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Lower refractive prediction accuracy of total keratometry using intraocular lens formulas loaded onto a swept-source optical biometer

Yukitaka Danjo[1] · Reina Ohji[1] · Sayo Maeno[1]

Abstract

Purpose To compare refractive outcomes calculated using intraocular lens (IOL) power calculation formulas loaded onto the IOLMaster 700 with the employment of anterior keratometry (K) and total keratometry (TK).

Methods A total of 225 eyes of 225 patients underwent uneventful cataract surgery and implantation of a single model of nontoric monofocal IOL by a single surgeon. All eyes underwent preoperative ocular biometric measurements with the IOLMaster 700. Refractive outcomes, including the mean numerical prediction error (MNE); standard deviation (SD); adjusted mean absolute prediction error (MAE); adjusted median absolute prediction error (MedAE); percentages of eyes with adjusted prediction error (PE) within $\pm 0.25, \pm 0.50, \pm 0.75$, and ± 1.00 diopter; and IOL Formula Performance Index (FPI), were compared between the K-based formula and the TK-based formula of Barrett Universal II (BUII), Haigis, SRK/T, Holladay 2, and Hoffer Q. Axial length (short, medium, and long) subgroup analyses and anterior and posterior keratometry (flat, medium, and steep) subgroup analyses were conducted.

Results The K-based formula performed better than the TK-based formula in the accuracy of refractive prediction of each IOL calculation formula: BUII-K (FPI 0.690), BUII-TK (0.677), Haigis-K (0.617), Haigis-TK (0.584), SRK/T-K (0.608), SRK/T-TK (0.595), Holladay 2-K (0.419), Holladay 2-TK (0.406), Hoffer Q-K (0.364), and Hoffer Q-TK (0.356). The subgroup analyses of refractive prediction outcomes showed that TK influenced the refractive outcomes in eyes with relatively normal ranges of axial length and anterior keratometry.

Conclusions Using TK instead of K leads to lower refractive prediction accuracy of the IOL power calculation formulas loaded on the IOLMaster 700.

Keywords Total keratometry · Intraocular lens formula · Refractive prediction accuracy · Swept-source optical biometer

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Key messages

- The measurement of the posterior corneal surface has the potential to achieve better refractive and astigmatic outcomes in IOL power calculation in eyes that have undergone previous laser vision correction surgery and toric IOL implantation.

- The use of total keratometry in IOL power calculations in eyes with nontoric monofocal IOL implantation is believed to better minimize postoperative refractive error.

- However, this study shows the contrary, suggesting that IOL power calculation formulas may need to be optimized for total keratometry and that there may be a measurement error of total keratometry with the IOLMaster 700.

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Introduction

Cataract surgery has increasingly become a refractive surgery in developed countries due to the improvement of surgical machines, examination apparatuses, surgical devices and techniques; the advent of premium intraocular lenses (IOLs); and the higher expectations of patients for quality of vision and life [1]. Against this background, IOL power calculation formulas have been updated to minimize the postoperative refractive error. IOL formulas are now categorized into historical/refraction-based, regression, vergence, artificial intelligence, and ray tracing [2]. In recent years, there has been a transition in the vergence formula from SRK/T [3] and Hoffer Q [4] to Haigis [5], Holladay 2 (unpublished), and Barrett Universal II (BUII) (unpublished). Among them, the BUII formula is reported to perform better than others by many articles [6–9] and in widespread use to determine the IOL power.

In addition to refining the IOL power calculation formula, swept-source optical coherence tomography (OCT) technology has revolutionized the measurement of ocular biometry with toric IOLs, multifocal IOLs, and laser vision correction (LVC), leading to the development of sophisticated devices such as the IOLMaster 700 (Carl Zeiss Meditec) [10, 11]. This device can measure total keratometry (TK) by combining anterior and posterior corneal surfaces, in addition to anterior keratometry (K) [12]. It has been reported that the measurement of posterior corneal astigmatism has the potential to reduce residual astigmatic error in toric IOL implantation [13, 14]. In fact, toric calculators with posterior corneal astigmatism measurement achieve comparable or better results in the prediction of postoperative astigmatic outcome [15, 16] and IOL power calculation in eyes that have undergone LVC [17, 18]. However, a considerable number of reports have shown that directly measured total corneal astigmatism (TCA) for toric IOL calculation is not superior to the calculated TCA, suggesting that the optimization of corneal astigmatism measurements is necessary [19–21]. Reports on the usefulness of TK for refractive outcomes in normal eyes implanted with nontoric IOLs are scarce. Fabian and Wehner reported that in comparison to standard K, a higher prediction accuracy can be expected by using TK values in relatively high astigmatic eyes (0.75 D or greater) [22]. Srivannaboon and Chirapapaisan reported that conventional K and TK for IOL calculation showed strong agreement with a nonsignificant trend toward better refractive outcomes using TK [23]. If the TK-based formula should be superior to the K-based formula in the prediction of postoperative refractive errors in normal eyes, then the K-based formula will be of no use.

Thus, this study aimed to determine whether the TK-based IOL power calculation formula performs better than the K-based formula in terms of refractive prediction accuracy. To this end, we compared the postoperative refractive errors calculated by BUII, Haigis, SRK/T, Holladay 2, and Hoffer Q (which are built-in formulas of the IOLMaster 700) with use of K and TK, and we conducted subgroup analyses according to axial length and keratometry.

Methods

This retrospective study was approved by the institutional review board of Osaka Minato Central Hospital and adhered to the tenets of the Declaration of Helsinki.

The enrolled cataract eyes were measured preoperatively with the IOLMaster 700 to assess the following ocular biometric variables: axial length (AL), K, TK, posterior keratometry (PK), anterior chamber depth (ACD), lens thickness (LT), and white-to-white (WTW). All operations were performed by a single skilled surgeon (Y.D.) at Osaka Minato Central Hospital from September 1, 2019 to August 31, 2021. The eyes underwent uneventful phacoemulsification and implantation of a single IOL model (ZCBOOV, Johnson and Johnson Vision) through a temporal 2.4-mm clear corneal incision and were followed up for at least 1 month postoperatively. They achieved a corrected distance visual acuity (CDVA) of 20/32 or better. If both eyes of a patient were operated on, only the first eye was enrolled since the second eye may have been adjusted for IOL power calculation and surgical procedure based on the outcome of the first eye [24]. Eyes with previous ocular surgery, corneal irregular astigmatism, corneal epithelial damage, and significant vitreous opacity were excluded.

Preoperative examinations included CDVA, anterior autokeratometry (AK) measured with an autokeratometer (TONOREF III, NIDEK), corneal topography (TMS-4 N and CASIA2, TOMEY), and the measurement of AL, K, TK, PK, ACD, LT, and WTW with the IOLMaster 700 (version 1.90.12.05). Manifest CDVA and AK with the autokeratometer were measured at 1 month postoperatively. The CDVA was measured using a Landolt ring at 5 m, and the decimal acuity was converted to the Snellen equivalent of the visual acuity conversion chart [25]. To assess the surgically induced astigmatism (SIA), the AK and its astigmatic axis measured pre- and postoperatively with the autokeratometer were input into the computer program (http://links.lww.com/JRS/A281, accessed February 1, 2022) created by Næser [26]. The IOL power for implantation was determined by entering a target refraction into the TK-based BUII (BUII-TK) formula of IOLMaster 700. The postoperative predicted refractions were back-calculated from the implanted IOL power using BUII-K and -TK, Haigis-K and -TK, SRK/T-K

and -TK, Holladay 2-K and -TK, and Hoffer Q-K and -TK, all of which are the built-in formulas of IOLMaster 700. Both the BUII-K and the BUII-TK used all the variables, including K and TK, respectively, AL, ACD, LT, and WTW, to calculate IOL power. The lens factor for the BUII was $+2.15$, the a0, a1, and a2 for the Haigis $-0.329, +0.332$, and $+0.203$, respectively, the A-constant for the SRK/T 119.3, the ACD for the Holladay $2 + 5.951$, and the pseudophakic ACD for the Hoffer $Q + 5.98$.

The postoperative manifest refraction at 1 month after surgery was subtracted by the formula-predicted refraction calculated using the respective IOL formulas to obtain the postoperative prediction error (PE). The absolute value of PE was defined as the absolute prediction error (APE). The mean numerical prediction error (MNE) for the mean of the PE, the standard deviation (SD) of the PE, the mean absolute prediction error (MAE) for the mean of the APE, and the median absolute prediction error (MedAE) for the median of the APE were calculated. Since the MNE should ideally be zero, the adjusted PE was computed by subtracting the MNE from the PE to obtain the adjusted MNE (equal to zero), adjusted MAE, and adjusted MedAE. The percentages of eyes with adjusted PEs within $\pm 0.25, \pm 0.50, \pm 0.75$, and ± 1.00 diopter (D) calculated by the individual formulas were obtained. The IOL Formula Performance Index (FPI) proposed by Wolfgang Haigis, which is available in the On Demand section at www.escrs.org (accessed January 26, 2022) and introduced by Hoffer and Savini [27], was calculated to rank the accuracy of the formula.

Eyes were divided into 3 subgroups of short (AL < 22.5 mm), medium (AL ≧ 22.5 mm and < 25.5 mm), and long (AL ≧ 25.5 mm) based on the AL values; 3 subgroups of flat (AK < 42 D), medium (AK ≧ 42 D and < 46 D), and steep (AK ≧ 46 D) based on the preoperative mean autokeratometric values; and 3 subgroups of flat (PK ≧ −5.74 D), medium (PK < −5.74 D and ≧ −6.08 D), and steep (PK < −6.08 D) based on the interquartile range (IQR) of the preoperative mean PK: the value of −6.08 D for the 1st quartile and −5.74 D for the 3rd quartile.

Comparison of the MNE and the adjusted MAE between the K-based formula and the TK-based formula was conducted using the Wilcoxon signed rank test. Comparison of the SD between the IOL formulas was conducted using the heteroscedastic statistical method [28]. K and TK values of the subgroups were also compared using the Wilcoxon signed rank test. All analyses except for the heteroscedastic method were processed using BellCurve for Excel version 3.23 (Social Survey Research Information Co., Ltd.). The heteroscedastic method was performed by downloading the R Project Computing at https://www.r-project.org/ and the files at https://osf.io/nvd59/quickfiles (accessed May 27, 2022). A P value < 0.05 was considered statistically significant.

Results

A total of 225 eyes of 225 patients (109 right eyes, 126 females) were included in the study. The demographics and characteristics of the study population are shown in Table 1.

Comparison of postoperative refractive outcomes between the K-based and TK-based formulas

Comparisons of the postoperative refractive prediction outcomes derived from the individual IOL power calculation formulas using K and TK are shown in Table 2. Except for the BUII ($P = 0.420$), the TK-based formula had a significantly larger MNE, i.e., hyperopic shift, than the K-based formula for the Haigis ($P = 0.014$), SRK/T ($P = 0.004$), Holladay 2 ($P = 0.007$), and Hoffer Q ($P = 0.013$) formulas. The SD of the MNE was larger in the TK-based formula than in the K-based formula for each IOL power calculation formula. The heteroscedastic statistical method shows that there is a statistical significance in the SD between the BUII-K and the Holladay 2-TK, the Hoffer Q-K, and the Hoffer Q-TK, respectively, and between the BUII-TK and the Hoffer Q-K and the Hoffer Q-TK, respectively (Table 3). The adjusted MAE was significantly larger in the TK-based formula than in the K-based formula for the Haigis ($P = 0.043$) and the SRK/T ($P = 0.043$) and tended to be larger in the TK-based formula for the BUII ($P = 0.050$), the Holladay 2 ($P = 0.063$), and the Hoffer Q ($P = 0.072$). The adjusted MedAE was larger in the TK-based formula than in the K-based formula for each IOL power calculation formula. The BUII-K had higher percentages of eyes than the other formulas in all the brackets within $\pm 0.25, \pm 0.50, \pm 0.75$, and ± 1.00 D of the adjusted PE, except that those of the BUII-K and BUII-TK were equal in the bracket within ± 0.75 D (also shown in Figure 1). The accuracy of the IOL power calculation formulas was ranked by using the FPI. The BUII-K held the first place in the ranking of accuracy. Moreover, the K-based formula had a better FPI than the TK-based formula for each IOL power calculation formula.

Axial length and keratometry subgroup analyses of refractive prediction outcomes between K- and TK-based formulas

Table 4 shows the refractive prediction outcomes in 3 subgroups of short, medium, and long AL. In the short AL group, the SD was larger in each TK-based formula than in the corresponding K-based formula, and the adjusted MAE was significantly larger in the BUII-TK ($P = 0.030$) and the Holladay 2-TK ($P = 0.006$) than in the BUII-K and the Holladay 2-K, respectively. In the medium AL group, the

Table 1 Demographics of the study population

No. patients/eyes	225/225		
Male/female	99/126		
No. right/left eyes	109/116		
	Mean ± SD	Median	Range
Age (yr)	75.1 ± 8.8	76.5	44 to 94
Postop CDVA (logMAR)	− 0.05 ± 0.10	− 0.08	− 0.18 to 0.15
Preop mean autokeratometry (D)	44.24 ± 1.53	44.03	41.11 to 49.10
Preop autokeratometric astigmatism (D)	0.96 ± 0.63	0.82	0 to 3.78
Preop K (D)	44.26 ± 1.53	44.10	41.09 to 49.10
Preop TK (D)	44.28 ± 1.53	44.17	40.98 to 49.01
Preop PK (D)	− 5.93 ± 0.24	− 5.93	− 6.70 to − 5.33
SIA (D)	0.54 ± 0.38	0.45	0.03 to 2.18
AL (mm)	23.95 ± 1.50	23.75	20.47 to 30.02
ACD (mm)	3.06 ± 0.42	3.03	1.90 to 4.17
LT (mm)	4.60 ± 0.44	4.62	3.01 to 5.81
WTW (mm)	11.79 ± 0.44	11.8	10.4 to 13.1
Implanted IOL power (D)	20.58 ± 3.41	21	7.5 to 30

SD standard deviation, *postop* postoperative, *CDVA* corrected distance visual acuity, *logMAR* logarithm of minimum angle of resolution, *preop* preoperative, *D* diopter, *K* anterior corneal keratometry, *TK* total corneal keratometry, *PK* posterior corneal keratometry, *SIA* surgically induced astigmatism, *AL* axial length, *ACD* anterior chamber depth, *LT* lens thickness, *WTW* white-to-white, *IOL* intraocular lens

Table 2 Comparison of postoperative refractive outcomes between the K-based and TK-based IOL power calculation formulas

N = 225	MNE ± SD	Adjusted MAE	Adjusted MedAE	Percentages of eyes with adjusted PE (%)				FPI
				± 0.25 D	± 0.50 D	± 0.75 D	± 1.00 D	
BUII-K	0.115 ± 0.457	0.357	0.300	43.6	74.7	89.3	97.8	0.690
BUII-TK	0.120 ± 0.469	0.368	0.310	43.1	71.6	89.3	96.4	0.677
P value	0.420	0.050						
Haigis-K	− 0.088 ± 0.489	0.390	0.312	40.4	68.9	87.1	96.4	0.617
Haigis-TK	− 0.066 ± 0.501	0.403	0.360	36.9	68.4	85.3	96.4	0.584
P value	0.014*	0.043*						
SRK/T-K	0.077 ± 0.522	0.407	0.317	41.3	67.6	84.9	95.1	0.608
SRK/T-TK	0.099 ± 0.525	0.413	0.331	40.0	68.9	83.6	93.3	0.595
P value	0.004*	0.043*						
Holladay 2-K	− 0.178 ± 0.549	0.433	0.348	36.4	64.4	83.1	92.4	0.419
Holladay 2-TK	− 0.162 ± 0.563	0.444	0.382	36.9	61.8	82.2	92.9	0.406
P value	0.007*	0.063						
Hoffer Q-K	− 0.055 ± 0.566	0.435	0.330	35.6	66.2	80.9	91.6	0.364
Hoffer Q-TK	− 0.039 ± 0.576	0.445	0.371	37.3	65.8	81.3	90.7	0.356
P value	0.013*	0.072						

P values were computed using the Wilcoxon signed rank test

K anterior corneal keratometry, *TK* total corneal keratometry, *MNE* mean numerical prediction error, *SD* standard deviation, *MAE* mean absolute prediction error, *MedAE* median absolute prediction error, *PE* prediction error, *D* diopter, *FPI* IOL formula performance index, *BUII* Barrett Universal II

*Statistically significant

MNE was significantly larger, i.e., hyperopic shift, in each TK-based formula than in the K-based formula except for the BUII: the BUII (*P* = 0.123), the Haigis (*P* = 0.008), the SRK/T (*P* = 0.002), the Holladay 2 (*P* = 0.005), and the Hoffer Q (*P* = 0.008). The SD was larger in each TK-based formula than in the K-based formula except for SRK/T.

Table 3 Matrix of heteroscedastic P values between the IOL power calculation formulas

Formula	SD	HC adj P	HC adj P	HC adj P	HC adj P	HC adj P	HC adj P	HC adj P	HC adj P	HC adj P	HC adj P
BUII-K	0.457	1									
BUII-TK	0.469	7.05E−01	1								
Haigis-K	0.489	6.27E−01	8.91E−01	1							
Haigis-TK	0.501	4.09E−01	6.27E−01	8.91E−01	1						
SRK/T-K	0.522	1.46E−01	3.77E−01	7.61E−01	8.91E−01	1					
SRK/T-TK	0.525	9.69E−02	2.67E−01	7.05E−01	8.91E−01	8.91E−01	1				
Holladay2-K	0.549	3.61E−01	2.60E−01	6.04E−01	2.36E−01	8.91E−01	8.91E−01	1			
Holladay2-TK	0.563	4.49E−02*	5.75E−01	3.85E−01	5.88E−01	7.05E−01	7.05E−01	5.47E−01	1		
HofferQ-K	0.566	7.13E−04*	2.12E−03*	3.27E−01	2.04E−01	7.84E−01	7.84E−01	8.91E−01	8.91E−01	1	
HofferQ-TK	0.576	5.91E−05*	3.92E−03*	1.48E−01	3.20E−01	6.58E−01	6.46E−01	7.05E−01	7.05E−01	7.84E−01	1
		BUII-K	BUII-TK	Haigis-K	Haigis-TK	SRK/T-K	SRK/T-TK	Holladay2-K	Holladay2-TK	HofferQ-K	HofferQ-TK

P values were computed using the heteroscedastic method

SD standard deviation, HC adj P heteroscedastic adjusted P value, K anterior corneal keratometry, TK total corneal keratometry, BUII Barrett Universal II

*Statistically significant

The adjusted MAE of the medium AL group was larger in each TK-based formula than in the K-based formula, but the difference was not statistically significant. In the long AL group, there was no significant difference in the MNE and the adjusted MAE between the K-based and TK-based formulas for each IOL power calculation formula. However, the SD was larger in each TK-based formula than in the K-based formula.

Table 5 shows the refractive prediction outcomes in 3 subgroups of flat, medium, and steep AK. In the flat AK group, we found no significant difference in the MNE or the adjusted MAE between the K-based and TK-based formulas. In the medium AK group, the MNE was statistically significantly larger, i.e., hyperopic shift, in each TK-based formula than the K-based formula except for the BUII: the BUII ($P = 0.379$), the Haigis ($P = 0.021$), the SRK/T ($P = 0.013$), the Holladay 2 ($P = 0.011$), and the Hoffer Q ($P = 0.025$), while the adjusted MAE was larger in each TK-based formula, with statistical significance in the BUII formula ($P = 0.024$) but not in the other IOL power calculation formulas, namely, the Haigis ($P = 0.068$), the SRK/T ($P = 0.103$), the Holladay 2 ($P = 0.055$), and the Hoffer Q ($P = 0.073$). The SD was larger in each TK-based formula than in the K-based formula. In the steep AK group, there was no significant difference in the MNE and the adjusted MAE between the K-based and TK-based formulas, although the SD was larger in each TK-based formula than in the K-based formula.

Table 6 shows the refractive prediction outcomes in 3 subgroups of flat, medium, and steep PK. In the flat PK group, the MNE was significantly larger, i.e., hyperopic shift, in each TK-based formula than in the K-based formula ($P < 0.001$), while the adjusted MAE was significantly larger in each TK-based formula, except for the Haigis formula. The SD was larger in each TK-based formula than in the K-based formula except for the SRK/T. In the medium PK group, we found no significant difference in the MNE or the adjusted MAE between the K-based and TK-based formulas. In the steep PK group, the MNE was statistically significantly smaller, i.e., myopic shift, in each TK-based formula than in the K-based formula, while the adjusted MAE was smaller in the TK-based formula of the BUII, the Haigis, and the Hoffer Q and larger in that of the SRK/T and the Holladay 2, with no statistical significance.

Axial length and keratometry subgroup analyses of K and TK

The above results from the AL and keratometry subgroup analyses imply that TK influences refractive prediction outcomes in eyes with relatively normal ranges of axial length and anterior keratometry. In a total of 225 eyes, the mean K and the mean TK were 44.26 ± 1.53 D and 44.28 ± 1.53 D (Table 1), respectively; there

Fig. 1 Stacked histogram comparing the percentages of eyes within ± 0.25 D, ± 0.50 D, ± 0.75 D, and ± 1.00 D of the adjusted prediction error (PE) calculated by the individual formulas using anterior corneal keratometry (K) and total corneal keratometry (TK). *D* diopter, *BUII* Barrett Universal II
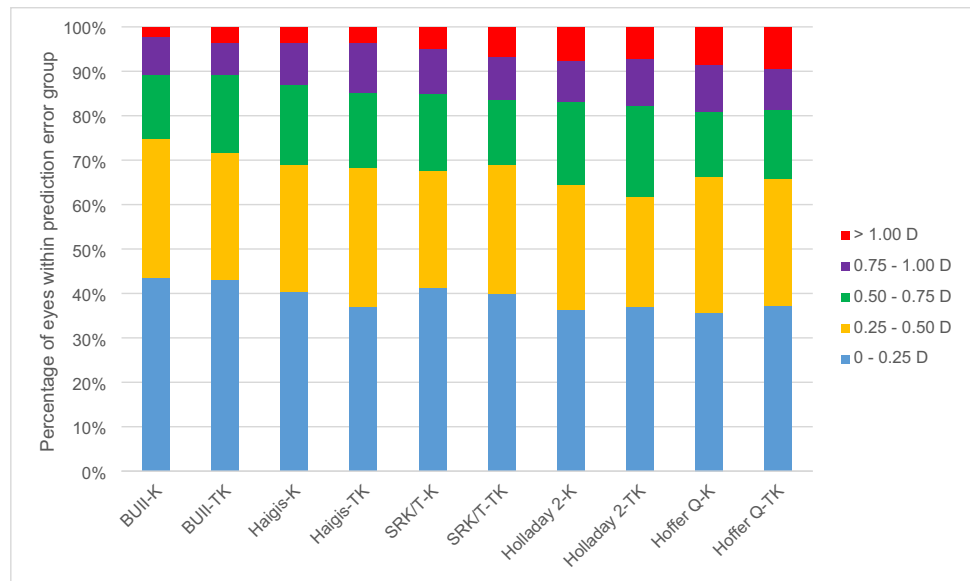
Table 4 Axial length subgroup analysis of refractive prediction outcomes between K-based and TK-based IOL power calculation formulas

	Short AL group (N=27)		Medium AL group (N=168)		Long AL group (N=30)	
	MNE±SD	Adjusted MAE	MNE±SD	Adjusted MAE	MNE±SD	Adjusted MAE
BUII-K	−0.047±0.607	0.489	0.129±0.434	0.338	0.182±0.408	0.343
BUII-TK	−0.059±0.638	0.526	0.140±0.442	0.345	0.167±0.424	0.352
P value	0.509	0.030*	0.123	0.292	0.358	0.465
Haigis-K	−0.121±0.601	0.493	−0.117±0.470	0.371	0.099±0.457	0.409
Haigis-TK	−0.127±0.618	0.518	−0.089±0.483	0.384	0.121±0.461	0.407
P value	0.857	0.108	0.008*	0.124	0.571	0.742
SRK/T-K	−0.127±0.631	0.515	0.102±0.500	0.385	0.115±0.515	0.432
SRK/T-TK	−0.131±0.632	0.533	0.130±0.498	0.388	0.130±0.535	0.441
P value	0.866	0.068	0.002*	0.221	0.502	0.276
Holladay 2-K	−0.499±0.685	0.624	−0.166±0.493	0.392	0.043±0.605	0.493
Holladay 2-TK	−0.499±0.703	0.657	−0.146±0.506	0.401	0.054±0.616	0.490
P value	0.923	0.006*	0.005*	0.264	0.600	0.992
Hoffer Q-K	−0.464±0.614	0.582	−0.050±0.508	0.390	0.282±0.610	0.553
Hoffer Q-TK	−0.466±0.619	0.599	−0.029±0.519	0.404	0.290±0.618	0.538
P value	0.923	0.140	0.008*	0.092	0.845	0.453

P values were computed using the Wilcoxon signed rank test

K anterior corneal keratometry, *TK* total corneal keratometry, *AL* axial length, *MNE* mean numerical prediction error, *SD* standard deviation, *MAE* mean absolute prediction error, *BUII* Barrett Universal II

*Statistically significant

was a statistically significant difference between them ($P = 0.006$). Therefore, K and TK were compared in the AL and keratometry subgroups (Table 7). The TK was statistically significantly larger than the K in both the medium AL group ($P = 0.003$) and the medium AK group ($P = 0.009$) but not in the other categories of AL and AK. On the other hand, in the PK subgroups, the TK was statistically significantly larger than the K in the flat PK group ($P < 0.001$), not different in the medium PK group, and statistically significantly smaller in the steep PK group ($P = 0.004$).

Discussion

This study showed that the BUII-K formula, but not the BUII-TK, is the best nontoric monofocal IOL power calculation formula among the built-in IOLMaster 700 formulas

Table 5 Anterior keratometry subgroup analysis of refractive prediction outcomes between K-based and TK-based IOL power calculation formulas

	Flat AK group (N=12)		Medium AK group (N=182)		Steep AK group (N=31)	
	MNE±SD	Adjusted MAE	MNE±SD	Adjusted MAE	MNE±SD	Adjusted MAE
BUII-K	0.210±0.438	0.387	0.143±0.446	0.341	−0.086±0.485	0.441
BUII-TK	0.258±0.427	0.356	0.148±0.458	0.355	−0.100±0.501	0.446
P value	0.272	0.530	0.379	0.024*	0.439	0.822
Haigis-K	−0.257±0.505	0.428	−0.078±0.487	0.384	−0.083±0.499	0.413
Haigis-TK	−0.205±0.511	0.421	−0.054±0.499	0.397	−0.080±0.520	0.431
P value	0.239	0.969	0.021*	0.068	0.930	0.308
SRK/T-K	0.419±0.464	0.463	0.141±0.483	0.379	−0.434±0.457	0.546
SRK/T-TK	0.482±0.466	0.469	0.163±0.483	0.384	−0.421±0.460	0.559
P value	0.182	0.784	0.013*	0.103	0.472	0.183
Holladay 2-K	−0.022±0.506	0.474	−0.119±0.516	0.406	−0.587±0.591	0.575
Holladay 2-TK	−0.027±0.503	0.446	−0.103±0.531	0.420	−0.582±0.601	0.584
P value	0.224	0.433	0.011*	0.055	0.814	0.499
Hoffer Q-K	−0.106±0.523	0.451	−0.005±0.549	0.421	−0.333±0.614	0.508
Hoffer Q-TK	−0.052±0.525	0.419	0.011±0.560	0.434	−0.327±0.620	0.517
P value	0.239	0.433	0.025*	0.073	0.681	0.468

P values were computed using the Wilcoxon signed rank test

AK anterior autokeratometry, *K* anterior corneal keratometry, *TK* total corneal keratometry, *MNE* mean numerical prediction error, *SD* standard deviation, *MAE* mean absolute prediction error, *BUII* Barrett Universal II

[*]Statistically significant

Table 6 Posterior keratometry subgroup analysis of refractive prediction outcomes between K-based and TK-based IOL power calculation formulas

	Flat PK group (N=57)		Medium PK group (N=112)		Steep PK group (N=56)	
	MNE±SD	Adjusted MAE	MNE±SD	Adjusted MAE	MNE±SD	Adjusted MAE
BUII-K	0.266±0.422	0.365	0.065±0.438	0.326	0.060±0.500	0.411
BUII-TK	0.350±0.431	0.395	0.064±0.437	0.335	−0.003±0.496	0.406
P value	<0.001*	0.035*	0.794	0.190	<0.001*	0.835
Haigis-K	−0.080±0.504	0.396	−0.142±0.450	0.369	0.009±0.538	0.429
Haigis-TK	0.010±0.515	0.420	−0.118±0.468	0.382	−0.038±0.546	0.426
P value	<0.001*	0.061	0.101	0.114	<0.001*	0.743
SRK/T-K	0.380±0.510	0.468	0.049±0.428	0.339	−0.177±0.560	0.479
SRK/T-TK	0.449±0.502	0.493	0.072±0.418	0.336	−0.204±0.539	0.484
P value	<0.001*	0.012*	0.077	0.657	0.003*	0.283
Holladay 2-K	0.039±0.516	0.457	−0.198±0.482	0.378	−0.359±0.637	0.518
Holladay 2-TK	0.122±0.525	0.484	−0.188±0.490	0.384	−0.398±0.622	0.523
P value	<0.001*	0.045*	0.065	0.597	<0.001*	0.225
Hoffer Q-K	0.059±0.548	0.435	−0.084±0.517	0.393	−0.114±0.662	0.520
Hoffer Q-TK	0.149±0.568	0.476	−0.076±0.521	0.397	−0.157±0.649	0.509
P value	<0.001*	0.002*	0.165	0.421	<0.001*	0.347

P values were computed using the Wilcoxon signed rank test

PK posterior corneal keratometry, *K* anterior corneal keratometry, *TK* total corneal keratometry, *MNE* mean numerical prediction error, *SD* standard deviation, *MAE* mean absolute prediction error, *BUII* Barrett Universal II

[*]Statistically significant

in terms of its accuracy of refractive prediction outcomes for normal eyes. The better performance of the K-based formula is true for the other IOL power calculation formulas. The use of TK degraded the formula performance substantially. The subgroup analysis of the refractive prediction outcomes suggests that TK affects the refractive outcomes in eyes with relatively normal ranges of axial length and anterior keratometry. We confirmed that this resulted from the significant differences between K and TK in the medium ranges of axial length and anterior keratometry. Our study demonstrated that use of TK instead of K leads to a lower refractive prediction accuracy of the IOL power calculation formula.

There are many factors influencing postoperative refractive errors following cataract surgery [29]. These include individual ocular characteristics; accuracy of ocular biometric measurement [30]; labeling of the IOL, including the material and configuration [31]; surgeon's skill; IOL power calculation formula, etc. Regarding ocular characteristics, irregular astigmatism such as keratoconus, long or short axial length, fragile ciliary zonules represented by pseudoexfoliation syndrome, eyes after LVC, etc. The accuracy of ocular biometric measurement has been improved by the recent OCT technology. Although the detailed labeling of IOLs is rarely publicized by the manufacturer, the production and quality control of IOLs are rigorous and under the regulation of the American National Standards Institute

(ANSI). The skill of experienced surgeons is much the same in terms of surgical complications and SIA. With respect to the IOL power calculation formula, the newer vergence formulas of BUII, Haigis, and Holladay 2 have been replacing the SRK/T and Hoffer Q, yet formulas based on new concepts are in the developmental stage. Aside from the individual ocular characteristics, numerous predecessors have made considerable effort in every field to minimize the postoperative refractive error. Nevertheless, not only can we not make this error zero, but we also (infrequently) encounter a refractive surprise.

The significance of TK is that direct measurement of total keratometry negates the systematic error related to the mathematical estimation of the posterior corneal curve based on the anterior corneal curve measurement. Savini et al. [32] showed that the mean K and the mean TK measured on 69 unoperated cataract eyes with IOLMaster 700 were 43.14 ± 1.37 D and 43.18 ± 1.37 D, respectively, with statistical significance ($P = 0.0006$). These results were consistent with our findings in the current study, although the researchers explained that this difference was not clinically significant without evaluating refractive prediction outcomes. However, they also mentioned that using the measured TCA is less accurate than using the predicted TCA for toric IOL calculation [21]. In fact, direct measurement of TCA is not superior to calculation of TCA in terms of obtaining better refractive astigmatism for toric IOL [19, 20]. The same was true for total keratometry or TK, as shown in the present study. Using TK is not accurate enough to achieve better refractive outcomes than using K. Recently, Ryu et al. [33] reported that MAE tended to be lower for TK-based than for K-based formulas in eyes undergoing femtosecond laser-assisted cataract surgery, and Chung et al. [34] showed a lower prediction accuracy of TK-based formulas than that of K-based formulas for multifocal IOLs. Our study reinforces this reality in terms of refractive prediction outcomes for nontoric monofocal IOLs. We demonstrated in the subgroup analysis of K and TK that, especially in the relatively normal ranges of axial length and anterior keratometry, there were significant differences between T and TK, which must have led to the lower refractive prediction accuracy of the TK-based formulas. This may require IOL formula adjustments, or there is a possibility that there is a gap between the accuracy of the anterior and posterior corneal refraction values in the measurement equipment. In the latter case, it is highly possible that the measurement error of TK, which is the sum of the two values, is greater than that of K, which is a single value. Our PK subgroup analysis may be a clue to this issue. In the flat PK group, the adjusted MAEs of the TK-based formulas were significantly larger than those of the K-based formulas except for Haigis. In contrast, in the steep PK group, all the adjusted

Table 7 Axial length and keratometry subgroup analyses of K and TK and the PK values corresponding to the subgroups

	Short AL group N = 27	Medium AL group N = 168	Long AL group N = 30
K (D)	46.17 ± 1.39	44.01 ± 1.31	43.97 ± 1.58
TK (D)	46.18 ± 1.38	44.03 ± 1.32	43.98 ± 1.56
P value	0.904	0.003*	0.797
PK (D)	−6.21 ± 0.23	−5.89 ± 0.21	−5.91 ± 0.26
	Flat AK group N = 12	Medium AK group N = 182	Steep AK group N = 31
K (D)	41.56 ± 0.33	43.99 ± 1.00	46.89 ± 0.90
TK (D)	41.62 ± 0.39	44.01 ± 1.01	46.89 ± 0.92
P value	0.209	0.009*	0.845
PK (D)	−5.53 ± 0.14	−5.89 ± 0.18	−6.31 ± 0.15
	Flat PK group N = 57	Medium PK group N = 112	Steep PK group N = 56
K (D)	42.70 ± 0.80	44.13 ± 0.83	46.11 ± 1.19
TK (D)	42.80 ± 0.86	44.15 ± 0.90	46.07 ± 1.25
P value	<0.001*	0.096	0.004*
PK (D)	−5.64 ± 0.10	−5.92 ± 0.10	−6.25 ± 0.13

P values were computed using the Wilcoxon signed rank test

K anterior corneal keratometry, *TK* total corneal keratometry, *PK* posterior corneal keratometry, *AL* axial length, *D* diopter, *AK* anterior autokeratometry

*Statistically significant

MAEs of the TK-based formulas were not significantly different from those of the K-based formulas, suggesting that using TK has no advantage over using K. Given no knowledge of the normal range of PK, we refrain from further discussions on this issue. Instead, we additionally show the values of PK corresponding to the subgroups in Table 7. Whether the issue of TK is because of a problem with the IOL formulas or because of a measurement error inherent in the IOLMaster 700 remains to be determined.

The strength of this study is that a single IOL model was implanted by a single skillful surgeon, which obviates the constant optimization and adjustment of the surgeon's factor. On the other hand, the weakness is the small sample size. However, this study should be exempt from such a criticism because of its elaborate design conforming to Hoffer and Savini's protocol [27]. Nonetheless, it is possible that the conclusions may change with continued data accumulation. It remains to be studied whether the TK-based formula performs better for eyes with toric and/or multifocal IOL implantation in reducing postoperative refractive error as well as postoperative astigmatism.

In conclusion, either the TK-based IOL power calculation formulas or the measurement of TK with the IOLMaster 700, or both, may need to be optimized.

Declarations

Ethics approval This retrospective study was approved by the institutional review board of Osaka Minato Central Hospital and adhered to the tenets of the Declaration of Helsinki.

Consent to participate Not applicable.

Consent for publication No informed consent was required in accordance with the institutional review board of Osaka Minato Central Hospital.

Conflict of interest The authors declare no competing interests.

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