ARTICLE

Estimation of effective lens position using a method independent of preoperative keratometry readings

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PURPOSE: To evaluate the validity of a keratometry (K)-independent method of estimating effective lens position (ELP) before phacoemulsification cataract surgery.

SETTING: Institute of Eye Surgery, Whitfield Clinic, Waterford, Ireland.

DESIGN: Evaluation of diagnostic test or technology.

METHODS: The anterior chamber diameter and corneal height in eyes scheduled for cataract surgery were measured with a rotating Scheimpflug camera. Corneal height and anterior chamber diameter were used to estimate the ELP in a K-independent method (using the SRK/T [ELP_{rs}] and Holladay 1 [ELP_{rh}] formulas).

RESULTS: The mean ELP was calculated using the traditional (mean ELP_s 5.59 mm $\pm$ 0.52 mm [SD]; mean ELP_h 5.63 $\pm$ 0.42 mm) and K-independent (mean ELP_{rs} 5.55 $\pm$ 0.42 mm; mean ELP_{rh} $\pm$ SD 5.60 $\pm$ 0.36 mm) methods. Agreement between ELP_s and ELP_{rs} and between ELP_h and ELP_{rh} were represented by Bland-Altman plots, with mean differences ($\pm$ 1.96 SD) of 0.06 $\pm$ 0.65 mm (range -0.59 to $+0.71$ mm; $P=.08$) in association with ELP_{rs} and -0.04 $\pm$ 0.39 mm (range -0.43 to $+0.35$ mm; $P=.08$) in association with ELP_{rh}. The mean absolute error for ELP_s versus ELP_{rs} estimation and for ELP_h versus ELP_{rh} estimation was 0.242 $\pm$ 0.222 mm (range 0.001 to 1.272 mm) and 0.152 $\pm$ 0.137 mm (range 0.001 to 0.814 mm), respectively.

CONCLUSION: This study confirms that the K-independent ELP estimation method is comparable to traditional K-dependent methods and may be useful in post-refractive surgery patients.

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As a result of improved predictability of refractive outcomes after cataract surgery, patients' expectations are high and attaining precise postoperative refraction within $\pm$0.50 diopter (D) of target is a realistic goal of the conscientious cataract surgeon. The accuracy of predicting the necessary power for an intraocular lens (IOL) is dependent on the accuracy of several preoperative measurements.[1,2] These include, depending on the formula used, some or all of the following: central corneal refractive power (keratometry [K] readings), axial length (AL) (biometry), horizontal corneal diameter (horizontal white to white), anterior chamber depth (ACD), lenticular thickness, preoperative refraction, and the age of the patient.[1–3]

Definitions of ACD vary according to context, and this should be acknowledged in any discussion of ACD. The clinical definition of ACD in the normal phakic eye is straightforward and refers to the distance from the cornea to the anterior surface of the lens. Anatomically, ACD refers to the distance between the posterior surface of the cornea; however, in an optical context (such as when discussing ACD in an IOL power formula), the distance is normally measured from the anterior surface of the cornea and includes the corneal thickness. This is justified, in part, by the position of the second principal plane of the cornea, which is close to the anterior surface (actually about 0.05 mm in front of the cornea).[3]

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However, the endpoint of the ACD distance is much more complex. Many formulas do not use the anterior surface of the IOL as the reference point but instead use the effective lens position (ELP), defined as the effective distance from the anterior surface of the cornea to the lens plane as if the lens were of infinite thinness. The ELP may be back-calculated as the effective ACD "predicting" the actual postoperative refraction on a given data set. Hence, the ELP is formula-dependent and need not reflect the true ACD in the anatomic sense. This is the case for an ACD defined by the manufacturer on an IOL container along with the A-constant. The ACD in this context is most often based on the Binkhorst formula and cannot be taken to reflect the true postoperative IOL position in the pseudophakic eye.[3] For the sake of clarity we will, henceforth, refer to the postoperative ACD as the postoperative IOL position.

Models based on statistically analyzed relationships between some or all of the previously mentioned preoperative measurements of the eye and the postoperative IOL position have been used to predict the ELP in the preoperative setting. Thus, estimation of ELP remains an empirical component to all ocular biometric formulas predicting refractive outcomes after cataract surgery, and different models for doing this are important determinants of the accuracy of formulas for predicting refractive outcomes after cataract surgery.[4] The predictability of ELP has improved in recent years as a result of enhancements in the formulas used and the accuracy of the preoperative measurements of ocular biometric variables.

In 1975, Fyodorov et al.[5] derived an equation based on an individual eye's K and AL to estimate ELP. Indeed, it is well known that in eyes that have had corneal refractive surgery, the pre-refractive surgery K (preoperative K) may be unknown, rendering the predictability of the ELP problematic, thereby contributing to poor predictability of refractive outcomes after cataract surgery in such eyes.[6]

Ho et al.,[6] in 2008, described a regression-analysis derived form of the Fyodorov equation[5] to calculate a theoretical corneal radius that can be used to estimate the ELP, independently of preoperative keratometry readings.

The Pentacam (Oculus Optikgeräte GmbH) is a rotating Scheimpflug camera designed to image the anterior segment. It provides topographic maps of the anterior and posterior corneal surfaces, pachymetry maps, and biometric measurements of the anterior segment.[6–8] In this way, the Pentacam-measured anterior chamber diameter (measured from anterior chamber angle to anterior chamber angle) and corneal height (measured from the internal cornea to the line connecting the anterior chamber angles) can be used to calculate the theoretical corneal radius.[6] Ho et al.[6] report good agreement with this K-independent ELP estimate compared with traditional K-dependent ELP estimation methods using the Holladay 1 and SRK/T formulas. However, Ho et al. did not measure the postoperative IOL position; therefore, their conclusions were based solely on estimation errors before cataract surgery.

The K-independent ELP methods described by Ho et al.,[6] could represent an important advance in cataract surgery for patients who have had previous corneal refractive surgery. We will henceforth refer to this method as the K-independent ELP estimation. We performed a study to compare K-dependent ELP estimation methods and K-independent ELP estimation methods.

PATIENTS AND METHODS

This prospective study comprised cataractous eyes of consecutive patients with no visually consequential ocular comorbidity, all of whom had uneventful phacoemulsification cataract surgery between November 2008 and May 2009. Eyes with a history of trauma or ocular surgery were excluded. The South East Regional Ethics Committee approved the study, and the study protocol adhered to the tenets of the Declaration of Helsinki. Valid and informed consent was secured from each patient before enrollment. All applicable institutional and governmental regulations concerning the ethical use of human volunteers were followed during this research.

All patients had a complete ophthalmic examination including, automatic K (IOLMaster, version 5, Carl Zeiss Meditec AG), ocular biometry (IOLMaster), and a Pentacam scan. In this study, the Pentacam system was set to acquire 25 images per scan at the automatic release mode (images captured automatically). To obtain the Pentacam-measured corneal height, the Scheimpflug image in the horizontal meridian was displayed. The software (version 1.16) showed the locations of the anterior chamber angles. A line connecting the 2 points of the anterior chamber angles was drawn. Then, a line was drawn from the anterior corneal vertex,

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which intersected and was perpendicular to the line connecting the anterior chamber angles. The distance from the posterior corneal surface to the intersection point was termed *corneal height*. The distance between the 2 anterior chamber angle points was termed *anterior chamber diameter* (the measured anterior chamber diameter from angle to angle) (Figure 1).[6]

The Appendix (available at http://jcrsjournal.org) outlines the equations used by Ho et al.[6] to estimate ELP using 4 methods (equations 2 to 5). Equation 1 is a formula for calculating the theoretical corneal radius, which is a substitute for keratometry in subsequent K-independent formulas (equations 3 and 5).[6] Equation 2 describes a formula that estimates ELPs, which is the ELP estimate obtained when using the SRK/T formula with K in the traditional fashion. Equation 3 describes a formula that estimates ELPrs, which is the ELP estimate obtained when using the SRK/T formula with the theoretical corneal radius used instead of K. Equation 4 describes a formula that estimates ELPh, which is the ELP estimate obtained when using the Holladay 1 formula with K in the traditional fashion. Equation 5 describes a formula that estimates ELPrh, which is the ELP estimate obtained when using the Holladay 1 formula with the theoretical corneal radius used instead of keratometry. The ELP was calculated for all study eyes by the SRK/T and Holladay 1 formulas using K-dependent (equations 2 and 4) and K-independent ELP estimation methods (equations 3 and 5), respectively.

Surgical Technique

In each study eye, surgery was performed using topical anesthesia (proxymetacaine hydrochloride 0.5%) through a 2.75 mm superior clear corneal incision. A continuous curvilinear capsulorhexis was completed after sodium hyaluronate 1.0% (Healon) was injected. Hydrodissection was performed using a balanced salt solution. The irrigation solution contained 16% gentamicin sulfate (80 mg Genticin in 500 mL fortified balanced salt solution [BSS Plus]). After removal of the nucleus using torsional phaco technology (Infiniti, Alcon laboratories, Inc.), irrigation/aspiration of soft lens matter was performed. Then, a foldable, posterior chamber IOL (Tecnis ZA9003, Advanced Medical Optics Inc.; A-Constant 119.1; ACDconst 5.6; surgeon factor 1.85) was implanted in the capsular bag with an introducer (AMO EmeraldT Series Unfolder and Cartridge, Advanced Medical Optics, Inc.). Stromal hydration was then performed to achieve wound integrity; a 10-0 nylon suture was placed in the corneal wound when wound integrity was deemed inadequate by the surgeon. Intracameral cefuroxime (1 mg Zinacef in 0.1 mL of sterile water for injection) was administered via the paracentesis. Then, a single drop of apraclonidine 1% (Iopidine 1%) and an aliquot of fucidic acid 1% ointment (Fucithalmic) were administered to the corneal surface.

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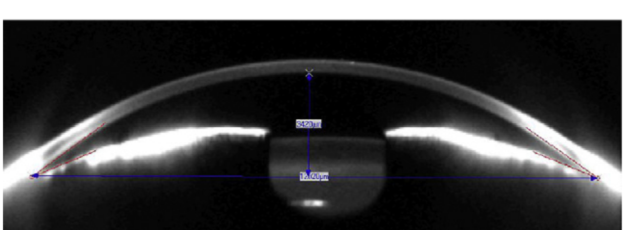

Figure 1. Scheimpflug image showing the distance from the posterior corneal surface of the vertex to the line connecting the anterior chamber angles (corneal height).

Postoperative Examination

Patients were examined 2 weeks postoperatively; in cases in which a corneal suture was in situ, it was removed at this visit. Patients were then reexamined 6 weeks postoperatively, when postoperative IOL position was calculated using the inbuilt calipers on the Pentacam screen (Figure 1); this was done because of the possible failure of the Scheimpflug system to automatically identify the anterior surface of the IOL.[9]

Statistical Analysis

Data were analyzed using an Aabel software package (version 3.0.3, GigaWiz Ltd. Co.). Agreement between the respective K-dependent and K-independent methods of ELP estimation is represented by Bland-Altman plots and expressed in terms of mean bias ± 1.96 standard deviations (SD). Correlations were calculated using the Pearson correlation coefficient (r), and a P value less than 0.05 was taken as statistically significant; the r^2 value is also documented for completeness.

The differences (arithmetic and absolute) between the ELP estimates were calculated using traditional K-dependent and their respective and new K-independent estimation methods. This yielded the mean arithmetic estimation error (ME) and the mean absolute estimation error (MAE). When using the SRK/T formula to calculate the ELP_s and the ELP_{rs}, the ME_s = mean ELP_{rs} - mean ELP_s and the MAE_s = mean absolute ELP_{rs} - mean absolute ELP_s. When using the Holladay 1 formula to calculate the ELP_h and the ELP_{rh}, the ME_h = mean ELP_{rh} - mean ELP_h and the MAE_h = mean absolute ELP_{rh} - mean absolute ELP_h.

RESULTS

The study enrolled 95 cataractous eyes of 95 consecutive patients. The biometric data in 95 unoperated eyes (Table 1) were used to estimate the ELP using K-dependent (ELPs and ELPh) and K-independent methods (ELPrs and ELPrh). In the study, the mean ELPs calculated using preoperative K values in the SRK/T formula (equation 2) was 5.59 mm ± 0.52

Table 1. Characteristics of the 95 virgin eyes used to develop formulas to derive the ELP using keratometry-dependent and keratometry-independent methods.

Characteristic	Mean ± SD	Range
Age (y)	70.2 ± 10.7	38 to 88
Spherical equivalent (D)	−0.89 ± 4.54	−20.38 to +7.63
Anterior corneal radius (mm)	7.79 ± 0.30	7.25 to 8.25
Axial length (mm)	23.88 ± 1.80	20.66 to 30.50
H_m (mm)	3.49 ± 0.37	2.34 to 4.41
AG_m (mm)	11.74 ± 0.74	9.51 to 13.71

AG_m = Pentacam-measured anterior chamber diameter from angle to angle; H_m = Pentacam-measured corneal height

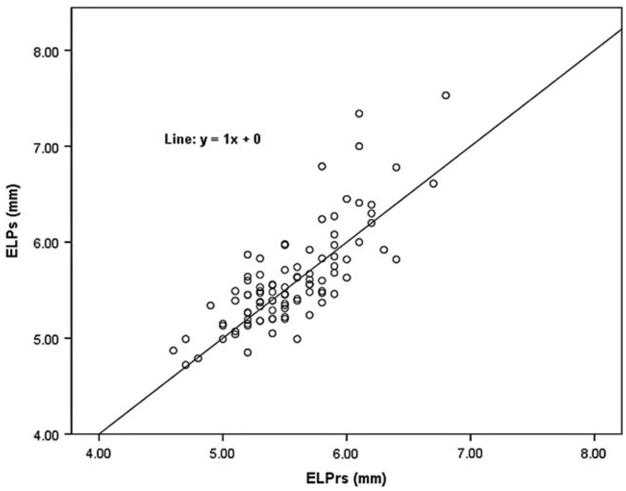

Figure 2. Scattergram of the ELP estimate obtained when using the SRK/T formula in a K-dependent method (ELPs) versus the ELP estimate obtained when using the SRK/T formula with the theoretical corneal radius in a K-independent method (ELPrs). The line of agreement is shown.

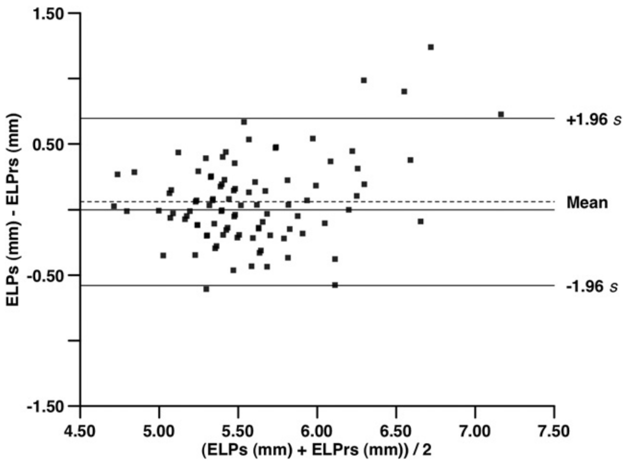

Figure 3. Bland-Altman plot of the difference between the ELP estimate obtained when using the SRK/T formula in a K-dependent method (ELPs) and the ELP estimate obtained when using the SRK/T formula with the theoretical corneal radius in a K-independent method (ELPrs). The line of mean difference (*dotted line*) and limits of $\pm$1.96 SD (*solid line*) are shown.

(SD) and was significantly and positively correlated with K-independent ELPrs (5.55 $\pm$ 0.42 mm) ($r = 0.781$, $r^2 = 66.1\%$, $P < .001$; Figure 2) when the theoretical corneal radius values were used in the SRK/T formula (equation 3). Agreement between ELPs and ELPrs is represented by the Bland-Altman plot in Figure 3, with a mean difference ($\pm$1.96 SD, range) of 0.06 $\pm$0.65 mm (range $-$0.59 to $+$0.71 mm) in association with ELPrs. The ME_s for ELPs estimation versus ELPrs estimation was 0.061 $\pm$ 0.241 mm (range $-$0.589 to 1.272 mm) and the MAE for ELPs estimation versus ELPrs estimation was 0.242 $\pm$ 0.222 mm (range 0.001 to 1.272 mm). Agreement between postoperative IOL position and ELPrs is represented by the Bland-Altman plot in Figure 4, with a mean difference ($\pm$1.96 SD) of 1.22 $\pm$ 0.82 mm (range $+$0.40 to $+$2.04 mm) in association with ELPrs.

The mean ELPh calculated using preoperative K readings in the Holladay 1 formula (equation 4) was 5.63 $\pm$ 0.42 mm and was significantly and positively correlated with K-independent ELPrh (5.60 $\pm$ 0.36 mm) ($r = 0.874$, $r^2 = 76.4\%$, $P < .001$; Figure 5), when the

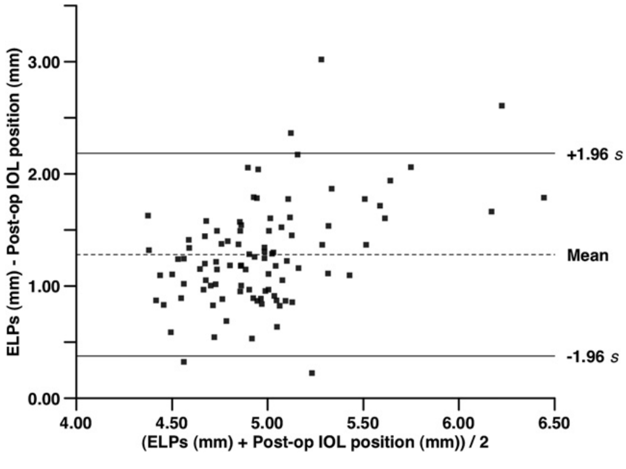

Figure 4. Bland-Altman plot of the difference between the postoperative IOL position and the ELP estimate obtained when using the SRK/T formula with the theoretical corneal radius used instead of K (ELPrs). The line of mean difference (*dotted line*) and limits of $\pm$1.96 SD (*solid line*) are shown.

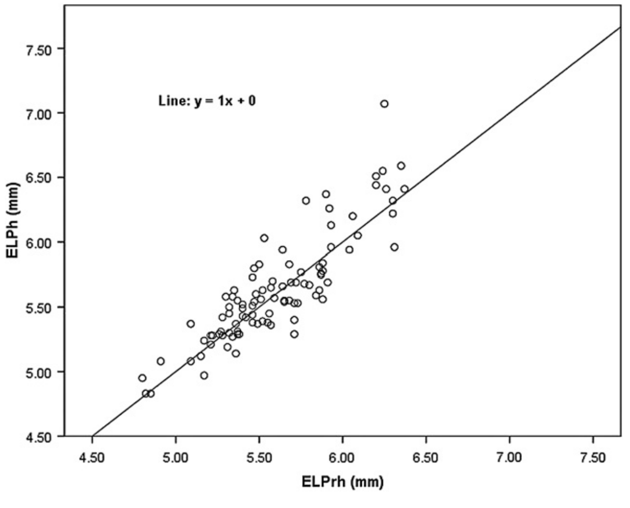

Figure 5. Scattergram of the ELP estimate obtained when using the Holladay 1 formula in a K-dependent method (ELPh) versus the ELP estimate obtained when using the Holladay 1 formula with the theoretical corneal radius in a K-independent method (ELPrh). The line of agreement is shown.

preoperative theoretical corneal radius values were used in the Holladay 1 formula (equation 5). Agreement between ELPh and ELPrh is represented by the Bland Altman plot in Figure 6, with a mean difference ($\pm$ 1.96 SD) of -0.04 ± 0.39 mm (range -0.43 to $+0.35$ mm) in association with ELPrh. The mean arithmetic estimation error (ME_h = mean ELPrh − mean ELPh) was -0.037 ± 0.203 mm (range -0.814 to 0.417 mm), and the mean absolute error (MAEh = mean absolute ELPrh − mean absolute ELPh) was 0.152 ± 0.137 mm (range 0.001 to 0.814 mm). Agreement between the postoperative IOL position and ELPrh is represented by the Bland-Altman plot in Figure 7, with a mean difference ($\pm$1.96 SD) of 1.27 ± 0.73 mm (range $+0.54$ to $+2.00$ mm) in association with ELPrh.

DISCUSSION

The relationship between ELP calculated using K-dependent and K-independent methods was positive and significant, and agreement between the 2 techniques was good. Thus, we could expect clinically comparable refractive outcomes after cataract surgery using K-independent and K-dependent methods of ELP estimation.

The ME_s and ME_h in our study were slightly greater (0.061 ± 0.241 mm and -0.037 ± 0.203 mm, respectively) than those reported by Ho et al.[6] (-0.011 ± 0.263 mm and -0.0004 ± 0.167 mm, respectively) but are broadly comparable with those reported in the former study, which generated equations 1, 3, and 5 by regression analysis from the data in their own study (thus explaining the better agreement that they report). In our study, when the SRK/T formulas used K-independent methods to calculate the ELP (ELPrs), it exhibited a slight tendency toward overestimation (and consequential hyperopic shift) relative to K-dependent ELP estimation methods (ELPs), in contrast to slight underestimation in the Ho et al. study.[6] However, ELPrh yielded a slight underestimation (and consequential myopic shift) in both studies. The mean absolute errors of ELP estimation reported in our study (ELPrs: 0.242 mm; ELPrh: 0.152 mm) are less than half the distance between a sulcus-positioned IOL and an IOL implanted in the capsular bag (approximately 0.75 mm),[10] which results in a 1.05 D difference in the IOL plane,[10] equivalent to 0.78 D in the spectacle plane.[10] This is consistent with the findings of Olsen,[11] who reported that a 0.1 mm difference in postoperative IOL position corresponded to a 0.14 D change in power in the IOL plane.

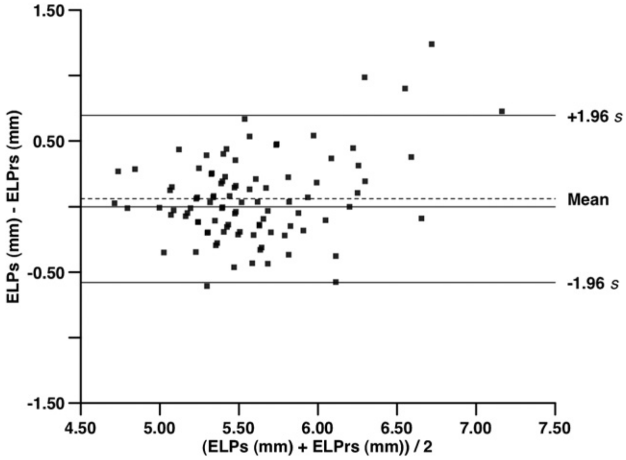

Figure 6. Bland-Altman plot of the difference between the ELP estimate obtained when using the Holladay 1 formula with K in the traditional fashion (ELPh) and the ELP estimate obtained when using the Holladay 1 formula with the theoretical corneal radius used instead of K (ELPrh). The line of mean difference (*dotted line*) and limits of $\pm$1.96 SD (*solid line*) are shown.

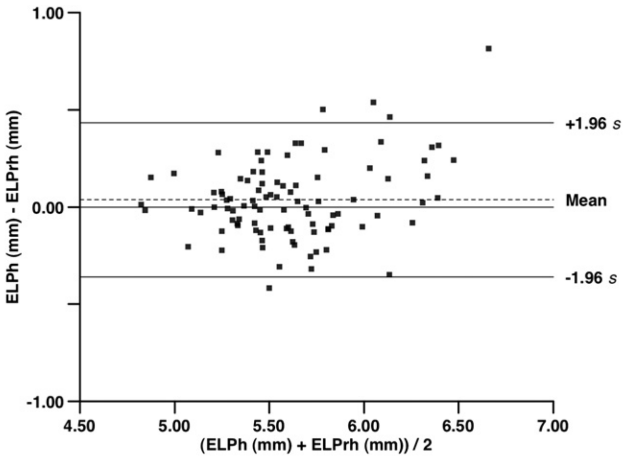

Figure 7. Bland-Altman plot of the difference between the postoperative IOL position and the ELP estimate obtained when using the Holladay 1 formula with the theoretical corneal radius used instead of K (ELPrh). The line of mean difference (*dotted line*) and limits of $\pm$1.96 SD (*solid line*) are shown.

In our study, the approximate mean and maximum discrepancies in the IOL plane were 0.34 D and 1.78 D for ELPrs (mean discrepancy = MAEs $\times$ 1.4; maximum discrepancy = maximum absolute error of ELPs $\times$ 1.4). In terms of the discrepancy in the spectacle plane (discrepancy in IOL plane $\times$ 0.743),[10] this would be represented by estimated mean and maximum discrepancies of 0.25 D and 1.32 D, respectively. Similarly, the approximate mean and maximum discrepancies in the IOL plane were 0.21 D and 1.14 D, respectively, for ELPrh (mean discrepancy = MAEh $\times$ 1.4; maximum discrepancy = maximum absolute error of ELPh $\times$ 1.4).[11] In terms of the discrepancy in the spectacle plane, this would be represented by estimated mean and maximum discrepancies of 0.16 D and 0.84 D, respectively.

With regard to the ELPrs, the calculated discrepancy in the spectacle plane between K-dependent and K-independent estimation methods was less than 0.50 D in

90.5% of cases, less than 1.00 D in 97.9% of cases, and less than 2.00 D in 100% of cases. With regard to the ELPrh, the calculated discrepancy in the spectacle plane between K-dependent and K-independent estimation methods was less than 0.50 D in 96.8% of cases and less than 1.00 D in 100% of cases.

In our study, the mean postoperative manifest refraction spherical equivalent (MRSE) prediction error was 0.51 ± 0.45 D (range −1.95 to +1.16 D; where 66.3% were <0.5 D, 87.4% were <1.0 D, 100% were <2.0 D). These results compare favorably with other studies that determined the mean postoperative MRSE prediction error after phacoemulsification cataract surgery, in which the mean postoperative MRSE prediction error is reported as follows: 45.5% to 92.0% of cases were less than 0.50 D[12–21] and 41% to 100% of cases were less than 1.00 D.[12–21] In our study, the calculated discrepancies in the spectacle plane between K-dependent and K-independent estimation methods using the SRK/T or Holladay 1 formula were less than our mean postoperative MRSE prediction errors and also compare favorably with typically reported mean postoperative MRSE prediction errors in the literature.[12–21] These calculated discrepancies also compare favorably with studies of patients having phacoemulsification cataract surgery who have previous laser in situ keratomileusis, in which it is reported that between 13% and 67% of patients had a mean postoperative MRSE within ±0.50 D of target, between 25% and 100% had a reported mean postoperative MRSE within ±1.00 D of target, and between 79% and 100% had a reported mean postoperative MRSE within ±2.00 D of target.[22–24]

Possible sources of the slightly differing results between our study and that of Ho et al.[6] in terms of ELP may be the differences in age and AL between the 2 sample populations. Our sample had a mean age of 70.2 ± 10.7 years, over double that of Ho et al.'s sample (34.4 ±16.1 years); given that the ELP is positively correlated with age (ELP increases with age),[4] this may account for the slight tendency toward overestimation with the SRK/T K-independent ELP estimation method in our study compared with that of Ho et al.[6] However, this relationship between ELP and age fails to explain the observed discrepancy between the slight underestimation seen when using the Holladay 1 K-independent ELP estimation method in our study compared with that of Ho et al.

While our sample was less myopic, with a mean spherical equivalent of −0.89 ±4.54 D, than that of Ho et al. (−5.84 ± 3.92 D),[6] and this is reflected further in the differing mean AL in the 2 studies (current study: 23.88 ± 1.80 mm; Ho et al.: 25.73 ±1.59 mm), it has been shown that estimates of the ELP are independent of preoperative refractive error[3,25] but correlate positively with AL.[3,25] In a study of the accuracy of prediction of refractive outcomes after cataract surgery using various formulas, including SRK/T and Holladay 1, Narváez et al.[18] found a similar trend (which did not reach statistical significance) reflected in varying refractive outcomes (range of MAE: 0.02 to 0.10 D) after phacoemulsification cataract surgery between groups of eyes with differing ALs; the observed discrepancy is similar in order of magnitude to the discrepancy between our study and that of Ho et al.[6] Despite the differences in population samples, however, it is noteworthy that the K-independent ELP method appears to be relatively robust, with comparable estimation errors (ME_s, ME_h, MAE_s and MAE_h) in both studies.

We compared this new method of K-independent ELP estimation with the existing K-dependent ELP methods as well as with the anatomic postoperative IOL position, and to our knowledge this relationship has not been previously investigated for the SRK/T and Holladay 1 formulas. We found that the ELP was significantly greater than the anatomic postoperative IOL position by a mean difference of 1.27 mm ($P<.001$, Student paired t test). This is in agreement with the theoretical model proposed by Holladay and Maverick.[26] Despite this discrepancy, the ELP (ELPrs and ELPrh) was significantly and positively correlated with the postoperative IOL position. Jin et al.,[27] in a study designed to predict postoperative IOL position using formulas different from those in our study (Haigis algorithm: $r = 0.6$; Olsen 2 algorithm: $r = 0.46$), report levels of correlation similar to those in our study (postoperative IOL position versus ELPrs: $r = 0.43$; postoperative IOL position versus ELPrh: $r = 0.48$). Although this correlation reached significance ($P<.01$ for both methods in our study), the correlations between postoperative IOL position and ELP were not strong enough in themselves for reliable prediction of postoperative IOL position.[27]

Refractive laser surgery alters corneal thickness and K values but does not alter ACD or corneal height measured from the endothelial surface.[28] It follows, therefore, that a method of ELP estimation, where the required biometric parameters are unchanged by refractive laser surgery, such as the K-independent ELP estimation method described here, would be extremely useful in post-refractive patients contemplating cataract surgery. It has been shown that the refractive index of the cornea is reduced after refractive surgery for myopia in a linear relationship with the attempted correction, as governed by the following equation: Post refractive surgery corneal refractive index = 1.338 + 0.0009856 × attempted correction.[29]

Because only 11 post-refractive surgery patients had cataract surgery in Ho et al.'s study,[6] our results would support the view that this new K-independent ELP estimation method appears to have the validity to warrant formal testing, in the form of a concordance study with existing K-dependent methods,[6,30] in the context of a large cohort of patients scheduled for cataract surgery but who have had previous refractive laser surgery. Such a study would have to take the corneal refractive index changes induced by refractive surgery into account, on an individual basis.

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