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Prediction of intraocular lens position based on crystalline lens shape measured using anterior segment optical coherence tomography

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Objective: To evaluate methods for predicting postoperative intraocular lens (IOL) position on the basis of whole crystalline lens images taken using anterior segment optical coherence tomography (AS-OCT).
Methods: The study included 178 eyes from 99 patients who underwent cataract surgery. Whole crystalline lens images were preoperatively taken using a prototype swept-source AS-OCT device. The anterior capsule, lens equator, and posterior capsule depths were determined from the crystalline lens image, and postoperative IOL positions were predicted using these parameters. Postoperative refractive errors calculated using predicted IOL position were compared with those calculated using the Haigis, Hoffer Q, Holladay 1, and SRK/T formulas.
Results: The mean postoperative refractive error for each formula was zeroed out, resulting in standard deviations of ±0.48, ±0.51, ±0.50, ±0.53, and ±0.46 D using the Haigis, Hoffer Q, Holladay 1, SRK/T, and AS-OCT formulas, respectively. Significant differences were found between the Hoffer Q and AS-OCT formulas and between the SRK/T and AS-OCT formulas.
Conclusion: Regarding the IOL power calculation, predicting postoperative IOL position using the whole crystalline lens image was more accurate than that using the Hoffer Q and SRK/T formulas.

Key words: cataract surgery, intraocular lens power calculation, anterior segment optical coherence tomography

Introduction

Cataract surgery includes elements of refractive surgery. Since premium lenses, such as aspheric, multifocal, and toric intraocular lenses (IOLs), have become available, requests for improving postoperative visual ability have been increasing.[1] Therefore, reducing refractive errors after cataract surgery to achieve desired postoperative refraction and visual outcomes has become more important.

The causes of refractive errors after cataract surgery have been quantified and analyzed[2] giving: measurement accuracy of preoperative biometry, prediction accuracy of IOL fixing position, manufacturer's product accuracy, and others.[3] Among those, accurate prediction of IOL position has been reported to be a main determinant of IOL power errors, accounting for up to 35.5% of postoperative refractive errors.[2]

Biometric analysis of the anterior segment of the eye using various parameters would be helpful for accurately predicting the IOL position. If there are no complications, such as posterior capsule ruptures, IOLs are inserted into the crystalline lens capsule. Therefore, the positions of the parts of a crystalline lens, such as anterior capsule depth (ACD; equal to anterior chamber depth) and posterior capsule depth [PCD; equal to ACD + lens thickness (LT)], are useful for predicting the IOL position. Measuring these parameters using an optical low-coherence reflectometry biometry device (Lenstar LS900, Haag Streit, Köniz, Switzerland) has become possible, and a new IOL power calculation method has been recently reported.[4]

However, the device cannot acquire images of the entire crystalline lens but can only measure the length of each type of tissue. Scheimpflug instruments have been developed to obtain anterior segment images and to

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predict the IOL position;[5,6] however, the instruments currently available cannot capture posterior capsule images because they are designed only to acquire images of the cornea and the anterior capsule.

Anterior segment optical coherence tomography (AS-OCT) is a new instrument that can capture anterior segment images. Some reports have described the use of AS-OCT for predicting the IOL position. Tang et al.[7] identified the crystalline lens capsule position and determined that IOL position could be predicted by measuring the preoperative corneal thickness, ACD, and LT. Hirnschall et al.[8] reported a method of predicting IOL position using intraoperative ACD with a capsular tension ring.

In these previous studies,[7,8] the effects of the crystalline lens shape on the postoperative IOL position were not described. We hypothesized that the crystalline lens shape would be more useful. The diameters of IOLs are designed to be larger than those of the crystalline lens. It is natural to consider that the haptics of IOLs should be fixed at a region that represents the largest crystalline lens dimension (the equator).

We developed a prototype swept-source AS-OCT that could capture an image with a depth range of 12 mm, as previously reported.[9] In the present study, we used this AS-OCT to examine the entire crystalline lens shape and used appropriate parameters for the anterior tissues. On the basis of these parameters, we more accurately predicted the postoperative IOL position and evaluated the accuracy of the refractive predictions.

Materials and Methods

Patients

This prospective observational study enrolled patients who were scheduled for cataract surgery at Kitasato University Hospital, Kanagawa, Japan. Other than cataracts, none of the patients had eye diseases that would cause visual impairment. Exclusion criteria included patients with preoperative corneal astigmatism of >2.0 Dioptor (D), previous intraocular surgery, and postoperative corrected distance visual acuity of <0.15 logMAR (0.7 Decimal). The refractive prediction error was calculated by subtracting the predicted postoperative refraction from the postoperative spherical equivalent 1 month after surgery, as measured using an autokerato-refractometer (RKT7700; Nidek, Aichi, Japan).

The study protocols were approved by the Institutional Review Board for observation and epidemiological study, Kitasato University (B14-31). All patients were treated according to the Declaration of Helsinki and gave written informed consent. This clinical trial was registered with the University Hospital Medical Information Network Clinical Trial Registry (000024094).

Preoperative examination

Preoperative axial length (AL) and anterior corneal curvature were measured using IOLMaster (Model-500, software version 5, Carl Zeiss Meditec AG, Jena, Germany). The IOL insertion power was calculated using the SRK/T formula.

Surgical technique

The surgery was performed by one of two experienced surgeons (KS or ST). Cataracts were removed by phacoemulsification via a 2.8-mm temporal clear corneal incision. A monofocal IOL (AQ-110NV; STAAR Surgical, CA, USA, Manufacturer's A const. 119.0, pACD 5.55) was then implanted into the capsular bag using a preset injector after performing curvilinear capsulorrhexis without suturing.

OCT imaging

A prototype AS-OCT system was used for measurements 1 day before and 1 month after the cataract surgery. The system used a Fabry-Perot light source (Axsun Technologies, model SSOCT 1310) with a center wavelength of 1,310 nm.[9,10] At the 1,300-nm wavelength, Kerbage, et al.[11] and Gora, et al.[12] demonstrated the ability to reach depths of 4 and 8 mm; nonetheless, this was insufficient to reach the posterior surface of the crystalline lens. We introduced an external Mach-Zehnder interferometer to generate a data sampling clock[13,14] and obtained a depth range of 12 mm.[9] The power of the procession imaging of AS-OCT was <14 mW, which was within the safety limit established by the American National Standard Institute.[15]

In addition, we developed an analytical program for correcting AS-OCT images to automatically obtain measurements from the images. Image warping because of refraction at the tissue boundaries was corrected to determine lateral dimensions. We applied Snell's law at each boundary and then obtained corrected images to determine the crystalline lens position (Figure 1). The following refractive indices were used: 1.377 for the cornea, 1.337 for the aqueous humor, 1.420 for the crystalline lens, and 1.413 for the silicone IOL.[16-18] The parameters set are shown in Figure 2.

IOL power calculation

A Gaussian optic-based thin lens formula based on the vergence formula was used as a tool to calculate the

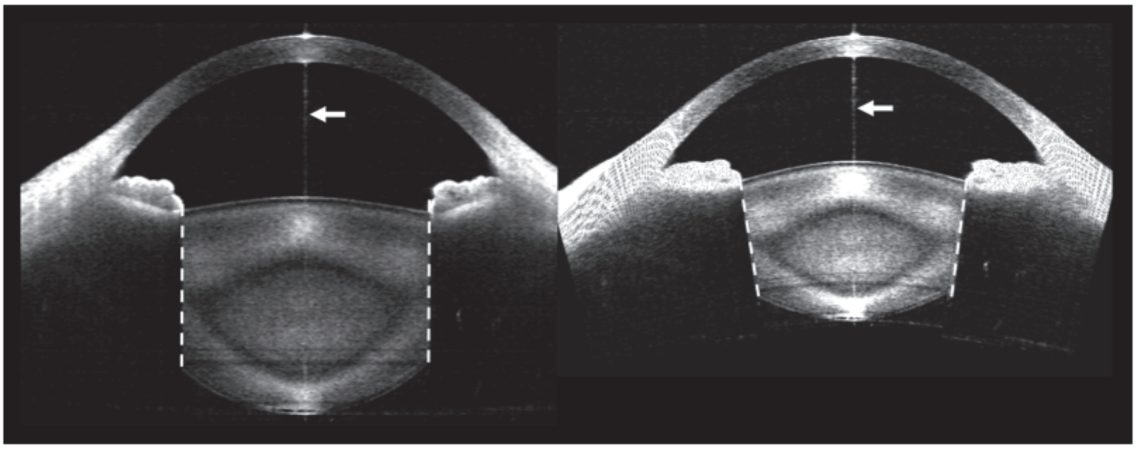

Figure 1. Preoperative crystalline lens images taken using our prototype anterior segment optical coherence tomography (AS-OCT) system. Left: Schematic image of the eyes of a 61-year-old man before refractive index correction. The arrows indicate the corneal reflex, at which point the laser beam passed through the anterior surface of the cornea vertically. Right: After correction according to the refractive index of the cornea, anterior chamber aqueous, and crystalline lens. The dotted line, representing the crystalline lens edges, is parallel to the optical axis in the uncorrected image but is not in the corrected image.

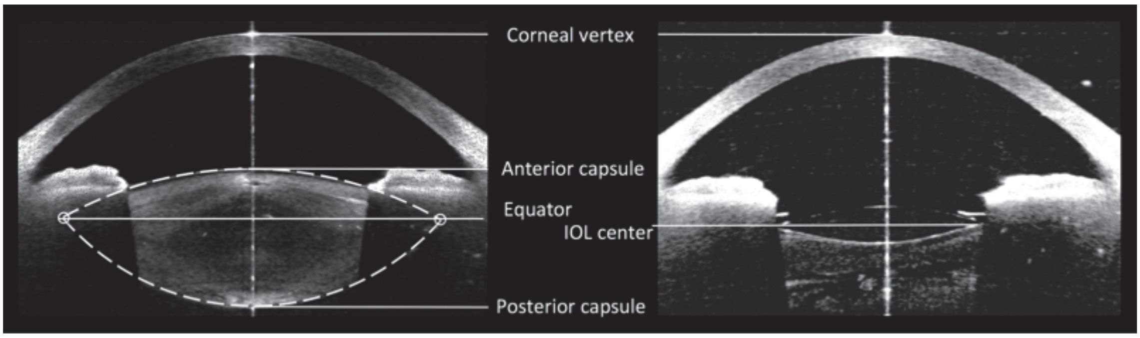

Figure 2. Schematic of the parameters set to the images using the AS-OCT. Left: Schematic of the eye before surgery. Right: After surgery. Images were corrected according to the refractive index, and the depth of each type of tissue from the corneal vertex was measured. The equator position was defined as the intersection of the two curves of the anterior and posterior surfaces of the crystalline lens, approximated by the two circles.

expected postoperative refractive outcomes.[19]

$$P = \frac{N}{A - C - 0.05} - \frac{N}{\frac{N}{K + R} - C - 0.05}$$

P is the implanted IOL power (D), A is AL, C is the ACD, N is the refraction index, and K is the corneal power.

Statistical analysis

Pearson's and Spearman's correlation coefficients (for parametric data and nonparametric data, respectively) were used to evaluate the association between the parameters. Paired *t*-test and Wilcoxon signed-rank test were performed to analyze differences (for parametric data and nonparametric data, respectively). The distributions of measurements were analyzed with Kolmogorov-Smirnov test.

Fisher's exact tests were used to compare the percentages of the eyes for which the prediction errors were within ±0.50 D and ±1.00 D. All statistical analyses were performed using the R software (2.13.0, R Foundation for Statistical Computing, http://www.R-project.org). P values of <0.05 were considered to be statistically significant.

Results

The study included 178 eyes from 99 patients (110 eyes from 61 women). The preoperative demographics of the study population are shown in Table 1. The mean anterior capsule, equator, posterior capsule, and postoperative IOL central depth from the corneal epithelium were 3.42 ± 0.38, 4.84 ± 0.35, 7.90 ± 0.28, and 5.21 ± 0.23

Table 1. Preoperative demographics of the study population that underwent cataract surgery

	Age (year)	Pre-operative Rx (D)	Axial length (mm)	Anterior corneal curvature (mm)	Pre-operative ACD (mm)	CD (mm)	IOL power (D)	Pre-operative Rx (D)
Mean	69.5	-1.39	24.05	7.61	3.12	11.9	20.5	-1.45
SD	7.8	3.92	1.52	0.24	0.37	0.4	3.6	1.15
Min	38	-18.50	21.65	7.11	2.11	10.7	11.0	-4.38
Median	70	-0.25	23.60	7.64	3.15	11.9	21.0	-0.25
Max	85	4.75	28.10	8.42	4.00	12.7	26.0	0.50

Rx, refraction; D, diopter; ACD, anterior chamber depth; CD, corneal diameter; IOL, intraocular lens; SD, standard deviation; Min, minimum; Max, maximum

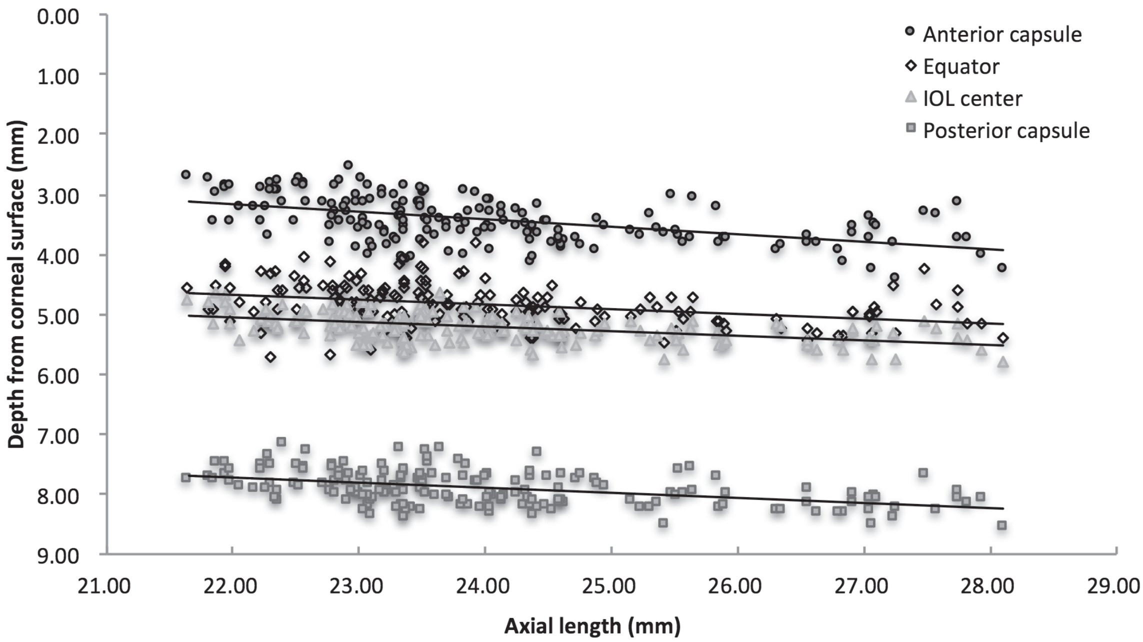

Figure 3. Correlation between the positions of the anterior chamber capsule, equator, posterior capsule, and IOL central depth

Table 2. Results of the correlation analysis and stepwise multiple regression analysis to select variables relevant to postoperative intraocular lens central depth

Variables	Spearman correlation coefficient	P value	Partial regression coefficient	Standardized partial regression coefficient	P value
Axial length (mm)	0.504	<0.001	0.018	0.116	0.046
Anterior corneal curvature (mm)	0.113	0.601	Not included	–	–
Corneal diameter (mm)	0.362	0.003	Not included	–	–
Anterior capsule depth (mm)	0.708	<0.001	0.275	0.454	<0.001
Equator depth (mm)	0.585	<0.001	0.088	0.136	0.033
Posterior capsule depth (mm)	0.548	<0.001	0.208	0.258	<0.001
			1.776	Constant	Adjusted R^2 = 0.60

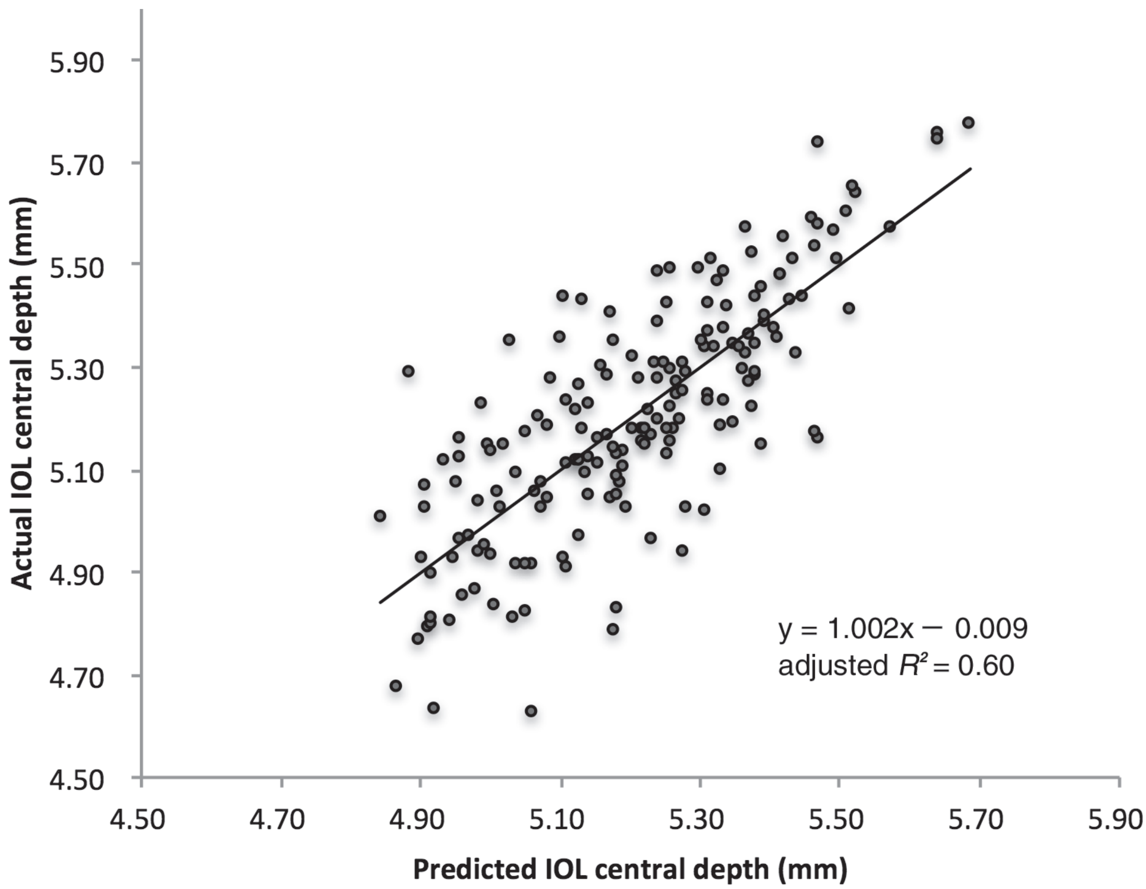

Figure 4. Correlation between the predicted IOL central depth and its actual depth.

Table 3. Refractive error after cataract surgery using intraocular lens power calculation formula

	Formulas				
	Haigis	Hoffer Q	Holladay 1	SRK/T	AS-OCT
ME ± SD (D)	0.00 ± 0.48	0.00 ± 0.51	0.00 ± 0.50	0.00 ± 0.53	0.00 ± 0.46
Max	1.03	1.03	0.99	1.08	0.98
Min	-1.11	-1.20	-1.20	-1.28	-1.11
Range	2.14	2.23	2.19	2.36	2.09
MedAE (D)	0.36	0.39	0.39	0.41	0.35
Eyes within 0.5 D (%)	0.71	0.70	0.70	0.65	0.73
Eyes within 1.0 D (%)	0.95	0.94	0.94	0.92	0.97
Constants	1.44	5.54	1.72	118.72	

ME, mean arithmetical error; SD, standard deviation; Max, maximum; Min, minimum; MedAE, median absolute error

Constants: Optimized constants for the Haigis (A0), Hoffer Q (pACD), Holladay 1 (surgeon factor), SRK/T (A constant) formulas.

mm, respectively. Figure 3 illustrates the association between AL and each parameter. All parameters were positively correlated with AL (Spearman's rank correction r = 0.53, 0.40, 0.46, and 0.50, respectively; $P < 0.001$ for all parameters).

The multiple regression analysis results are shown in Table 2. There was a significant correlation between the predicted and actual IOL central depth (Figure 4). Multiple regression analysis was performed to predict the IOL central depth on the basis of the preoperative measurements of the axial length, anterior corneal radius, corneal diameter, anterior capsule depth, equator depth, and posterior capsule depth. The regression formula was: IOL central depth (mm) = 0.018 × AL + 0.275 × ACD + 0.088 × equator + 0.208 × PCD + 1.776 (mm). The adjusted R^2 between the predicted and actual values was 0.60 ($P < 0.001$).

Table 3 shows the overall prediction errors in terms of the mean arithmetical error, standard deviation, median absolute error, and percentage of the eyes within ±0.50 D and ±1.00 D. The formulas predict different lens positions[20] and have constants to optimize the mean refraction to zero. The differences between the AS-OCT formula and the Haigis, Hoffer Q, Holladay 1, and SRK/T formulas provided P values of 0.118, 0.014, 0.091, and 0.003, respectively. Significant differences were observed when the AS-OCT formula was compared with the Hoffer Q and SRK/T formulas. There were no significant differences in the percentages of the eyes, with prediction errors within ±0.50 D and ±1.00 D.

Discussion

A more accurate method for predicting postoperative IOL position should improve the accuracy of IOL power calculations. Many methods have been used to predict postoperative IOL position. For example, early theoretical formulas such as the Binkhorst I formula used a fixed IOL position.[21] The Binkhorst II and Hoffer formulas predicted IOL position on the basis of AL only.[22,23] Fyodorov predicted IOL position from the corneal curvature and AL.[24]

Theoretical formulas such as the Haigis, Hoffer Q, Holladay 1 and 2, and SRK/T formulas are currently used for calculating IOL power. The Hoffer Q, Holladay 1, and SRK/T formulas use the corneal curvature and AL to calculate IOL position.[25-27] In contrast, the Haigis formula uses AL and preoperative ACD without corneal curvature.[28] The Holladay 2 formula includes additional parameters such as LT and age.[29] Thus, several attempts to predict IOL position have been made using various biometric parameters; however, no biometric parameters have been discovered to have a direct association with the IOL position.

Researchers recently suggested that IOL position depends on the capsular bag. Norrby and Koranyi[30,31] proposed the concept of the lens haptic plane, which is assumed to coincide with the postoperative position of the equator of the capsular bag. Olsen et al.[32] invented and reported the concept of the C constant, defined as the ratio of the preoperative LT by which the IOL will locate itself after surgery. The C constant does not focus on the position of the crystalline lens equator but rather indicates the association between the crystalline lens shape and IOL position.

In the present study, we predicted the IOL position using the equator position. However, the equator position could not be directly examined with AS-OCT because light cannot pass through the iris. Therefore, we approximated two circular curves on the anterior and posterior capsules and assumed that the intersections of the two circles were the equators. In the approximation of the curves, a quadratic curve was also used. Nevertheless, the results were not significantly different. The crystalline lens shape was essential for defining the equator position. To the best of our knowledge, this study is the first to describe such a prediction on the basis of the crystalline lens shape.

We aimed to evaluate methods for predicting the postoperative IOL position on the basis of the crystalline lens images taken using AS-OCT. The data showed that the Hoffer Q and Holladay 1 formulas provided similar results with regard to almost every parameter, the Haigis and AS-OCT formulas were slightly more accurate, however; and the SRK/T formula was the least accurate of both pairs of methods. Therefore, these data had important implications for developing appropriate imaging techniques for predicting IOL position and calculating IOL power.

The use of AS-OCT for cataract surgery has recently been formulated.[33] The results of the present study indicated that AS-OCT was also useful for calculating IOL power. In cataract surgeries using a femtosecond laser, analyzing the lens shape with intraoperative AS-OCT is essential. Therefore, there is a potential for an increase in accuracy by predicting IOL position on the basis of the measured lens shape.

AS-OCT may also have applications, such as laser in situ keratomileusis (LASIK), for cataract surgery after refractive surgery. In such surgeries, postoperative refraction is often more hyperopic than that indicated by calculations with conventional formulas.[34-36] The causes include the determination of proper K in an irregular cornea and the calculation of the IOL position. Mispredicting IOL position can be avoided by predicting the lens shape using AS-OCT. Therefore, AS-OCT is expected to have applications in LASIK and other types of cataract surgeries.

The present study has a few limitations. First, because it was a pilot study, the number of the eyes included was relatively small. The small sample of eyes would not be conducive to dividing them into groups to create the AS-OCT formula and evaluate it. From previous research including a large sample size, the predictability of the Hoffer Q formula was best for eyes with short AL of <21 mm and that of the SRK/T formula was best for eyes with long AL of >27 mm.[38] Further studies are warranted to evaluate the accuracy of all formulas according to AL. Second, the Haigis formula has three constants. More than 200 cases are generally required to optimize all three lens constants of the Haigis formula according to the Haigis website. In this study, we could optimize a0 only because the number of the eyes was 178. Therefore, the Haigis formula in which all three constants (a0, a1, and a2) are optimized would be more accurate than those provided in these results. Third, the postoperative measurements were taken only 1 month after the surgery. As described in the literature, the postoperative refraction would change over several weeks.[39,40] Therefore, a refraction measured 1 month after the surgery would not necessarily be a permanent refraction. And therefore, assessing IOL position changes in the long term is warranted.

In conclusion, we developed a method to predict IOL position using AS-OCT and whole crystalline images and found that the refractive error was similar to that of the Haigis and Holladay 1 formulas and less than that of the Hoffer Q and SRK/T formulas.

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