Use of the Crystalline Lens Equatorial Plane as a New Parameter for Predicting Postoperative Intraocular Lens Position

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• PURPOSE: **To assess whether preoperative crystalline lens equatorial plane (LEP) reliably predicts the postoperative position of the intraocular lens (IOL).**
• DESIGN: **Comparative, interventional case series.**
• METHODS: **Phacoemulsification and IOL implantation (Group I, ZCB00; Group II, EC-1PAL; and Group III, CT Asphina) were performed for 104 eyes. Lens geometry parameters, including LEP, were obtained from a femtosecond laser cataract surgery system prior to surgery. LEP was defined as the distance from the front surface of the cornea to the equatorial plane of the crystalline lens. Postoperative anterior chamber depth (ACD) was measured using a Scheimpflug camera. Median absolute error was calculated using an optical ray-tracing method that incorporated LEP into an individualized eye model, and the results were compared with those from the Haigis formula.**
• RESULTS: **Preoperative ACD (3.27 ± 0.39 mm [R = 0.428], 3.30 ± 0.47 mm [R = 0.591], and 3.49 ± 0.39 mm [R = 0.373] in Groups I, II, and III, respectively) and LEP (4.81 ± 0.29 mm [R = 0.570], 4.84 ± 0.27 mm [R = 0.634], and 4.97 ± 0.23 mm [R = 0.565] in Groups I, II, and III, respectively) were found to have significant positive correlations with postoperative ACD (5.24 ± 0.40 mm, 5.02 ± 0.31 mm, and 5.19 ± 0.26 mm in Groups I, II, and III, respectively). Stepwise regression analysis showed that postoperative ACD was significantly correlated with LEP in all groups. Median absolute errors predicted by the ray-tracing method using LEP were smaller than those from the Haigis formula in all groups.**
• CONCLUSIONS: **LEP is a promising measure from preoperative crystalline lens geometry and could serve as a new parameter to improve refractive outcomes in cataract surgery. (Am J Ophthalmol 2019;198:17–24. © 2018 Elsevier Inc. All rights reserved.)**

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CORRECTING REFRACTIVE ERROR AND CHANGING the crystalline lens to an intraocular lens (IOL) are 2 important aspects of cataract surgery. An accurate assessment of the distance between the cornea and the IOL, which is often referred to as the postoperative IOL position or the effective lens position (ELP), is critical to achieving a good postoperative refractive outcome. Because of the biomechanical interaction between the IOL and the capsular bag after cataract surgery, it is reasonable to hypothesize that IOL position is significantly affected by crystalline lens geometry and the position of the capsular bag in the anterior segment of the eye.[1–4] However, little work has been done to evaluate the relationship between lens geometry and IOL position after surgery. Hirnschall and associates[5] showed that it is possible to predict postoperative IOL position by measuring the intraoperative lens capsule after inserting a capsular tension ring during surgery. Postoperatively, Koeppl and associates[6] indirectly measured capsular bag diameter using gonioscopic measurement after cataract surgery in order to evaluate the correlation between IOL position and capsular bag size and reported that the IOL shifted less after surgery when it was placed in a large capsular bag in myopic eyes compared to when it had a small capsular bag in hyperopic eyes. Two other studies have used ultrasound biomicroscopy to measure thickness, size, and volume of the capsular bag[7] as well as other anterior segment parameters, including aqueous depth and trabecular meshwork–iris angle.[8]

Optical coherence tomography (OCT) is another popular method for measuring anterior segment parameters of the eye, such as lens geometry[9,10] or angle-to-angle depth.[11,12] Recent femtosecond laser systems for cataract surgery are equipped to perform 3-dimensional (3-D) OCT imaging. This capability enables the quantification of parameters related to crystalline lens geometry, including lens thickness (LT) and lens equatorial plane (LEP). In particular, LEP is defined as the distance from

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the anterior cornea to the lens equator, which is in turn defined as the horizontal plane that connects the intersection of the lens's anterior and posterior surface curvatures. This study was designed to test the hypothesis that the preoperative LEP is significantly correlated with postoperative IOL position.

METHODS

THIS COMPARATIVE, INTERVENTIONAL CASE SERIES included patients with cataracts who underwent phacoemulsification and IOL implantation. Exclusion criteria were (1) preexisting zonulysis, (2) other surgical procedures performed during the cataract surgery, (3) previous intraocular surgeries (including previous refractive corneal surgery), (4) intraoperative complications such as zonulysis, (5) poorly dilated pupils (<5 mm) before OCT scanning, (6) any conditions that may cause inaccurate OCT scanning of the lens posterior capsule (the software in the femtosecond cataract surgery system [Catalys; AMO, North Chicago, Illinois, USA] could not calculate the parameters related to lens geometry in 2 cases of anterior polar type cataract), (7) corneal pathologies, and (8) ocular comorbidities (eg, age-related macular degeneration). All patients in this study received femtosecond laser pretreatment using the femtosecond laser cataract surgery system (Catalys: AMO), followed by phacoemulsification and insertion of the IOL. A single surgeon (C-K.J.) who was well experienced with the femtosecond laser platform performed the surgery for all eyes. This study was conducted in accordance with the ethical standards of the Declaration of Helsinki and with the approval of the Institutional Review Board of Seoul St. Mary's Hospital, Seoul, South Korea (IRB #KC13DISI0534).

• **SURGICAL TECHNIQUES:** An hour before the femtosecond laser pretreatment, a blend of 0.5% tropicamide and 0.5% phenylephrine (Mydrin-P; Santen, Osaka, Japan) was administered 3 times. After sufficient pupil dilation had been confirmed, the pretreatment was performed in a separate room outside of the operating room. All laser procedures were performed under topical anesthesia using 0.5% proparacaine hydrochloride ophthalmic solution (Alcaine; Alcon, Fort Worth, Texas, USA). The diameter of the capsulotomies was set at 5.2 mm, and the center was set on the scanned capsule with the 3-D OCT. For anterior capsulotomy, the laser settings were as follows: horizontal spot spacing, 5 μm; vertical spot spacing, 10 μm; and pulse energy, 4 μJ.

After pretreatment, the patient was transferred to the operating room in order to receive topical anesthesia followed by cataract extraction and IOL insertion. Three different IOLs were used, and the patients were divided into 3 groups accordingly. All lenses were single-piece open loop-haptic IOLs without angulation (Group I: ZCB00; Abbott Medical Optics, Santa Ana, California, USA; and Group II: EC-1PAL; Aaren Scientific, Ontario, California, USA) or single-piece plate-haptic without angulation (Group III: CT Asphina; Zeiss, Jena, Germany). The phacoemulsification procedure was performed using a conventional technique. No intraoperative or postoperative complications occurred. All patients were prescribed antibiotic and steroid eye drops 4 times daily for 1 month after surgery.

• **MEASUREMENTS:** Preoperative clinical factors were evaluated, including intraocular pressure as well as uncorrected and corrected distance visual acuity. Keratometry, manifest refraction, and optical biometry were used to calculate IOL power using the Haigis formula, which is generally used for the normal range of axial length (AL).[13] Preoperative anterior chamber depth (ACD) was measured using partial-coherence interferometry optical biometry (IOLMaster 500; Carl Zeiss Meditec, Jena, Germany) and subsequently used in the Haigis formula in order to calculate refractive outcome. Preoperative ACD was defined as the distance from the anterior surfaces of the cornea and the lens.

The femtosecond laser cataract surgery system produced 3-D OCT images, and built-in image processing software provided the quantitative crystalline lens geometry, including LEP, LT, lens vaulting, and ACD. The LEP was defined as the distance from the central anterior surface of the cornea to the crystalline lens equator. The lens equator was rendered using 2 B-scan OCT images, including horizontal and vertical meridians, by the software (version 3.0) included in the femtosecond laser cataract surgery system. The lens equator was considered to be the imaginary plane that connects the anterior and posterior capsule surfaces, as shown in Figure 1. Lens vaulting was defined as the distance between the anterior lens surface and the lens equator quantifying the extent of the anterior surface's bulging from the lens equator. Postoperative ACD and manifest refraction were measured 2 months after surgery. A Scheimpflug camera (Pentacam; Oculus, Wetzlar, Germany) was used to measure postoperative ACD. All measurements were performed by the same trained examiner.

• **CALCULATION OF REFRACTIVE OUTCOMES FROM INDIVIDUALIZED MODEL EYE USING AN OPTICAL RAY-TRACING METHOD:** The parameter LEP, which was the focus of the present study, is not included as a variable in conventional formulas for calculating IOL power, such as the Haigis formula. Thus, we used an individualized model eye and optical ray tracing software (ZEMAX; Radiant Zemax, Redmond, Washington, USA) to evaluate refractive outcomes when LEP was used to calculate IOL power.

The individualized model eye was first established using an optical ray-tracing method based on information

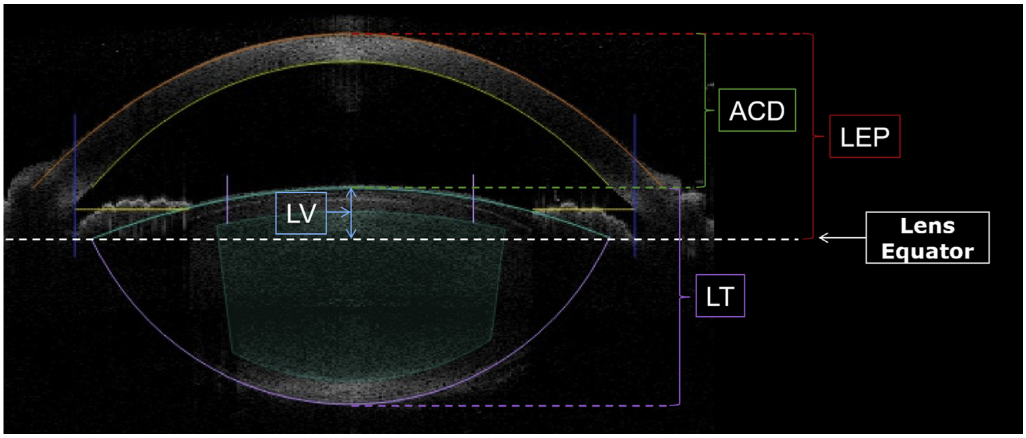

FIGURE 1. Anterior segment optical coherence tomography (AS-OCT) image illustrating measurement of the lens equatorial position (LEP), anterior chamber depth (ACD), lens vaulting (LV), and lens thickness (LT). The lens equator as well as the anterior and posterior surfaces of the lens can be identified from the AS-OCT image. The lens equatorial plane was determined using 2 lens equator meridians.

gathered after cataract surgery. To accurately represent corneal optics, corneal curvature and corneal thickness were both included in the ray-tracing model eye. A total of 18 aberrations up to the fifth Zernike radial order were used to determine the corneal curvature, and both those corneal aberrations and corneal thickness were measured with a Scheimpflug camera. Axial length, measured from partial-coherence interferometry, and postoperative ACD were used to estimate the IOL power that would make the model eye emmetropic. An IOL with the resulting estimated power was then placed at the LEP, which was determined from the preoperative biometry measurements. Residual refractive error, induced by the discrepancy between postoperative ACD and LEP, was assumed to be refractive outcome if LEP was used to calculate IOL power.

The 3 IOLs used in the present study each had a unique haptic design, including different haptic angles and shapes, causing offset from the LEP. Thus, in a manner similar to differing IOL constants, different offsets for each of the 3 IOLs were applied so that the mean prediction error in each IOL group was zero, and ray tracing–based prediction error (E_{ray}) was calculated in each patient.[14] The same process was applied to clinically measured prediction error, where $E_{clinical}$ was defined as the difference between the manifest refraction measured 2 months after the cataract surgery and the predicted refraction calculated from the Haigis formula. After calculating these parameters, E_{ray} was compared to $E_{clinical}$ for all 3 groups.

• **STATISTICAL ANALYSIS:** The Pearson correlation analysis was used to identify statistically significant correlations between postoperative ACD and preoperative parameters measured by 3-D OCT, including preoperative ACD, LEP, LT, and lens vaulting. To determine a combination of parameters that predict postoperative ACD most reliably, preoperative ACD and parameters related to lens geometry measured by OCT were adopted as explanatory variables in the present study. The statistically significant variable or combination of variables that were able to significantly predict postoperative IOL position were determined by stepwise regression analysis. Finally, median absolute error (MedAE) calculated from E_{ray} and $E_{clinical}$ were compared between 3 groups. *P* values less than .05 were considered statistically significant. All statistical analyses were performed using SPSS version 18.0 (SPSS Inc, Chicago, Illinois, USA).

RESULTS

ONE HUNDRED AND SIX EYES WERE INCLUDED IN THIS study, but 2 cases of anterior polar type cataract were excluded because the software in the femtosecond cataract surgery system could not calculate the lens geometry parameters. Thus, 104 eyes (78 [75%] female) were enrolled in the present study. There were no significant differences in age or sex of the subjects between the 3 groups. Preoperative biometry measurements revealed no significant differences between the 3 groups in terms of AL, keratometry for the front and back surfaces, central corneal thickness, or ACD (Table 1).

Figure 2. shows the results of the linear correlation analyses that were used to investigate the relationships between postoperative ACD, measured by Scheimpflug photography, and various preoperative parameters related to lens geometry. Preoperative ACD, measured by the OCT included in the femtosecond laser cataract surgery device, showed a weak positive correlation with the postoperative ACD in Group III (R = 0.373, *P* = .03) and a

TABLE 1. Baseline Demographics of Patients Who Underwent Femtosecond Laser–Assisted Cataract Surgery

	Group I	Group II	Group III	*P* Value
Number	34	36	34	
Age (years)	67 (45–82)	66 (40–81)	65 (34–81)	.491[a]
Sex (male:female), n	11:23	6:30	9:25	.308[b]
Axial length (mm)	23.86 ± 1.35	24.09 ± 1.82	24.35 ± 2.08	.511[a]
Keratometry (D)				
Front surface	43.76 ± 1.70	44.24 ± 1.55	44.21 ± 1.27	.291[a]
Back surface	−6.42 ± 0.30	−6.48 ± 0.28	−6.51 ± 0.31	.347[a]
Central corneal thinckness (μm)	558.5 ± 24.7	541.1 ± 25.3	551.3 ± 31.3	.082[a]
Anterior chamber depth (mm)	3.27 ± 0.39	3.30 ± 0.47	3.49 ± 0.39	.062[b]

Data are presented as mean ± standard deviation for all variables except number, age (median and range), and sex.
[a] *P* value determined by χ^2.
[b] *P* value determined by 1-way analysis of variance.

moderate positive correlation in Group I (R = 0.428, *P* = .011) and Group II (R = 0.591, *P* < .001). Preoperative LEP, measured by 3-D OCT, showed a moderate positive correlation with postoperative ACD in all groups (Group I: R = 0.570, *P* < .001; Group II: R = 0.634, *P* < .001; Group III: R = 0.565, *P* = .001). Neither LT nor lens vaulting showed a significant statistical correlation with postoperative ACD. LEP was the only statistically significant predictor for postoperative ACD by stepwise regression analysis. The coefficient of determination for LEP in Groups I, II, and III was 32.4%, 40.2%, and 31.9%, respectively (Table 2).

The mean E_{ray} for each IOL style and formula was zeroed out before comparing them to $E_{clinical}$. As a result, the offset for LEP in Groups I, II, and III were 0.5, 0.15, and 0.3 mm, respectively. For each of the 3 groups, the amount of change for the offset value was correlated to the manufacturer-supplied A-constant (119.3, 117.8, and 118.3 for Groups I, II, and III, respectively).

The MedAE from E_{ray} was smaller than the MedAE from $E_{clinical}$ in all groups (Table 3). E_{ray} values for all subjects were within ±1 diopter (D). $E_{clincical}$ results showed that 94.1%, 94.4%, and 91.2% of all subjects were within ±1 D in Groups I, II, and III, respectively. Both the first and the third quartiles of absolute values for E_{ray} (0.27 and 0.04 D, 0.34 and 0.03 D, 0.36 and 0.05 D in Groups I, II, and III, respectively) were smaller than the corresponding values for $E_{clinical}$ (0.40 and 0.13 D, 0.59 and 0.14 D, 0.55 and 0.19 D in Groups I, II, and III, respectively), as shown in Figure 3.

DISCUSSION

IN THIS STUDY, WE EVALUATED A NEW PARAMETER, LEP, AS a predictor for postoperative IOL position after cataract surgery. Among the optical biometry measurements, including measurements related to crystalline lens geometry, we found that LEP was the best predictor of postoperative IOL position. The other parameters evaluated in this study included preoperative ACD, LT, and lens vaulting. We also demonstrated that the improved ability to predict postoperative IOL position based on LEP has the potential to reduce variability and error of refractive outcomes after cataract surgery.

Currently, no device is able to image the entire anterior segment of the eye or analyze the complete crystalline lens biometry. Ultrasound biomicroscopy and magnetic resonance imaging are able to quantify the lens geometry behind the iris; however, these methods have relatively poor image resolution and are difficult to use in a clinical environment, making them less desirable for use in cataract surgery.[15] The femtosecond laser device for cataract surgery employed in this study includes a spectral-domain OCT system configured with an equivalent 10 μm depth resolution and an axial range of over 15.0 mm in water. This system is able to provide information about the biometry of the anterior segment, including lens geometry, at high resolution. However, OCT scanning cannot perfectly visualize the lens equator because part of the crystalline lens is obscured behind the iris; therefore, embedded software on the device sets an imaginary line to visualize the lens equator based on images of the 2 meridians of the lens equator. The distance from the anterior surface of the cornea to the equatorial line of the lens was defined as the LEP (Figure 1). To our knowledge, the present study is the first to introduce the LEP measured by 3-D OCT as a parameter for IOL power calculation.

Because the lens parameters were calculated by proprietary software built into the laser system that was used in this study, repeatability and accuracy of the measurements are unknown. More importantly, the system is not able to image the entire lens profile, especially the area behind the iris. However, it has been previously demonstrated that

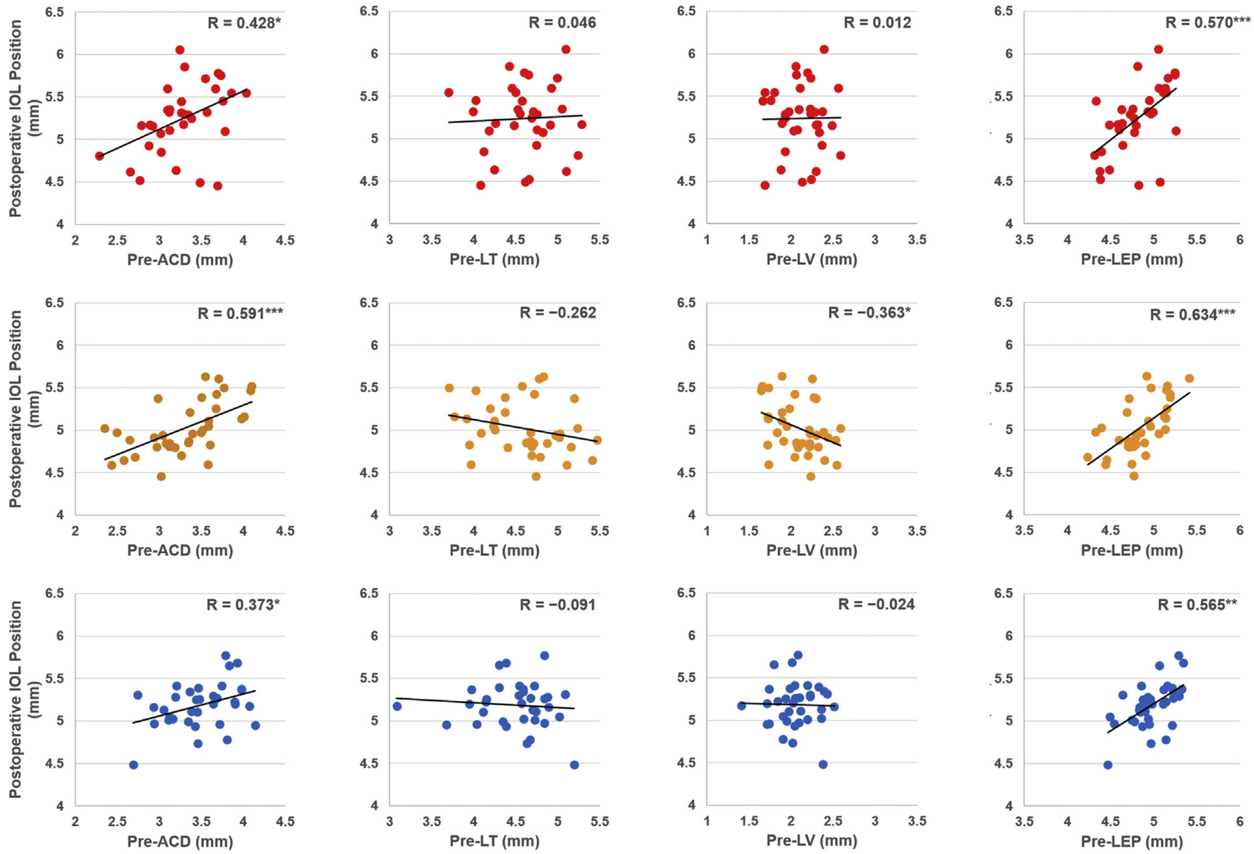

FIGURE 2. Scatterplots illustrating the correlations between postoperative intraocular (IOL) position and preoperative biometric measurements, including anterior chamber depth (ACD) and lens geometry (Group I: Top row; Group II: Middle row; Group III: Bottom row). **P* < .05, ***P* < .01, ****P* < .001. LEP = lens equatorial plane; LT = lens thickness; LV = lens vaulting; OCT = optical coherence tomography.

TABLE 2. Results of Stepwise Regression Analysis Showing That Only Preoperative Lens Equatorial Plane Was a Significant Predictor of Postoperative Anterior Chamber Depth

	Group I			Group II			Group III		
Preoperative Parameter	B	β	f (p)	B	β	f (p)	B	β	f (p)
Pre-LEP	0.796	0.570	3.920[b]	0.720	0.634	4.779[b]	0.636	0.565	3.873[a]
(Constants)	1.409	-	1.439	1.538	-	2.105	2.022	-	2.472
F		15.370[b]			22.842[b]			14.997[a]	
R^2		0.324			0.402			0.319	

Pre-LEP = preoperative lens equatorial plane.
[a]$P < .01$.
[b]$P < .001$.

the anterior and posterior capsules can be accurately identified by the proprietary INTEGRated Algorithm Guidance imaging system.[16] Based on this information, an imaginary capsular surface was set, and parameters related to lens geometry could be calculated as numerical values by software built into the device. Unfortunately, this process could have potentially introduced error into the lens geometry estimations, including the LEP estimations, in the present study. To ensure that the lens equator behind the iris and the LEP measurements are accurate, more advanced technology, such as magnetic resonance imaging, should be employed in a future study.

TABLE 3. Comparison of Prediction Error Resulting From Haigis Formula and the Ray-Tracing Method

	Haigis Formula	Ray-Tracing Method
Median absolute error (D)		
Group I	0.24	0.13
Group II	0.30	0.10
Group III	0.35	0.15
Eyes Within Prediction Error (%)		
±0.25 D		
Group I	52.9	70.6
Group II	47.2	66.7
Group III	26.5	61.8
±0.50 D		
Group I	82.4	94.1
Group II	69.4	86.1
Group III	64.7	91.2
±1.00 D		
Group I	94.1	100.0
Group II	94.4	100.0
Group III	91.2	100.0

D = diopter.

Almost all formulas for estimating IOL power are essentially based on a simplified model eye that assumes a thin cornea and lens.[1] In this way, IOL power can be calculated using the Gaussian equation of paraxial optics.[8] Corneal power and AL can be accurately determined using optical or ultrasound imaging technology, leaving ELP as the only variable that cannot be accurately measured. Thus, ELP is predicted based on preoperative ocular biometry measurements. In recent IOL power calculation formulas, the accuracy of predicting ELP has been improved by taking various preoperative biometry data into consideration, including keratometry, AL, ACD, age, and so on.[4,8,17–19] For example, the Hoffer Q, which is based on a Q formula, estimates the ELP using the AL and the tangent of the keratometry; the Holladay 1 formula uses the Fyodorov corneal height formula, which in turn uses AL and keratometry, as does the SRK/T.[4,17,18] The Holladay 2 formula uses logarithms of 7 relevant predictors: AL, keratometry, corneal diameter, preoperative refraction, ACD, LT, and patient age (listed in order of decreasing importance).[19] Finally, the Haigis formula uses AL and preoperative ACD with 3 constants to estimate ELP.[8]

Lens geometry is considered to be an important factor in newly developed IOL power calculation methods, such as the Olsen-C formula and the new Shammas formula.[20,21] To predict ELP, the Olsen-C formula uses preoperative ACD and lens geometry to calculate a C constant for each IOL, while the new Shammas formula uses ante-nucleus distance, which is the distance between the anterior corneal surface and the anterior nucleus surface of the lens, as well as nuclear thickness and AL. Although

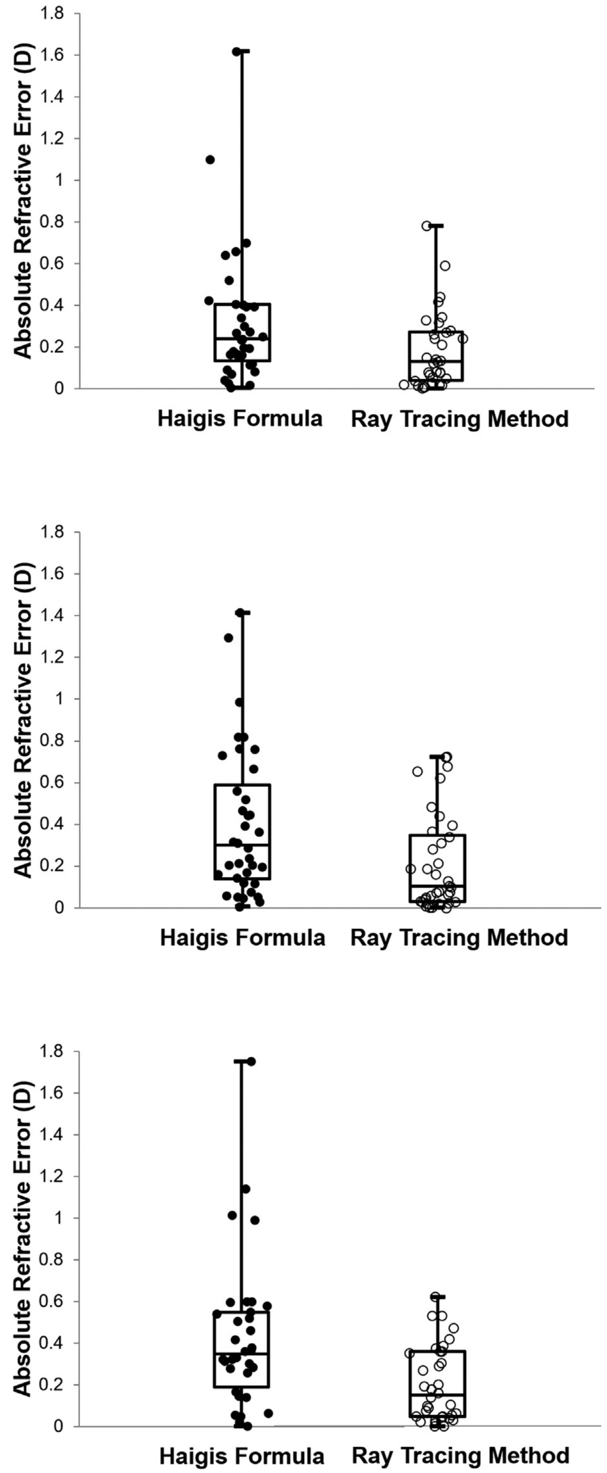

FIGURE 3. Absolute prediction error for the ray-tracing method and for clinical outcomes in 3 groups (Group I: Top; Group II: Middle; Group III: Bottom) presented as jitter and box plots. Median, quartile, minimum, and maximum values for absolute prediction error in each group are displayed on these plots.

these formulas have been shown to yield good estimates of postoperative IOL position, ACD and LT may not be sufficient to predict the postoperative IOL plane. The key hypothesis tested in the present study was that the IOL would most likely be placed at the lens equator after implantation. Our results suggest that a new IOL formula that uses LEP instead of preoperative anterior chamber depth or LT would ensure a more accurate IOL power calculation. Although additional studies employing larger sample sizes are required to confirm our findings, we report that LEP can be used as a measure of the IOL's axial position after its implantation, and, more importantly, that this parameter can be used to develop a new IOL power calculation method that is customizable for each patient.

The study by Olsen and Hoffmann[20] demonstrated that effective IOL power estimated from ray tracing based on actual IOL design parameters including radii of curvature of both surfaces and thickness improved refractive outcome after cataract surgery. They reported a smaller MedAE (0.29 and 0.21 D in public hospital and private clinic data, respectively) compared to the Haigis formula. Our study using LEP found even smaller MedAE (0.13 D, 0.10 D, and 0.15 D in Groups I, II, and III, respectively). It should be noted that these studies investigated 2 different contributing factors—that is, effective IOL power and IOL position—thus, this comparison might not be precise. However, it is conceivable that advances made from those studies could be combined and further improve the accuracy of refractive outcomes after IOL implantation in the future.

It is important to note that LEP might not be exactly the same as IOL position; that is, there might be a constant offset between LEP and IOL position. The magnitude of this offset depends on the mechanical properties of each IOL haptic.[22,23] For example, angulated haptic IOLs show a postoperative forward shift.[22,24,25] The 3 IOL types used in the present study had different mechanical haptic designs, which might have had differing effects on postoperative IOL position. Typically, unique IOL constants, such as the A-constant or the ACD constant, are defined by each IOL's characteristics, including haptic design, postoperative position within the eye, biometry measurement settings, surgeon's factor, and so on.[26–28] Although a certain IOL constant is provided by IOL manufactures, surgeons are able to optimize these constants to improve refractive outcomes.[29] Thus, we applied the same adjustment for each of the 3 IOLs when estimating refractive outcomes using LEP as a predictor.

Additionally, factors other than mechanical properties can affect the offset between LEP and IOL. For example, the weak intensity of anterior capsular opacification in the hydrophilic IOLs could add to a postulated anterior shift.[25] The mechanical interaction of the capsular bag with the IOL could also affect IOL position, as is seen in the forces on IOL haptics resulting from capsular fibrosis.[30] These hard-to-control factors can increase the variability in predicting individual IOL position, and in the future this variation could be reduced by customizing the size of the IOL haptic to the capsular bag diameter.

Although the femtosecond laser–assisted cataract surgery system used in the study is a powerful tool to measure the preoperative lens geometry, it requires the patient to be supine and increases surgery cost significantly, which makes it difficult to be used widely. However, it would be possible to upgrade a commercially available anterior segment OCT system by adding an advanced image processing algorithm to quantify crystalline lens geometry automatically. The present study identifies LEP as a promising parameter of preoperative crystalline lens geometry that can serve as an accurate predictor of postoperative IOL position. We believe that the use of LEP for IOL power calculation can be a practical choice for use in the clinic and might make it possible to improve refractive outcomes for cataract surgery.

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