, Inc.; Santa Ana, CA, USA) IOL at our institute between August 2011 and Jan 2021. We excluded patients who had a best-corrected visual acuity (BCVA) of less than 20/40 in the operated eye after cataract surgery, patients with traumatic cataracts, a history of previous ocular surgery (e.g. refractive surgery), complicated cataract surgery (e.g. posterior capsular ruptures), or postoperative complications. Institutional Review Board approval was obtained from the Korea University Ansan Hospital, Gyeonggi, Korea for this study (2021AS0078). All research and data collection adhered to the tenets of the Declaration of Helsinki.

Patient examination

Preoperative K, ACD and AL were measured using an IOLMaster 500 (Carl Zeiss Meditec, Jena, Germany). Intraocular lens (IOL) power was calculated using the Haigis, Hoffer Q, Holladay 1, SRK/T and Barrett Universal II formulas. Because IOLMaster 500 does not provide the Barrett Universal II formula, an online calculator was used (Barrett GD 2019). The Haigis formula IOL constants a_0, a_1 and a_2 were −1.302, 0.210 and 0.251, respectively, the A-constant was 119.3 for the SRK/T formula, pseudophakic ACD was 5.80 for the Hoffer Q formula, the surgeon factor was 2.02 for the Holladay 1 formula, and the Barrett Universal II A-constant was 119.39 (Haigis W 2016; Barrett GD 2019). Postoperative uncorrected visual acuity, BCVA and manifest refraction were measured at postoperative visits between 4 and 10 weeks.

Surgical technique

All phacoemulsification and IOL implantations were performed by one of eleven experienced surgeons at our institute. After topical anesthesia with proparacaine hydrochloride 0.5% (Paracaine; Hanmi Pharm, Seoul, Korea or Alcaine; Alcon Laboratories Inc, Fort Worth, TX, USA), a 2.75-mm clear corneal incision was made and a continuous curvilinear capsulorrhexis (CCC) slightly smaller than the IOL optic size was created with a 26-gauge needle and CCC forceps. A standard phacoemulsification technique was used and the IOL was inserted into the capsular bag using an injector system.

Algorithmic IOL power calculation formula selection

To determine an algorithm that selects IOL power calculation formulas (Haigis, Hoffer Q, Holladay 1, SRK/T and Barrett Universal II) by a biometry subgroup composed of biometric parameters, the present study measured the area under the curve (AUC) of the refractive prediction error figure of the formulas by K, ACD and AL, as proposed by Melles et al. (2018) using the IMAGEJ program (Figure 1; 1.43u, https://imagej.nih.gov/ij; National Institutes of Health, Bethesda, MD, USA). The unit of measurement of the refractive prediction error figure was changed from distance in pixels to dioptre using Set Scale. Next, the AUC was selected and measured by using the 'Polygon Selection tool' of IMAGEJ (Eom et al. 2013b; Eom et al. 2016). The measured AUCs were recorded to be a positive or negative value depending on whether postoperative refractive errors are hyperopia or myopia, respectively. The sum of the AUCs measured by each biometry subgroup (K, ACD and AL) was defined as refractive prediction error predicted by IOL power calculation formulas selected by the combination of three biometric parameters: K in 1.00 D steps, ACD in 0.25-mm steps, and AL in 1.00-mm steps (Fig. 1).

To prevent repetition of refractive prediction errors by the formulas owing to the correlation between K and AL or ACD and AL, a linear relation table was compiled of the correlation analysis between the biometric values of eyes enrolled in this study. If ACD and AL values are linearly related and the AUC of the refractive prediction error of the formulas by ACD and AL has the same sign, the larger error was selected for the sum of AUC. For example, as AL is positively correlated with ACD, the larger AUC of ACD and AL will be selected for the sum of AUC because the AUC of the refractive prediction error of the Hoffer Q formulas by ACD (Fig. 1B) and AL (Fig. 1C) have the same sign in eyes with K between 46.0 and 47.0 D, ACD between 2.50 and 2.75 mm, and AL between 21.0 and 22.0 mm.

In the Hoffer Q, Holladay 1 and SRK/T formulas, only K is used to predict ELP by assuming that the ACD is deep for a steep K. Thus, to prevent the refractive prediction errors from being duplicated and added again in the situation that the refractive prediction error tendency by K and ACD is the same in the Hoffer Q, Holladay 1 and SRK/T formulas, the larger AUC of the refractive prediction error based on K and ACD was used when K and ACD deviate from average and the sign of the AUC is the same.

Comparing the sum of AUC of refractive prediction error predicted by the four formulas (Haigis, Hoffer Q, Holladay 1 and SRK/T) in each biometry subgroup of the combination of three biometric parameters (K, ACD and AL), the formula with the lowest absolute value of refractive prediction error calculated by the sum of AUC was set as the IOL power calculation formula to be used in the biometry subgroups composed of the combination. However, if the first- and second-place formulas with the smallest absolute values of the sum of AUC exhibit a slight difference of less than double, and the signs of the sum of AUC are different from each other, the formula with a negative value (myopic shift) of the sum of AUC was selected as a formula for IOL power calculation (the algorithmic selection

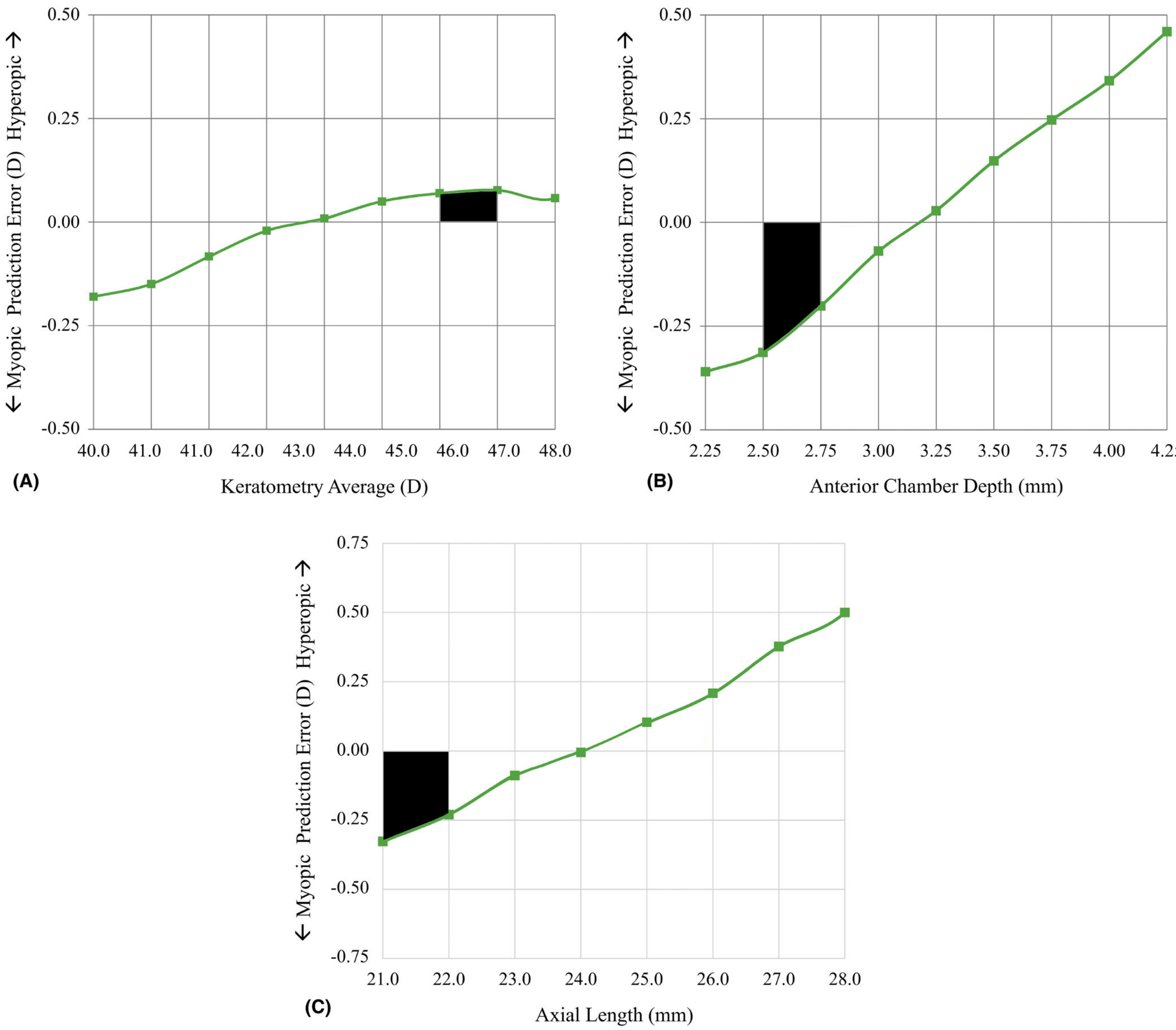

Fig. 1. An example of measurements of the area under the curve (black area) of refractive prediction error in eyes with keratometry between 46.0 and 47.0 D (A), anterior chamber depth between 2.50 and 2.75 mm (B), and axial length between 21.0 and 22.0 mm (C) in the Hoffer Q formula.

method using four formulas). In the same way, comparing the five formulas, the formula with the lowest absolute value of the sum of AUC in the biometry subgroups combined with the three biometric parameters was selected as the IOL power calculation formula to be used in the relevant biometry subgroup (the algorithmic selection method using five formulas).

Main outcome measures

The median absolute error (MedAE) and mean absolute error (MAE) were defined as the median absolute value and mean absolute value of the refractive prediction error, respectively. The refractive prediction error was defined as the difference between the manifest refraction measured between 4 to 10 weeks postoperatively and the preoperative refraction predicted by the Haigis, Hoffer Q, Holladay 1, SRK/T and Barrett Universal II formulas (refractive prediction error = postoperative manifest refraction − preoperative predicted refraction). In terms of accuracy, the MedAE and the percentage of eyes that achieved a postoperative refractive prediction error within ±0.50 D from the preoperative predicted refraction of the algorithmic selection methods using the four or five formulas were compared to those of the conventional IOL power calculation formulas, Haigis, Hoffer Q, Holladay 1, SRK/T and Barrett Universal II .

Statistical analysis

Descriptive statistics for all patient data were obtained using statistical software (Statistical Package for Social Sciences Statistics Standard 20; IBM Corp., Armonk, NY, USA). Statistical analyses included the linear regression analysis, Friedman's test and chi-square tests. Results were considered statistically significant if the p-value was <0.05.

Results

The mean age of patients enrolled in this study was 67.1 ± 10.9 years (range: 19–93 years). Of these, 671 patients were male (40.6%) and there were 810 right eyes (49.0%). Before cataract surgery, the mean K value was measured to be 44.29 ± 1.65 D (range: 37.44–49.86 D), the mean ACD value 3.08 ± 0.48 mm (range: 1.55–4.79 mm), and the mean AL 23.54 ± 1.23 mm (range: 20.32–30.20 mm). The mean IOL power applied to the surgery was 21.3 ± 2.9 D (range: 10.0–27.0 D; Table 1). Table 2 shows distribution of the number and percentage of eyes in each biometry subgroup of the combination of three biometric parameters. Linear regression analysis showed that AL was negatively correlated with K (K = −0.796 AL + 63.039, $R^2 = 0.356$ and $p < 0.001$) and positively correlated with ACD (ACD = 0.197 AL −1.558, $R^2 = 0.257$ and $p < 0.001$).

The measurements of AUC in the refractive prediction error trend curve of each IOL power calculation formula by K, ACD and AL, as proposed by Melles et al. (2018), are shown in Fig. 2. Figure 3 shows the recommended IOL power calculation formula by the algorithmic selection method using four formulas in each biometry subgroup of the three biometric parameters, K, ACD and AL. In each AL subgroup in 1.00 mm steps, the number of K-ACD combinations was 64, and that of overall K-ACD-AL combinations was 448. In the algorithmic selection method using four formulas, the Haigis formula was selected in 153 out of the 448 K-ACD-AL combinations, SRK/T in 117, Holladay 1 in 110 and Hoffer Q in 68. Therefore, the Haigis formula was selected the most.

Figure 4 shows the recommended IOL power calculation formula by the algorithmic selection method using five formulas in each biometry subgroup of the three biometric parameters. As with the four formulas, there were 448 K-ACD-AL combinations. In the algorithmic selection method using five formulas, the Haigis formula was selected in 115 out of the 448 K-ACD-AL combinations, SRK/T in 26, Holladay 1 in 48, Hoffer Q in 38 and Barrett Universal II in 221 which shows that Barrett Universal II formula was selected the most.

When the four formulas were used as algorithmic selection methods, there was regularity that the Haigis formula was selected for flat K and SRK/T for steep K in the eyes with AL of more than 26.0 mm. When the algorithmic selection method used five formulas, the SRK/T formula was replaced by Barrett Universal II formula, and it was also regularly found that the Haigis formula was selected for flat K and Barrett Universal II formula for steep K in the eyes with AL of more than 26.0 mm.

The MedAEs (interquartile range) of Haigis, Hoffer Q, Holladay 1, SRK/T and Barrett Universal II were 0.27 (0.13:0.49), 0.30 (0.15:0.58), 0.27 (0.11:0.51), 0.29 (0.12:0.49) and 0.26 (0.08:0.48) D, respectively, and the MAEs (±standard deviation) were 0.33 ± 0.26, 0.41 ± 0.35, 0.34 ± 0.29, 0.35 ± 0.29 and 0.31 ± 0.26 D, respectively. Friedman's test indicated the best results in postoperative refractive error prediction were obtained using Barrett Universal II formula, followed by Haigis formula (Table 3). The MedAE and MAE calculated by the algorithmic selection methods using four formulas were 0.19 (0.06:0.42) and 0.27 ± 0.26 D, respectively, and by using five formulas they were 0.21 (0.07:0.44) and 0.28 ± 0.26 D, respectively. Collectively, these results revealed that the two algorithmic selection methods proposed in the present study offer better results than the Haigis and Barrett Universal II

Table 1. Clinical characteristics of cataract patients and their eyes in a study of algorithmic intraocular lens power calculation formula selection according to the keratometry, anterior chamber depth and axial length (*n* = 1653).

Parameter	Mean (SD)	Range
Age, years	67.1 (10.9)	19–93
Sex		
Male, *n* (%)	671 (40.6)	
Female, *n* (%)	982 (59.4)	
Laterality		
Right eye, *n* (%)	810 (49.0)	
Left eye, *n* (%)	843 (51.0)	
Keratometry, D*	44.29 (1.65)	37.44–49.86
Anterior chamber depth, mm*	3.08 (0.48)	1.55–4.79
Axial length, mm*	23.54 (1.23)	20.32–30.20
IOL power, D	21.3 (2.9)	10.0–27.0

Data are mean (SD) except for sex and laterality, which are *n* (%).
D = dioptres, IOL = intraocular lens, SD = standard deviation.
* Keratometry, anterior chamber depth and axial length measured by IOLMaster 500.

Table 2. Distribution of the number and percentage of eyes in each biometry subgroup of the combination of three biometric parameters of keratometry, anterior chamber depth and axial length (*n* = 1653).

		ACD (mm)			
AL (mm)	K (D)	<2.75	2.75–3.25	3.25–3.75	≥3.75
<22.0 (*n* = 154)	<42.0	0 (0.00)	0 (0.00)	0 (0.00)	0 (0.00)
	42.0–44.0	5 (0.30)	1 (0.06)	0 (0.00)	0 (0.00)
	44.0–46.0	32 (1.94)	12 (0.73)	0 (0.00)	0 (0.00)
	≥46.0	53 (3.21)	45 (2.72)	6 (0.36)	0 (0.00)
22.0–23.5 (*n* = 706)	<42.0	8 (0.48)	2 (0.12)	1 (0.06)	0 (0.00)
	42.0–44.0	68 (4.11)	87 (5.26)	27 (1.63)	2 (0.12)
	44.0–46.0	107 (6.47)	190 (11.49)	85 (5.14)	7 (0.42)
	≥46.0	26 (1.57)	67 (4.05)	26 (1.57)	3 (0.18)
23.5–25.0 (*n* = 623)	<42.0	17 (1.03)	34 (2.06)	19 (1.15)	1 (0.06)
	42.0–44.0	44 (2.66)	125 (7.56)	149 (9.01)	30 (1.81)
	44.0–46.0	14 (0.85)	66 (3.99)	76 (4.60)	34 (2.06)
	≥46.0	1 (0.06)	5 (0.30)	5 (0.30)	3 (0.18)
≥25.0 (*n* = 170)	<42.0	1 (0.06)	8 (0.48)	29 (1.75)	9 (0.54)
	42.0–44.0	2 (0.12)	11 (0.67)	25 (1.51)	26 (1.57)
	44.0–46.0	4 (0.24)	13 (0.79)	22 (1.33)	16 (0.97)
	≥46.0	0 (0.00)	0 (0.00)	4 (0.24)	0 (0.00)

Values are presented as number (percentage).
ACD = anterior chamber depth, AL = axial length, D = dioptres, K = keratometry.

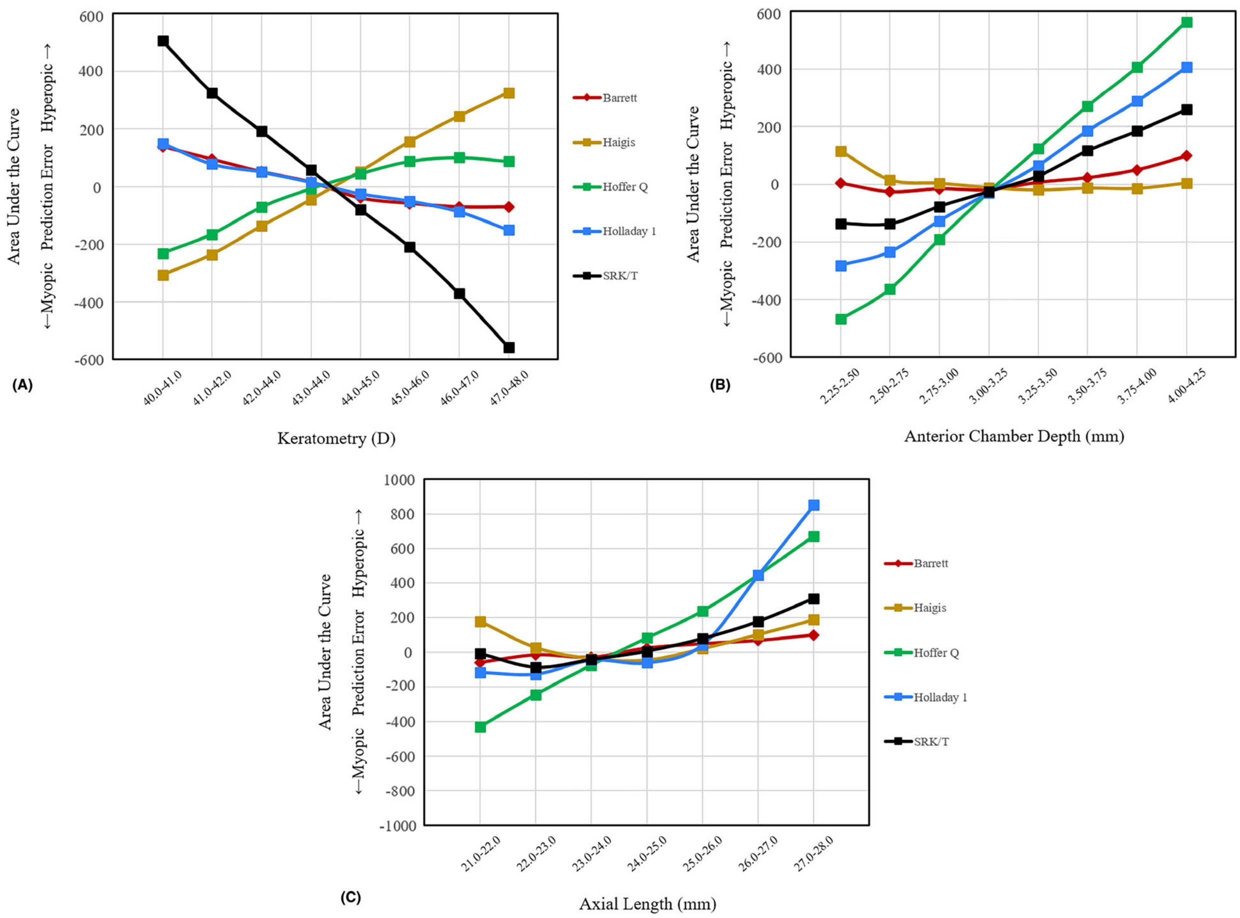

Fig. 2. The measurements of the area under the curve in the refractive prediction error trend curve of each intraocular lens power calculation formula by keratometry (A), anterior chamber depth (B) and axial length (C).

formulas for IOL power calculation. However, there was no significant difference between MedAEs calculated by the algorithmic selection method using four or five formulas (Table 4).

The percentages of postoperative refractive prediction error within ±0.50 D were 76.4%, 71.0%, 75.0%, 75.9% and 77.4% in the Haigis, Hoffer Q, Holladay 1, SRK/T and Barrett Universal II formulas, respectively (Table 3), which were significantly smaller than those of the algorithmic selection method using four (82.8%) and five (81.1%) formulas (Table 4).

Discussion

This study proposed an IOL power calculation formula selection method using four (Haigis, Hoffer Q, Hollday1 and SRK/T) or five (the four formulas including Barrett Universal II.) formulas. The formulas were compared in the 448 combinations of K-ACD-AL subgroups and the formula with the lowest absolute value of the sum of AUCs measured by each biometry subgroup (K, ACD and AL) was selected for the IOL power calculation. The results of this study demonstrated that the algorithmic selection methods using four or five formulas provided more accurate postoperative refractive error prediction than the IOL power calculation by each conventional formula. The recommended IOL power calculation formula by this study is presented in the tables of Figs 3 and 4. Users can select the recommended formula depending on the biometric values of patients by referring to the table.

In the present study, the formula selection by the method using four formulas tended to be simplified in eyes with AL of more than 26.0 mm compared to those with an average or shorter AL and indicated that the Haigis formula should be selected for flat K and the SRK/T formula for steep K. The reason for these results could be the tendency of constant refractive errors by K values in the Haigis and SRK/T formulas. The conventional IOL power calculation formulas, such as Haigis and SRK/T formulas, showed a tendency of postoperative hyperopic shift in long eyes. Previous studies have reported that postoperative refractive errors have a myopic shift for flat K and a hyperopic shift for steep K in the Haigis formula (Reitblat et al. 2017; Melles et al. 2018). Therefore, if K is flat in eyes with long AL, the postoperative refractive errors might shift toward emmetropization in the Haigis formula because the myopic shift tendency by flat K cancels out the hyperopic shift tendency of long eyes. Conversely, in the SRK/T formula, postoperative refractive errors tend to be myopia for steep K and are hyperopia for flat K (Eom et al. 2013; Reitblat et al. 2017; Melles et al. 2018). Accordingly, if K is steep in eyes with long AL, eyes might shift toward emmetropization because the myopic shift tendency by steep K cancels out the hyperopic shift tendency of long eyes.

AL (mm)	K (D) \ ACD (mm)	2.25-2.50	2.50-2.75	2.75-3.00	3.00-3.25	3.25-3.50	3.50-3.75	3.75-4.00	4.00-4.25
21.0-22.0	40.0-41.0	Haigis	Holladay1	Holladay1	Holladay1	Holladay1	Haigis	Haigis	HofferQ
	41.0-42.0	Haigis	Haigis	Holladay1	Holladay1	Holladay1	Haigis	Haigis	HofferQ
	42.0-43.0	Haigis	Haigis	Haigis	Haigis	Holladay1	Haigis	Haigis	Haigis
	43.0-44.0	SRK/T	SRK/T	SRK/T	SRK/T	Holladay1	HofferQ	HofferQ	HofferQ
	44.0-45.0	SRK/T	SRK/T	SRK/T	SRK/T	SRK/T	SRK/T	HofferQ	HofferQ
	45.0-46.0	SRK/T	SRK/T	Holladay1	Holladay1	Holladay1	SRK/T	HofferQ	SRK/T
	46.0-47.0	Holladay1	Holladay1	Holladay1	Holladay1	Holladay1	HofferQ	HofferQ	SRK/T
	47.0-48.0	Holladay1	Holladay1	Holladay1	Holladay1	Holladay1	Holladay1	HofferQ	HofferQ
AL (mm)	K (D) \ ACD (mm)	2.25-2.50	2.50-2.75	2.75-3.00	3.00-3.25	3.25-3.50	3.50-3.75	3.75-4.00	4.00-4.25
22.0-23.0	40.0-41.0	Haigis	Holladay1	Holladay1	Holladay1	Holladay1	Holladay1	HofferQ	HofferQ
	41.0-42.0	Haigis	Holladay1	Holladay1	Holladay1	Holladay1	Holladay1	HofferQ	Haigis
	42.0-43.0	Haigis	Haigis	Holladay1	Holladay1	Holladay1	HofferQ	Haigis	Haigis
	43.0-44.0	SRK/T	Haigis	Haigis	Haigis	Haigis	Haigis	Haigis	Haigis
	44.0-45.0	SRK/T	Haigis	Haigis	Haigis	Haigis	SRK/T	Haigis	Haigis
	45.0-46.0	SRK/T	SRK/T	Holladay1	Holladay1	HofferQ	HofferQ	SRK/T	SRK/T
	46.0-47.0	Holladay1	Holladay1	Holladay1	HofferQ	HofferQ	Holladay1	Holladay1	SRK/T
	47.0-48.0	Holladay1	Holladay1	Holladay1	HofferQ	HofferQ	HofferQ	Holladay1	Holladay1
AL (mm)	K (D) \ ACD (mm)	2.25-2.50	2.50-2.75	2.75-3.00	3.00-3.25	3.25-3.50	3.50-3.75	3.75-4.00	4.00-4.25
23.0-24.0	40.0-41.0	Holladay1	Holladay1	Holladay1	Holladay1	HofferQ	HofferQ	HofferQ	Haigis
	41.0-42.0	Haigis	Holladay1	Holladay1	Holladay1	HofferQ	HofferQ	HofferQ	Haigis
	42.0-43.0	SRK/T	SRK/T	Holladay1	Holladay1	HofferQ	HofferQ	Haigis	Haigis
	43.0-44.0	SRK/T	Haigis	SRK/T	SRK/T	Haigis	Haigis	Haigis	Haigis
	44.0-45.0	SRK/T	Haigis	Haigis	Haigis	Haigis	Haigis	Haigis	Haigis
	45.0-46.0	SRK/T	SRK/T	HofferQ	HofferQ	Holladay1	Holladay1	SRK/T	SRK/T
	46.0-47.0	Holladay1	Holladay1	HofferQ	HofferQ	Holladay1	Holladay1	SRK/T	SRK/T
	47.0-48.0	Holladay1	Holladay1	HofferQ	HofferQ	Holladay1	Holladay1	Holladay1	Holladay1
AL (mm)	K (D) \ ACD (mm)	2.25-2.50	2.50-2.75	2.75-3.00	3.00-3.25	3.25-3.50	3.50-3.75	3.75-4.00	4.00-4.25
24.0-25.0	40.0-41.0	Holladay1	Holladay1	Holladay1	Holladay1	HofferQ	Holladay1	Haigis	Haigis
	41.0-42.0	Haigis	Holladay1	HofferQ	Holladay1	HofferQ	Holladay1	Haigis	Haigis
	42.0-43.0	Haigis	SRK/T	HofferQ	Holladay1	HofferQ	Holladay1	Haigis	Haigis
	43.0-44.0	SRK/T	Haigis	SRK/T	SRK/T	Holladay1	Haigis	Haigis	Haigis
	44.0-45.0	SRK/T	Haigis	Haigis	Haigis	Holladay1	Haigis	Haigis	Haigis
	45.0-46.0	SRK/T	Haigis	HofferQ	Holladay1	Holladay1	SRK/T	SRK/T	SRK/T
	46.0-47.0	HofferQ	HofferQ	HofferQ	Holladay1	Holladay1	Holladay1	Holladay1	SRK/T
	47.0-48.0	HofferQ	HofferQ	HofferQ	Holladay1	Holladay1	Holladay1	Holladay1	SRK/T
AL (mm)	K (D) \ ACD (mm)	2.25-2.50	2.50-2.75	2.75-3.00	3.00-3.25	3.25-3.50	3.50-3.75	3.75-4.00	4.00-4.25
25.0-26.0	40.0-41.0	Holladay1	Holladay1	HofferQ	HofferQ	HofferQ	HofferQ	Haigis	Haigis
	41.0-42.0	Haigis	Holladay1	Holladay1	HofferQ	HofferQ	HofferQ	Haigis	Haigis
	42.0-43.0	Haigis	Haigis	Holladay1	Holladay1	Haigis	Haigis	Haigis	Haigis
	43.0-44.0	SRK/T	Haigis	SRK/T	Holladay1	Haigis	Haigis	Haigis	Haigis
	44.0-45.0	SRK/T	HofferQ	SRK/T	SRK/T	SRK/T	SRK/T	Haigis	Haigis
	45.0-46.0	SRK/T	HofferQ	Holladay1	Holladay1	Holladay1	SRK/T	SRK/T	SRK/T
	46.0-47.0	HofferQ	HofferQ	Holladay1	Holladay1	Holladay1	Holladay1	SRK/T	SRK/T
	47.0-48.0	HofferQ	HofferQ	Holladay1	Holladay1	Holladay1	Holladay1	Holladay1	SRK/T
AL (mm)	K (D) \ ACD (mm)	2.25-2.50	2.50-2.75	2.75-3.00	3.00-3.25	3.25-3.50	3.50-3.75	3.75-4.00	4.00-4.25
26.0-27.0	40.0-41.0	HofferQ	Haigis	Haigis	Haigis	Haigis	Haigis	Haigis	Haigis
	41.0-42.0	Haigis	Haigis	Haigis	Haigis	Haigis	Haigis	Haigis	Haigis
	42.0-43.0	HofferQ	Haigis	Haigis	Haigis	Haigis	Haigis	Haigis	Haigis
	43.0-44.0	HofferQ	Haigis	Haigis	Haigis	Haigis	Haigis	Haigis	Haigis
	44.0-45.0	SRK/T	SRK/T	SRK/T	SRK/T	SRK/T	SRK/T	SRK/T	Haigis
	45.0-46.0	SRK/T	SRK/T	SRK/T	SRK/T	SRK/T	SRK/T	SRK/T	SRK/T
	46.0-47.0	HofferQ	SRK/T	SRK/T	SRK/T	SRK/T	SRK/T	SRK/T	SRK/T
	47.0-48.0	HofferQ	SRK/T	SRK/T	SRK/T	SRK/T	SRK/T	SRK/T	SRK/T
AL (mm)	K (D) \ ACD (mm)	2.25-2.50	2.50-2.75	2.75-3.00	3.00-3.25	3.25-3.50	3.50-3.75	3.75-4.00	4.00-4.25
27.0-28.0	40.0-41.0	Haigis	Haigis	Haigis	Haigis	Haigis	Haigis	Haigis	Haigis
	41.0-42.0	Haigis	Haigis	Haigis	Haigis	Haigis	Haigis	Haigis	Haigis
	42.0-43.0	Haigis	Haigis	Haigis	Haigis	Haigis	Haigis	Haigis	Haigis
	43.0-44.0	HofferQ	Haigis	Haigis	Haigis	Haigis	Haigis	Haigis	Haigis
	44.0-45.0	SRK/T	SRK/T	SRK/T	SRK/T	Haigis	Haigis	Haigis	Haigis
	45.0-46.0	SRK/T	SRK/T	SRK/T	SRK/T	SRK/T	SRK/T	SRK/T	SRK/T
	46.0-47.0	SRK/T	SRK/T	SRK/T	SRK/T	SRK/T	SRK/T	SRK/T	SRK/T
	47.0-48.0	SRK/T	SRK/T	SRK/T	SRK/T	SRK/T	SRK/T	SRK/T	SRK/T

Fig. 3. Table of recommended intraocular lens power calculation formula by the algorithmic selection method using four formulas in each biometry subgroup of the combination of three biometric parameters: keratometry, anterior chamber depth and axial length.

AL (mm)	ACD (mm) / K (D)	2.25-2.50	2.50-2.75	2.75-3.00	3.00-3.25	3.25-3.50	3.50-3.75	3.75-4.00	4.00-4.25
21.0-22.0	40.0-41.0	Haigis	Barrett	Holladay1	Holladay1	Holladay1	Haigis	Haigis	HofferQ
	41.0-42.0	Haigis	Haigis	Holladay1	Barrett	Holladay1	Haigis	Haigis	HofferQ
	42.0-43.0	Barrett	Barrett	Barrett	Barrett	Holladay1	Barrett	Haigis	Haigis
	43.0-44.0	Barrett	Barrett	SRK/T	SRK/T	Holladay1	Barrett	Barrett	Barrett
	44.0-45.0	Barrett	Barrett	Barrett	SRK/T	SRK/T	SRK/T	HofferQ	Barrett
	45.0-46.0	Barrett	Barrett	Barrett	Barrett	Holladay1	Barrett	Barrett	Barrett
	46.0-47.0	Barrett	Barrett	Barrett	Barrett	Holladay1	Barrett	Barrett	Barrett
	47.0-48.0	Barrett	Barrett	Barrett	Barrett	Barrett	Barrett	Barrett	Barrett
AL (mm)	ACD (mm) / K (D)	2.25-2.50	2.50-2.75	2.75-3.00	3.00-3.25	3.25-3.50	3.50-3.75	3.75-4.00	4.00-4.25
22.0-23.0	40.0-41.0	Haigis	Holladay1	Holladay1	Holladay1	Holladay1	Holladay1	HofferQ	HofferQ
	41.0-42.0	Haigis	Barrett	Holladay1	Holladay1	Holladay1	Holladay1	HofferQ	Haigis
	42.0-43.0	Haigis	Barrett	Barrett	Barrett	Holladay1	HofferQ	Haigis	Haigis
	43.0-44.0	Barrett	Barrett	Barrett	Barrett	Haigis	Haigis	Haigis	Haigis
	44.0-45.0	Barrett	Barrett	Barrett	Barrett	Barrett	Barrett	Barrett	Haigis
	45.0-46.0	Barrett	Barrett	Barrett	Barrett	HofferQ	Barrett	Barrett	Barrett
	46.0-47.0	Barrett	Barrett	Barrett	Barrett	HofferQ	Holladay1	Barrett	Barrett
	47.0-48.0	Barrett	Barrett	Barrett	Barrett	HofferQ	Barrett	Holladay1	Barrett
AL (mm)	ACD (mm) / K (D)	2.25-2.50	2.50-2.75	2.75-3.00	3.00-3.25	3.25-3.50	3.50-3.75	3.75-4.00	4.00-4.25
23.0-24.0	40.0-41.0	Barrett	Holladay1	Holladay1	Holladay1	HofferQ	HofferQ	HofferQ	Haigis
	41.0-42.0	Barrett	Barrett	Holladay1	Holladay1	HofferQ	HofferQ	Barrett	Haigis
	42.0-43.0	SRK/T	Barrett	Barrett	Holladay1	HofferQ	Barrett	Barrett	Haigis
	43.0-44.0	Barrett	Haigis	Barrett	Barrett	Barrett	Barrett	Haigis	Haigis
	44.0-45.0	Barrett	Haigis	Haigis	Haigis	Haigis	Haigis	Haigis	Haigis
	45.0-46.0	Barrett	Barrett	Barrett	HofferQ	Holladay1	Barrett	Barrett	SRK/T
	46.0-47.0	Barrett	Barrett	HofferQ	HofferQ	Holladay1	Holladay1	Barrett	Barrett
	47.0-48.0	Barrett	Barrett	Barrett	HofferQ	Barrett	Holladay1	Barrett	Barrett
AL (mm)	ACD (mm) / K (D)	2.25-2.50	2.50-2.75	2.75-3.00	3.00-3.25	3.25-3.50	3.50-3.75	3.75-4.00	4.00-4.25
24.0-25.0	40.0-41.0	Holladay1	Holladay1	Holladay1	Holladay1	HofferQ	Holladay1	Haigis	Haigis
	41.0-42.0	Haigis	Barrett	HofferQ	Holladay1	HofferQ	Holladay1	Haigis	Barrett
	42.0-43.0	Haigis	Barrett	Barrett	Holladay1	Barrett	Barrett	Haigis	Haigis
	43.0-44.0	Barrett	Barrett	Barrett	Barrett	Holladay1	Haigis	Haigis	Haigis
	44.0-45.0	Barrett	Haigis	Haigis	Haigis	Holladay1	Haigis	Haigis	Haigis
	45.0-46.0	Barrett	Barrett	HofferQ	Barrett	Barrett	Barrett	Barrett	SRK/T
	46.0-47.0	Barrett	Barrett	HofferQ	Barrett	Barrett	Barrett	Barrett	SRK/T
	47.0-48.0	Barrett	Barrett	HofferQ	Barrett	Barrett	Barrett	Barrett	Barrett
AL (mm)	ACD (mm) / K (D)	2.25-2.50	2.50-2.75	2.75-3.00	3.00-3.25	3.25-3.50	3.50-3.75	3.75-4.00	4.00-4.25
25.0-26.0	40.0-41.0	Holladay1	Holladay1	HofferQ	HofferQ	HofferQ	HofferQ	Haigis	Haigis
	41.0-42.0	Haigis	Holladay1	Holladay1	HofferQ	HofferQ	HofferQ	Haigis	Haigis
	42.0-43.0	Haigis	Barrett	Barrett	Holladay1	Barrett	Barrett	Haigis	Haigis
	43.0-44.0	SRK/T	Haigis	SRK/T	Holladay1	Haigis	Haigis	Haigis	Haigis
	44.0-45.0	Barrett	Barrett	Barrett	Barrett	SRK/T	Barrett	Barrett	Haigis
	45.0-46.0	Barrett	Barrett	Barrett	Barrett	Barrett	Barrett	Barrett	Barrett
	46.0-47.0	Barrett	HofferQ	Barrett	Barrett	Holladay1	Barrett	Barrett	SRK/T
	47.0-48.0	Barrett	HofferQ	Barrett	Barrett	Barrett	Barrett	Barrett	Barrett
AL (mm)	ACD (mm) / K (D)	2.25-2.50	2.50-2.75	2.75-3.00	3.00-3.25	3.25-3.50	3.50-3.75	3.75-4.00	4.00-4.25
26.0-27.0	40.0-41.0	HofferQ	Haigis	Haigis	Haigis	Haigis	Haigis	Haigis	Haigis
	41.0-42.0	Haigis	Haigis	Haigis	Haigis	Haigis	Haigis	Haigis	Haigis
	42.0-43.0	HofferQ	Haigis	Haigis	Haigis	Haigis	Haigis	Haigis	Haigis
	43.0-44.0	HofferQ	Barrett	Haigis	Haigis	Haigis	Haigis	Haigis	Haigis
	44.0-45.0	SRK/T	Barrett	Barrett	Barrett	Barrett	Barrett	Barrett	Barrett
	45.0-46.0	Barrett	Barrett	Barrett	Barrett	SRK/T	SRK/T	SRK/T	Barrett
	46.0-47.0	Barrett	Barrett	Barrett	Barrett	Barrett	Barrett	Barrett	SRK/T
	47.0-48.0	Barrett	Barrett	Barrett	Barrett	Barrett	Barrett	Barrett	SRK/T
AL (mm)	ACD (mm) / K (D)	2.25-2.50	2.50-2.75	2.75-3.00	3.00-3.25	3.25-3.50	3.50-3.75	3.75-4.00	4.00-4.25
27.0-28.0	40.0-41.0	Haigis	Haigis	Haigis	Haigis	Haigis	Haigis	Haigis	Haigis
	41.0-42.0	Haigis	Haigis	Haigis	Haigis	Haigis	Haigis	Haigis	Haigis
	42.0-43.0	Barrett	Haigis	Haigis	Haigis	Haigis	Haigis	Haigis	Haigis
	43.0-44.0	Barrett	Barrett	Barrett	Barrett	Barrett	Haigis	Barrett	Barrett
	44.0-45.0	Barrett	Barrett	Barrett	Barrett	Barrett	Barrett	Barrett	Barrett
	45.0-46.0	Barrett	Barrett	Barrett	Barrett	Barrett	Barrett	Barrett	Barrett
	46.0-47.0	SRK/T	SRK/T	SRK/T	Barrett	SRK/T	Barrett	SRK/T	SRK/T
	47.0-48.0	Barrett	Barrett	Barrett	Barrett	Barrett	SRK/T	Barrett	Barrett

Fig. 4. Table of recommended intraocular lens power calculation formula by the algorithmic selection method using five formulas in each biometry subgroup of the combination of three biometric parameters: keratometry, anterior chamber depth and axial length.

Table 3. Median absolute error and mean refractive prediction error calculated by the Haigis, Hoffer Q, Holladay 1, SRK/T and Barrett Universal II formulas (n = 1653).

	Haigis	Hoffer Q	Holladay 1	SRK/T	Barrett U II	p-value
MedAE, D*	0.27 (0.13:0.49)	0.30 (0.15:0.58)	0.27 (0.11:0.51)	0.29 (0.12:0.49)	0.26 (0.08:0.48)	<0.001†
MAE, D‡	0.33 ± 0.26	0.41 ± 0.35	0.34 ± 0.29	0.35 ± 0.29	0.31 ± 0.26	
RE, D (range)	−0.03 (−1.69 to 1.22)	0.08 (−1.60 to 2.15)	−0.06 (−1.58 to 1.78)	−0.09 (−1.75 to 1.85)	−0.06 (−1.46 to 1.95)	
±0.25 D, n (%)	775 (46.9)	707 (42.8)	793 (48.0)	772 (46.7)	863 (52.2)	
±0.50 D, n (%)	1263 (76.4)	1174 (71.0)	1240 (75.0)	1255 (75.9)	1279 (77.4)	<0.001§
±0.75 D, n (%)	1526 (92.3)	1420 (85.9)	1498 (90.6)	1470 (88.9)	1539 (93.1)	
>±1.00 D, n (%)	23 (1.4)	122 (7.4)	50 (3.0)	68 (4.1)	21 (1.3)	

D = dioptres, IOL = intraocular lens, MAE = mean absolute error, MedAE = median absolute error, RE = mean refractive prediction error.
* Values are presented as median (interquartile range).
† Friedman's test comparing the five formulas.
‡ Values are presented as mean ± standard deviation.
§ Chi-square test.

Table 4. Median absolute error and mean refractive prediction error calculated by the Haigis and Barrett Universal II formulas and algorithmic intraocular lens calculation formula selection method using 4 formulas and 5 formulas (n = 1653).

	Haigis	Barrett U II	Using 4 formulas	Using 5 formulas	p-value
MedAE, D*	0.27 (0.13:0.49)	0.26 (0.08:0.48)	0.19 (0.06:0.42)	0.21 (0.07:0.44)	<0.001†
MAE, D‡	0.33 ± 0.26	0.31 ± 0.26	0.27 ± 0.26	0.28 ± 0.26	
RE, D (range)	−0.03 (−1.69 to 1.22)	−0.06 (−1.46 to 1.95)	−0.07 (−1.55 to 1.53)	−0.04 (−1.55 to 1.53)	
±0.25 D, n (%)	775 (46.9)	863 (52.2)	964 (58.3)	917 (55.5)	
±0.50 D, n (%)	1263 (76.4)	1279 (77.4)	1369 (82.8)	1341 (81.1)	< 0.001§
±0.75 D, n (%)	1526 (92.3)	1539 (93.1)	1555 (94.1)	1552 (93.9)	
>±1.00 D, n (%)	23 (1.4)	21 (1.3)	25 (1.5)	15 (0.9)	

D = dioptres, IOL = intraocular lens, MAE = mean absolute error, MedAE = median absolute error, RE = mean refractive prediction error.
* Values are presented as median (interquartile range).
† Friedman's test comparing the four formulas.
‡ Values are presented as mean ± standard deviation.
§ Chi-square test.

The SRK/T formula selected by the algorithmic selection method using four formulas was replaced by the Barrett Universal II formula by the algorithmic selection method using five formulas in eyes with AL of more than 26.0 mm. As a result, the Haigis formula was selected for flat K and Barrett Universal II formula for steep K in eyes with long AL. Consistent with the results of the previous study, these results imply that postoperative refractive errors are hyperopia for flat K and are myopia for steep K in the Barrett Universal II formula just as in the SRK/T formula (Reitblat et al. 2017; Melles et al. 2018). A comparison study for accuracy between nine IOL power calculation formulas showed that the Haigis and Barrett Universal II formulas offered the most accurate results in eyes with AL of more than 26 mm except with the Olsen formula (Cooke & Cooke 2016). Accordingly, it is reasonable to suggest that if the Haigis and Barrett Universal II formulas, which are believed to be accurate in eyes with long AL, are selected differently by K values, IOL power calculation by using the two formulas may provide more accurate results than using each formula alone.

The Hoffer Q formula is known to be accurate in eyes with short AL (Hoffer 1993; Gavin & Hammond 2008); however, recent studies have reported that the Hoffer Q formula is not that accurate, and other formulas, including Haigis, are more accurate in these eyes (Roh et al. 2011; Eom et al. 2014; Melles et al. 2018). The present study showed that as a result of using the algorithmic selection method using four formulas, the Hoffer Q formula was selected in a large number of biometry subgroups in eyes with AL of <22.0 mm and ACD deeper than 3.50 mm. In contrast, the formula was not selected in eyes with ACD shallower than 3.50 mm. Similar to the results of this study, a previous comparison for accuracy between the Haigis and Hoffer Q formulas in eyes with AL of <22.0 mm reported that the Haigis formula, when compared to the Hoffer Q formula, was more accurate in eyes with ACD of <2.40 mm.

In this study, the Barrett Universal II formula provided the most accurate results in postoperative refractive error prediction compared to other formulas, Haigis, Hoffer Q, Holladay 1 and SRK/T. However, the algorithmic selection method using five formulas, with the additional Barrett Universal II formula, did not exhibit further improvements in terms of IOL power calculation accuracy compared to the algorithmic selection method using the four formulas (Haigis, Hoffer Q, Holladay 1 and SRK/T). These results suggest that the algorithmic selection method using the four formulas depending on the combination of biometric parameters fully reflected the merits of each formula and, thus, further enhanced the accuracy compared to when each formula was used alone.

This study has several limitations. First, although preoperative biometry was measured using Lenstar 900 in the article of Melles et al. (2018), which is used as a reference in this study, IOL power calculations were based on biometric values measured by IOLMaster 500 in this study. The biometric values measured by the two biometric devices showed high accuracy (Kunert et al. 2016); however, the accuracy of IOL power calculation formulas may vary depending on biometric devices (Cooke & Cooke 2016). Indeed, Cooke & Cooke (2016) revealed that the accuracy of IOL power calculation formulas was altered depending on whether the biometric values were measured by the IOLMaster 500 or Lenstar 900. Second, there was no information on the tendency for refractive prediction error of IOL power calculation formulas in eyes with AL of <21.0 mm or more than 28.0 mm in the reference study (Melles et al. 2018). Thus, our results do not apply to those eyes. Third, this study was conducted retrospectively and involved eleven surgeons. Thus, a prospective study is needed to confirm the precision of the algorithmic selection method using five formulas in each biometry subgroup of combinations of the three biometric parameters suggested in this study.

In conclusion, the algorithm selection methods using the Haigis, Hoffer Q, Holladay 1, SRK/T and Barrett Universal II formulas for IOL power calculation according to biometry subgroups composed of the combination of three biometric parameters, K, ACD and AL, may more accurately predict postoperative refraction after cataract surgery compared to when conventional formulas are used separately.

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