ARTICLE

Estimation of the effective lens position using a rotating Scheimpflug camera

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PURPOSE: To describe a no-history method of estimating the effective lens position (ELP) for double-K intraocular lens (IOL) power calculation in eyes that had previous refractive surgery.

SETTING: Departments of Ophthalmology, Taipei Medical University Hospital and Taipei City Hospital, Taipei, Taiwan.

METHODS: The corneal height (H_m) and anterior chamber diameter (AG_m) in 106 unoperated eyes were measured using a rotating Scheimpflug camera. The theoretical anterior corneal radius (R_{rt}) was then derived from H_m and AG_m by regression and rearrangement of the Fyodorov equation. The ELP estimate was then calculated from R_{rt}. The performance of this ELP estimation method in double-K IOL power calculation and the performance of other methods were compared retrospectively in 11 eyes having cataract surgery that had previous refractive surgery. The refractive results 9 to 12 weeks after cataract surgery were selected for data analysis.

RESULTS: The new ELP estimation method, combined with the BESSt formula or the Savini et al. method for estimating post refractive–surgery corneal power (K_{post}) in the double-K SRK/T formula, provided the best IOL power prediction results. The mean arithmetic and absolute IOL prediction errors were −0.05 ± 0.62 diopters (D) and 0.49 ± 0.34 D, respectively, when combined with the BESSt formula and 0.03 ± 0.73 D and 0.60 ± 0.36 D, respectively, when combined with the Savini et al. method. With either combination, all 11 eyes were within ±1.00 D of the refractive prediction error.

CONCLUSION: This ELP estimation method may be helpful for IOL power calculation in post refractive–surgery eyes when historical data are unavailable.

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Intraocular lens (IOL) power calculations are difficult in eyes that have had refractive surgery.[1–6] There are 2 main sources of errors. First, inaccurate calculation of the corneal power from the anterior corneal radius can occur when the standardized keratometric index of 1.3375 is used. Second, incorrect estimation of the post cataract–surgery IOL position (effective lens position [ELP]) by third-generation or fourth-generation theoretical IOL power calculation formulas can occur when the corneal power value after refractive surgery (K_{post}) is used.[7,8] This leads to underestimation of the ELP and thus of IOL power, resulting in hyperopia even when the postoperative corneal power is derived by a clinical history method.[2,6]

To overcome these problems, several methods have been proposed;[5,9–21] of these, the double-K clinical history method seems to be promising.[7,8,13] In this method, the keratometry (K) value before refractive surgery (K_{pre}) is used for ELP estimation, and K_{post} is used for the IOL power calculation by the vergence formula. This approach improves the accuracy of the IOL power calculation after laser in situ keratomileusis (LASIK) and photorefractive keratectomy (PRK).[7,10,20,21] Although it is a good method, the double-K clinical history method requires knowledge

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of historical data, including the K_{pre} value. If the K_{pre} value is unavailable, it will be difficult to obtain the ELP used in the third-generation or fourth-generation formulas and thus difficult to apply the double-K method.

The Pentacam (Oculus) is a rotating Scheimpflug camera 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.[22,23] In this study, we first investigated the correlation between the Pentacam-measured corneal height (H_m) and the anterior corneal radius (R) through the Fyodorov et al. equation[24] in unoperated eyes. After establishing this correlation, we could derive the R_{pre} and thus the ELP estimate from the Pentacam-measured corneal height in a post refractive–surgery eye. After obtaining the K_{post} by previously described methods,[19–21] it became possible to calculate the IOL power in a double-K manner in an eye that has had refractive surgery even when historical data were unavailable. In this paper, we refer to this as the new ELP estimation method.

PATIENTS AND METHODS

Derivation of the Effective Lens Position Estimate

One hundred six patients were randomly selected at the ophthalmology clinic of Taipei City Hospital. Patients with corneal, lens, or retinal disease or with previous ocular surgery were excluded. All patients had a complete ophthalmic examination including automatic keratometry, biometry, and a Pentacam scan. To obtain the Pentacam-measured H_m, the Scheimpflug image in the horizontal meridian was displayed. The software 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, 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 H_m. The distance between the 2 anterior chamber angle points was termed AG_m (the measured anterior chamber diameter from angle to angle) (Figure 1). These measurements were repeated at least 5 times and then averaged. The Appendix shows the derivation process of the new ELP estimation method.

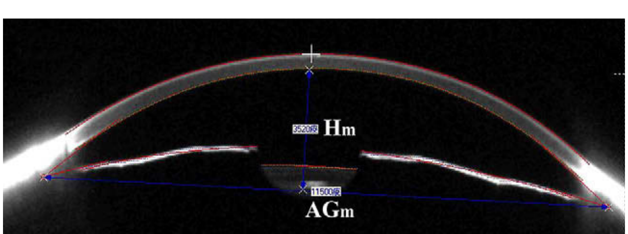

Figure 1. Scheimpflug image of the Pentacam. The distance from the posterior corneal surface of the vertex to the line connecting the anterior chamber angles was termed H_m. The distance between the 2 anterior chamber angle points was termed AG_m.

Analysis of Post Refractive–Surgery Eyes Having Cataract Surgery

All eyes in this analysis previously had myopic LASIK or automated lamellar keratoplasty. Before subsequent cataract surgery, H_m and AG_m were obtained by the Pentacam scan. The double-K clinical history method Holladay 1 or SRK/T formula was used to calculate the IOL power, when applicable. Various published no-history IOL power calculation methods were also used. The selection of IOL power was based on the IOL power calculation results, considering the refractive status in the fellow eye and the patient's lifestyle. The target refraction was set to fall within −2.00 to +0.25 diopters (D) according to the patient's lifestyle. In addition, the target refraction was set to fall within ±2.00 D from that in the fellow eye. Phacoemulsification and in-the-bag implantation of a foldable IOL (SA60AT, SN60AT, MA60MA, or MA60BM, all Alcon) were performed. The refractive error after cataract surgery was obtained between 9 and 12 weeks postoperatively. The Appendix shows the application of the new ELP estimation method in a double-K manner.

RESULTS

Derivation of the Effective Lens Position Estimate

The biometric data in 106 unoperated eyes were used for developing the formulas to derive the ELP estimate from the Pentacam-measured corneal height. The data are shown in Table 1. The scattergram of H_t (theoretical corneal height) versus H_m (the Pentacam-measured corneal height) is shown in Figure 2. These 2 variables had a statistically significant correlation ($r = 0.904$, $P < .0001$). The linear regression formula described in equation 6 in the Appendix is

$$Hrt = 0.4979H_m + 0.2425AG_m - 0.0141AL - 1.5672 (r = 0.941)$$

Figure 3 is a scattergram of H_t versus H_{rt} (the theoretical corneal height derived by regression). Figure 4

Table 1. Characteristics of the 106 virgin eyes used to develop formulas to derive the ELP estimate from the Pentacam-measured H_m.

Characteristic	Mean ± SD	Range
Age (y)	34.4 ± 16.1	19 to 77
Spherical equivalent (D)	−5.84 ± 3.92	−18.50 to + 2.50
Anterior corneal radius (mm)	7.77 ± 0.28	7.17 to 8.36
Axial length (mm)	25.73 ± 1.59	21.73 to 29.33
H_m (mm)	3.61 ± 0.31	2.74 to 4.33
AG_m (mm)	11.80 ± 0.57	9.45 to 13.28

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

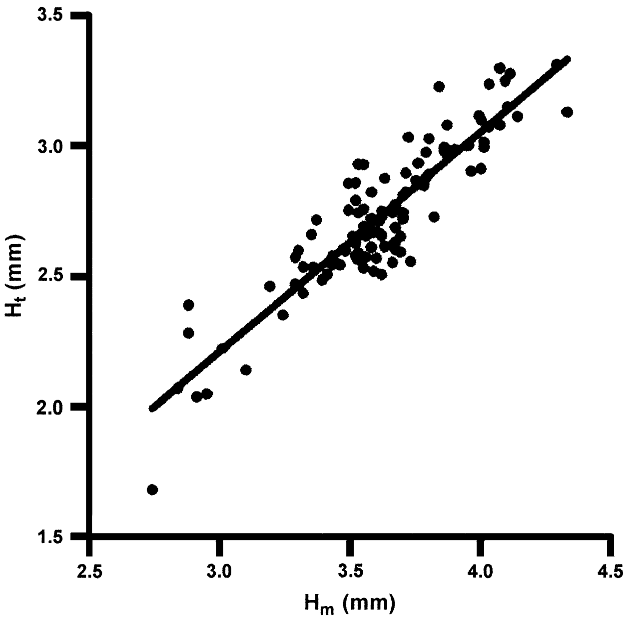

Figure 2. Scattergram of the theoretical corneal height (H_t) versus the Pentacam-measured corneal height (H_m) in the unoperated eyes.

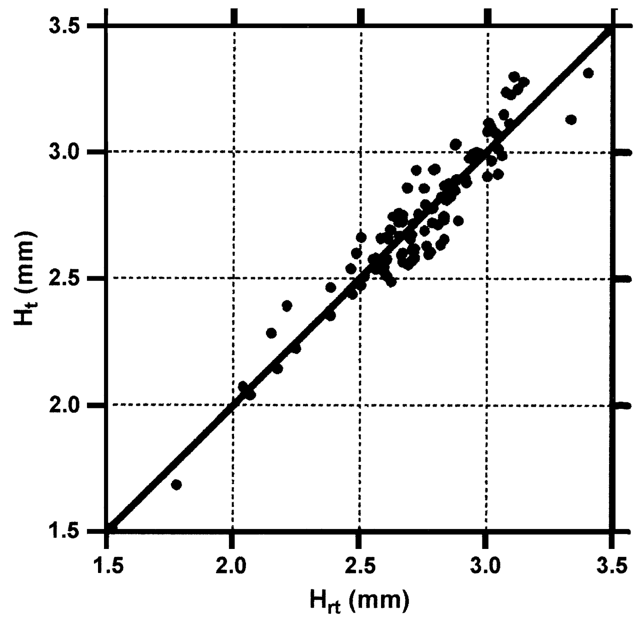

Figure 3. Scattergram of the theoretical corneal height (H_t) versus the theoretical corneal height derived by regression (H_{rt}) in the unoperated eyes.

is a scattergram of ELP_h (the ELP used in Holladay 1 formula calculation if R_m is known) versus ELP_{rh} (the ELP estimate obtained by the new method and used in Holladay 1 formula calculation when R_m is unknown) (assuming A constant = 118.4). The mean arithmetic error (ME) and mean absolute error (MAE) for the ELP_h estimation were -0.004 ± 0.167 and 0.138 ± 0.092 mm, respectively. Figure 5 is the scattergram of ELP_s (the ELP used in SRK/T formula calculation if R_m is known) versus ELP_{rs} (the ELP

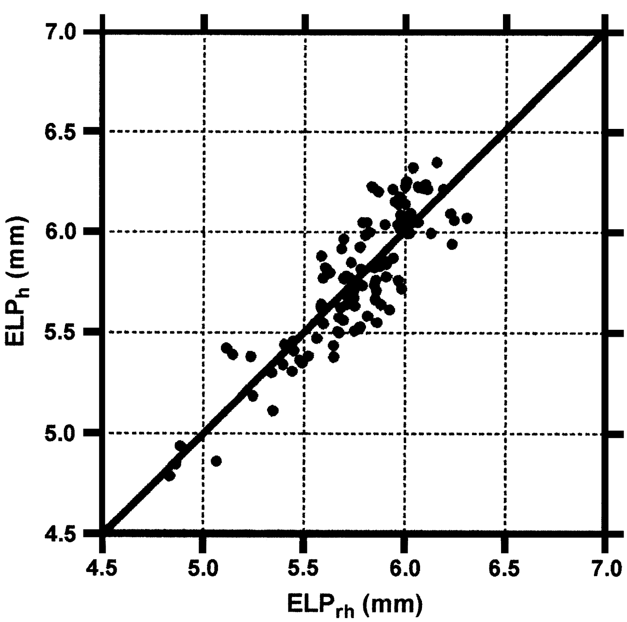

Figure 4. Scattergram of the ELP used for the Holladay 1 formula when the anterior corneal radius is known (ELP_h) versus the ELP estimate obtained by the new method and used in the Holladay 1 formula (ELP_{rh}) in unoperated eyes (A constant = 118.4).

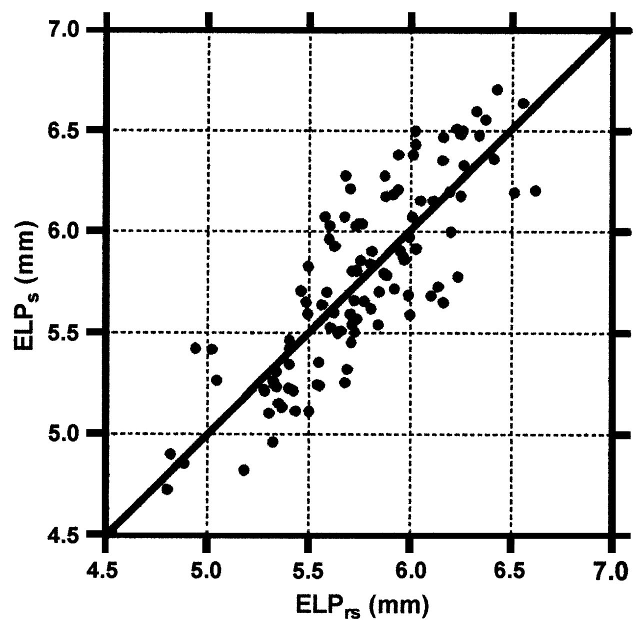

Figure 5. Scattergram of the ELP used for the SRK/T formula when anterior corneal radius is known (ELP_s) versus the ELP estimate obtained by the new method and used in the SRK/T formula (ELP_{rs}) in unoperated eyes (A constant = 118.4).

estimate obtained by the new method and used in SRK/T formula calculation when R_m is unknown) (assuming A = 118.4). The ME and MAE for ELP_s estimation were −0.011 ± 0.263 mm and 0.219 ± 0.145 mm, respectively.

Analysis of Post Refractive–Surgery Eyes Having Cataract Surgery

Eleven eyes of 8 patients having cataract surgery after previous myopic refractive surgery were included. The demographic data are shown in Table 2.

Table 3 shows the ME and MAE values for IOL prediction using different no-history IOL prediction methods (except the double-K clinical history method). The numbers of eyes within certain ranges of refractive prediction errors are shown in Table 4. Among the no-history methods, the new ELP estimation method combined with the BESSt formula or the Savini et al. method for estimating K_{post} in the double-K SRK/T formula [(ELP + BESSt + double-K SRK/T or ELP + Savini + double-K SRK/T)] provided the best IOL prediction results (referred to as the 2 best methods in the following text). The IOL powers calculated with these 2 methods did not significantly differ from the benchmark values (P = .779 and P =.888, respectively; paired t test). Variances in the mean IOL prediction error were small (0.38 and 0.53 D), indicating good consistency in prediction performance. All 11 eyes had a refractive prediction error within ±1.00 D with both methods.

The new ELP estimation method combined with the BESSt formula or the Savini et al. method for estimating K_{post} in the double-K Holladay 1 formula [(ELP + BESSt + double-K Holladay 1) or (ELP + Savini + double-K Holladay 1)] gave small variances of the mean IOL prediction error (0.56 D and 0.50 D) that were not statistically different from those of the 2 best methods (all $P > .05$, F test). The mean ME and MAE for IOL prediction were significantly different from those of the 2 best methods (all $P < .05$, paired t test). The refractive prediction error was within ±1.00 D in 7 eyes using the (ELP + BESSt + double-K Holladay 1) method and in 8 eyes using the (ELP + Savini + double-K Holladay 1) method.

The Shammas-PL formula produced a larger variance of the mean IOL prediction error than the 2 best methods (P = .007 and P = .015, F test). Seven eyes had a refractive prediction error within ±1.00 D. The single-K Savini and single-K BESSt formulas produced an ME for IOL prediction ranging from +2.25 to +2.46 D, leaving the eyes hyperopic. Of the 11 eyes, 0, 4, 2, and 7 had a refractive prediction error within ±1.00 D using the (single-K Savini + Holladay 1), (single-K Savini +SRK/T), (single-K BESSt + Holladay 1), and (single-K BESSt + SRK/T) methods, respectively. The single-K Rosa et al. method resulted in 5 eyes with a refractive prediction error within ±1.00 D (with either Holladay 1 or SRK/T). However, it gave large variances of the mean IOL prediction error (11.53 D and 12.62 D with Holladay 1 and SRK/T, respectively), indicating inconsistency in prediction performance. In 2 eyes (cases 3 and 4) with high residual myopia after previous refractive surgery (−11.00 D and −11.75 D), it gave unacceptably large IOL prediction errors (−8.35 to −7.83 D). The single-K Ferrara et al. method gave large mean IOL prediction error and variance.

The IOL prediction result using the double-K clinical history method (DK CHM, which is history

Table 2. Demographics of each case having cataract surgery after previous keratorefractive surgery.

Case	Age (y)	AL (mm)	SE Before Refractive Surgery (D)	Refractive Surgery	SE After Refractive Surgery (D)	SimK Before Cataract surgery (D)	IOL Power Implanted (D)	A Constant	SE After Cataract Surgery
1	40	29.89	−14.875	LASIK	+0.125	37.56	21.5	118.4	−1.625
2	47	27.67	−11.625	LASIK	−1.625	40.30	22.0	118.4	−0.75
3	43	35.12	−24.00	ALK	−11.00	40.60	7.0	118.4	−1.00
4	43	35.14	−24.75	ALK	−11.75	41.04	5.0	118.9	−0.375
5	51	32.81	−15.25	ALK	−1.75	34.00	14.0	118.9	+2.50
6	55	24.77	−3.375	LASIK	+0.125	39.85	25.0	118.4	−0.50
7	53	30.56	−14.75	LASIK	−1.75	34.81	18.5	118.4	+1.00
8	53	30.71	−15.00	LASIK	−0.125	35.07	20.0	118.4	+0.25
9	50	29.33	−15.25	LASIK	−0.25	37.55	22.5	118.4	−0.625
10	64	29.74	NA	LASIK	NA	39.54	18.5	118.4	−2.00
11	64	29.81	NA	LASIK	NA	39.25	15.5	118.4	+1.125

AL = axial length; ALK = automated lamellar keratoplasty; IOL = intraocular lens; LASIK = laser in situ keratomileusis; NA = not available; SE = spherical equivalent; SimK = simulated keratometry

Table 3. Mean arithmetic and absolute IOL prediction errors using different methods not requiring data from before refractive surgery (implanted IOL power − predicted IOL power).

Method	DK ELP + Savini	DK ELP + BESSt	SK Rosa	SK Ferrara	SK Savini	SK BESSt	DK CHM*	Shammas†
Holladay 1								
ME‡								
Mean ± SD	1.19 ± 0.71	1.10 ± 0.75	−1.56 ± 3.40	−6.16 ± 6.10	2.46 ± 0.96	2.39 ± 1.02	1.15 ± 1.37	1.06 ± 1.95
Range	0.16 to 2.60	0.12 to 2.50	−8.04 to 1.97	−18.47 to −0.49	1.50 to 4.42	1.10 to 4.35	−0.77 to 4.05	−1.67 to 4.58
MAE								
Mean ± SD	1.19 ± 0.71	1.10 ± 0.75	2.36 ± 2.84	6.16 ± 6.10	2.46 ± 0.96	2.39 ± 1.02	1.32 ± 1.19	1.59 ± 1.50
Range	0.16 to 2.60	0.12 to 2.50	0.09 to 8.04	0.49 to 18.47	1.50 to 4.42	1.10 to 4.35	0.06 to 4.05	0.09 to 4.58
SRK/T								
ME‡								
Mean ± SD	0.03 ± 0.73	−0.05 ± 0.62	−1.56 ± 3.55	−5.98 ± 6.22	2.34 ± 1.04	2.25 ± 1.10	−0.10 ± 1.49	—
Range	−1.18 to 1.19	−0.87 to 1.09	−8.35 to 2.05	−18.51 to −0.30	1.17 to 4.37	0.75 to 4.30	−2.24 to 2.69	
MAE								
Mean ± SD	0.60 ± 0.36	0.49 ± 0.34	2.46 ± 2.94	5.98 ± 6.22	2.34 ± 1.04	2.25 ± 1.10	1.11 ± 0.91	—
Range	0.08 to 1.19	0.07 to 1.09	0.15 to 8.35	0.30 to 18.51	1.17 to 4.37	0.75 to 4.30	0.20 to 2.69	

DK = double-K method; DK CHM = double-K clinical history method; ELP = effective lens position estimation with our method; MAE = mean absolute error; ME = mean arithmetic error; SK = single-K method

*This method requires historical (pre–refractive surgery) data (ie, it is not a no-history method). It is presented here for comparison. In this study, the data from refractive surgery were available in 9 of 11 eyes.

†This method is independent of the Holladay 1 and SRK/T IOL power calculation formulas.

‡A positive value indicates that the method predicts an IOL of lower power than the power of the implanted IOL, which would leave the eye hyperopic. A negative value indicates that the method predicts an IOL of higher power than the power of the implanted IOL, which would leave the eye myopic.

dependent) in the 9 eyes with available history is also shown in Tables 3 and 4. The (DK CHM + SRK/T) gave slightly better results than (DK CHM + Holladay 1). Of the 9 eyes, 6 eyes and 5 eyes had a refractive prediction error within ±1.00 D using the (DK CHM + SRK/T) method and (DK CHM + Holladay 1) method, respectively.

DISCUSSION

This study describes an ELP estimation method using the Pentacam-measured H_m (corneal height) and its application in double-K IOL power calculation in post refractive–surgery eyes without available historical data. Our ELP estimation method gave good estimation for ELP to be used in Holladay 1 and SRK/T formulas when the anterior corneal radius was not known.

The improvement in IOL power prediction accuracy made by the double-K method[7,10,20,21] indicates that K_{pre} is more valuable than K_{post} for estimating the ELP. Several methods for directly measuring the K_{post} have been proposed.[11,15,16,19–21,25] However, there is still no satisfactory approach to estimate the ELP and K_{pre}. Any method that estimates K_{pre} from only K_{post}

Table 4. Eyes within a certain refractive prediction error by assuming that 1.0 D of IOL prediction error produces 0.7 D of refractive error at the spectacle plane.

	Number of Eyes							
Method	DK ELP + Savini	DK ELP + BESSt	SK Rosa	SK Ferrara	SK Savini	SK BESSt	DK CHM	Shammas
Holladay 1								
Within ±0.5 D	2	4	4	1	0	0	3	3
Within ±1.0 D	8	7	5	2	0	2	5	7
Within ±2.0 D	11	11	9	3	6	8	8	9
SRK/T								
Within ±0.5 D	8	7	4	1	0	1	5	0
Within ±1.0 D	11	11	5	2	4	7	6	0
Within ±2.0 D	11	11	9	4	7	11	9	0

DK = double-K method; DK CHM = double-K clinical history method; ELP = effective lens position estimation with our method; SK = single-K method and axial length is susceptible to unacceptable error. For example, if there is a cornea with K_{post} = 36.0 D and an axial length of 26.0 mm, it can result from ablation of 4.0 D on the cornea by LASIK of an unoperated eye with K_{pre} = 40.0 D or from ablation of 9.0 D on the cornea of an unoperated eye with K_{pre} = 45.0 D. In this example, 1 eye with K_{pre} of 40.0 D and the other eye with K_{pre} of 45.0 D have the same K_{post} (36.0 D) and axial length (26.0 mm). The actual K_{pre} (40.0 D versus 45.0 D), ELP_h (5.38 mm versus 6.24 mm, calculated by the Holladay 1 formula, assuming A = 118.4), ELP_s (5.06 mm versus 6.31 mm, calculated by the SRK/T formula, assuming A = 118.4), and IOL_p (22.68 D versus 24.30 D with Holladay 1 formula; 22.37 D versus 24.73 D with SRK/T formula; calculated by the double-K method targeting emmetropia, assuming A = 118.4) in these 2 eyes differ greatly. However, the 2 eyes have identical K_{post} and axial length values. Any mathematical function using only K_{post} and axial length as independent variables (eg, single-K method with various direct K_{post} estimation method, single-K Rosa method, single-K Ferrara method, Shammas-PL formula) will not simultaneously generate accurate estimations of the dependent variables of K_{pre}, ELP, and IOL_p in both eyes in this example.

The Savini et al. method[21] and the BESSt formula[19] calculated a K_{post} close to the history-derived K_{post}. In our study, when the K_{post} estimation method of the Savini et al. or the BESSt formula was combined with our ELP estimation method in a double-K manner, it resulted in more accurate IOL power prediction than when the Savini et al. or BESSt formula was used in a single-K manner. This suggests that our ELP estimation method augmented the IOL prediction accuracy of the K_{post} estimation method in the same manner such as the Savini et al. method or the BESSt formula that gave K_{post} estimates close to the actual K_{post}.

The Rosa et al. method[12,13] and the Ferrara et al. method[18] calculates a modified K_{post} value that is modified according to the axial length and is not approximate to the true K_{post}. These methods modify the K value to compensate for the errors induced by not knowing the ELP and inaccurate K_{post} measurement by the keratometer. Although the single-K Rosa et al. method provided good IOL prediction results in 5 of 11 eyes in our series, in 2 eyes (cases 3 and 4) with high undercorrections after the previous refractive surgery (residual refractive error −11.00 D and −11.75 D), both the Rosa et al. method and Ferrara et al. method gave unacceptably high IOL prediction errors (−7.83 to −8.35 D and −18.51 to −17.56 D, respectively). Both methods are axial-length related so if such a high undercorrection occurs after previous myopic refractive surgery, the methods will end in large myopic errors. In the Shammas-PL formula,[17] the ELP is set to a constant for all eyes for a specific IOL type. It did not produce satisfactory IOL prediction results in our study.

The contact lens over-refraction method was not used in this study because it is impossible to accurately measure the refraction when the best corrected visual acuity is worse than 20/80. In addition, it is not reliable in eyes after ablative keratorefractive surgery.[20] The Haigis et al.[26] and Hoffer Q[27] formulas were not used in this study because they do not rely on the Fyodorov et al. corneal height formula[24] to calculate the ELP. There were other no-history methods for K_{post} estimation, including the Maloney method and the Maloney method modified by Wang et al.[20] Both require data from the Humphrey Atlas, which was not available in our institutions, and they have not been validated with the Pentacam device. Therefore, these 2 methods are not presented.

The findings in this study have to be interpreted in the context of the following limitations: First, most post refractive–surgery eyes in this study had emmetropia or mild residual myopia after the refractive surgery (except cases 3 and 4, which had high residual myopia); no eye had moderate or high hyperopia. Further studies are required to evaluate whether our method can be applied to patients with various amounts of residual refractive errors after previous refractive surgery (especially residual hyperopia). Second, axial length values were obtained by ultrasound biometry in this study. Using the axial length obtained from another device (eg, partial coherence interferometry) in our formulas might not be justified. Third, a 1-piece or 3-piece acrylic foldable IOL was implanted in all the eyes having cataract surgery in this study. Further studies are needed to evaluate the accuracy of our ELP estimation method when applied to IOLs of different types. Finally, our results were based on only 11 post refractive–surgery eyes that had cataract surgery. This was partially because most of those who had refractive surgery were too young to have developed clinically significant cataract. Larger numbers of post refractive–surgery eyes that need cataract surgery are required to test the effectiveness of our method.

In summary, this study proposed a method for estimating the ELP and K_{pre} and its application in IOL power calculation in post refractive–surgery eyes without historical data. Further study using a larger series of eyes is needed to evaluate the accuracy of our ELP estimation method in IOL power calculation.

APPENDIX

Derivation of the Effective Lens Position Estimate

In the Holladay et al. 1 formula,[28] the effective lens position (ELP) is determined by

$$ELP = 0.56 + H + SF \quad (1)$$

where 0.56 is the corneal thickness; H is the corneal height and determined by the Fyodorov et al. equation[24];

$$H = R - \sqrt{R^2 - (AG_h/2)^2} \quad (2)$$

SF is the surgeon factor and is the distance from the anterior iris plane to the optical plane of the IOL and is determined by the A constant (A) of the IOL by SF = 0.5663A − 65.60; R is the anterior corneal radius; AG_h is the anterior chamber diameter from angle to angle used for the Holladay 1 formula; and AG_h = axial length (AL) × 12.5/23.45 (if AG_h > 13.5, AG_h = 13.5). The Fyodorov et al. equation regards the cornea as a section of a sphere, the base of which is the anterior iris plane.[29] In the SRK/T formula,[30] the Fyodorov et al. equation is also the most important element in determining the ELP.

$$ELP = H + ACD_{const} - 3.336 \quad (3)$$

$$H = R - \sqrt{R^2 - (Cw/2)^2} \quad (4)$$

where Cw (corneal width) = −5.41 + 0.58412 LCOR + 0.098 × 337.5/R; LCOR is the corrected AL, where if AL ≤24.4, LCOR = AL and if AL >24.4, LCOR = −3.446 + 1.716 AL − 0.0237 $(AL)^2$; and ACD_{const} = 0.62467A − 68.747.

The well-established accuracy of the Holladay 1 and SRK/T formulas in intraocular lens (IOL) power prediction and their theoretical properties indicate that Fyodorov et al.'s simulation of a "section of a sphere" works well in practice, and there must be excellent correlation among Fyodorov et al.'s estimate of corneal height ($H = R - \sqrt{R^2 - (AG/2)^2}$), the actual corneal height, and the ELP. This correlation should not be changed after surgeries such as LASIK or PRK if the value of R_{pre}, instead of R_{post}, is used for R in the Fyodorov et al.'s equation. We would use this correlation to estimate the ELP in post refractive–surgery eyes without knowledge of the R_{pre} value.

With the Fyodorov et al. equation, we calculated the theoretical corneal height (H_t) by

$$H = R_m - \sqrt{{R_m}^2 - (AG_m/2)^2} \quad (5)$$

where R_m is the autokeratometer-measured anterior corneal radius. To establish the correlation between H_t and H_m, we developed the linear regression function *f*, the value of which was H_{rt} (theoretical corneal height derived by regression) and approximated H_t,

$$H_t \cong H_{rt} = f(H_m, AG_m, AL) \quad (6)$$

A stepwise linear regression was performed using SPSS 13.0 for Windows to develop the linear regression function in equation 6. By rearranging the Fyodorov et al. equation, we obtained the theoretical anterior corneal radius by regression (R_{rt}) from H_{rt} and AG_m through the following steps:

$$H_{rt} = R_{rt} - \sqrt{{R_{rt}}^2 - (AG_m/2)^2} \quad (7)$$

then $\sqrt{{R_{rt}}^2 - (AG_m/2)^2} = R_{rt} - H_{rt}w$

By squaring both sides,

$${R_{rt}}^2 - {AG_m}^2/4 = {R_{rt}}^2 - 2R_{rt}H_{rt} + {H_{rt}}^2$$

$$2R_{rt}H_{rt} = {H_{rt}}^2 + {AG_m}^2/4$$

$$\therefore R_{rt} = \frac{4{H_{rt}}^2 + {AG_m}^2}{8H_{rt}} \quad (8)$$

In an unoperated eye with unknown R_m, however, H_m, AG_m, and AL can still be obtained. Therefore, H_{rt} can be obtained by equation 6, and the R_{rt} can be obtained by equation 8. The R_{rt} can be used as an estimate of R_m. Then, R_{rt} can be used in equations 1 and 2 for estimation of the corneal height and ELP used in the Holladay 1 formula as follows:

$$H_{rh} = R_{rt} - \sqrt{{R_{rt}}^2 - (AG_h/2)^2} \quad (9)$$

$$ELP_{rh} = 0.56 + H_{rh} + SF \quad (10)$$

where H_{rh} and ELP_{rh} are the corneal height and ELP estimates obtained by our method and used in the Holladay 1 IOL power calculation. The ELP value used for Holladay 1 formula calculation if R_m is known is designated ELP_h. The ELP_h estimation error is computed by

$$ELP_h \text{ estimation error} = ELP_{rh} - ELP_h$$

R_{rt} can be similarly used in equations 3 and 4 for estimation of the corneal height and ELP used in the SRK/T formula.

$$H_{rs} = R_{rt} - \sqrt{{R_{rt}}^2 - (Cw/2)^2} \quad (11)$$

$$ELP_{rs} = H_{rs} + ACD_{const} - 3.336 \quad (12)$$

where H_{rs} and ELP_{rs} are the corneal height and ELP estimates obtained by our method and used in the SRK/T IOL power calculation. The ELP value used for SRK/T formula calculation if R_m is known is designated ELP_s. The ELP_s estimation error is computed by

$$ELP_s \text{ estimation error} = ELP_{rs} - ELP_s$$

Application of the ELP Estimation Method in Double-K IOL Power Calculation

To apply our ELP estimation method for double-K IOL power calculation when historical data are unavailable, we assumed that R_{pre} (also K_{pre} = 337.5/R_{pre}), which is used for ELP determination in the double-K clinical history method, was unavailable. Using our method as described above, H_{rt} and R_{rt} can be obtained by equations 6 and 8, respectively. Using the R_{rt} as an estimate of R_{pre}, the corneal height and ELP estimates (H_{rh}, ELP_{rh}, H_{rs}, ELP_{rs}) to be used in the double-K Holladay 1 and double-K SRK/T calculations were obtained by equations 9 to 12.

The K_{post} to be used in the double-K method was obtained by the following previously published methods requiring no historical data.

1. The Savini et al. method[21]: K_{post} = (the simulated K value obtained by corneal topography × 376/337.5) − 4.98.

2. The BESSt formula as described by Borasio et al.[19]: K_{post} is calculated based on the Pentacam measurement and Gaussian optics formula. A correcting factor was introduced to compensate for steep and flat corneas to produce the final version of the formula.

The double-K Holladay 1 formula and double-K SRK/T formula (R_{rt} for ELP_{rh} and ELP_{rs} calculation; and K_{post} for the vergence formula) were then applied to obtain the IOL power targeting the actual refractive error after cataract surgery, and this was termed IOL_p (predicted IOL power). The power of the IOL actually implanted was designated IOL_b and used as the benchmark. The IOL prediction error was computed by

$$\text{IOL prediction error} = IOL_b - IOL_p$$

A positive value indicates that the method predicts an IOL of lower power than the power of the implanted IOL; this would leave the eye hyperopic.

Other no-history IOL power prediction methods were also applied for comparison. The above-mentioned algorithm can also be applied to calculate the IOL prediction error of these IOL power prediction methods. These no-history IOL power prediction methods include the following:

1. The Shammas-PL formula[17]: $K_{post} = 1.14 \times K - 6.8$, where K is the keratometric reading after refractive surgery, and then Shammas-PL formula is applied.
2. The Rosa et al. method[12,13]: The post refractive–surgery keratometer-measured anterior corneal radius is multiplied by a correcting factor (R factor = 0.0276AL + 0.3635). The single-K Holladay 1 and SRK/T formulas were then applied.
3. The theoretical variable refractive index (TRI) method by Ferrara et al.[18]: $TRI = -0.0006(AL)^2 + 0.0213AL + 1.1572$. The corrected corneal power $= (TRI - 1) \times 1000/$(anterior corneal curvature in mm). The single-K Holladay 1 and SRK/T formulas were then applied.
4. The single-K Holladay 1 or SRK/T method with the K_{post} estimation methods described above.

Criteria for Evaluating Intraocular Lens Prediction Results

The IOL prediction results were evaluated by the following criteria[20]:

1. Mean arithmetic IOL prediction error (ME for IOL prediction).
2. Mean absolute IOL prediction error (MAE for IOL prediction).
3. Variance of the ME for IOL prediction (smaller variance indicates better consistency of the prediction performance).
4. The number of the eyes within a certain range of refractive prediction error (±0.50 D, ±1.00 D, and ±2.00 D). Assuming that 1.00 D of the IOL prediction error results in 0.70 D of refractive error at the spectacle plane,[9,20] the number of eyes with a refractive prediction error within ±0.50 D (an IOL prediction error within ±0.71 D), within ±1.00 D (an IOL prediction error within ±1.43 D), and within ±2.00 D (an IOL prediction error within ±2.86 D) were computed for each method.

The mean IOL prediction errors were compared using the paired *t* test. The variances of the ME for IOL prediction were tested using the *F* test for variance. A *P* value less than 0.05 was considered statistically significant.

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