Comparison of intraocular lens power calculation methods after myopic laser refractive surgery without previous refractive surgery data

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PURPOSE: To compare the accuracy of intraocular lens (IOL) power calculation methods for post-myopic excimer laser surgery patients without previous refractive surgery data using the Holladay IOL Consultant Program and the American Society of Cataract and Refractive Surgery (ASCRS) IOL Power Calculator.

SETTING: Wang Vision Cataract and LASIK Center, Nashville, Tennessee, USA.

DESIGN: Case series.

METHODS: Eight methods were used to calculate IOL power: Holladay 2 partial coherence interferometry (PCI)-K, Holladay 2 FlatK, Wang-Koch-Maloney, Shammas No-History, Haigis-L, ASCRS-Average, ASCRS-Min, and ASCRS-Max. The optimum IOL power corresponding to the target refraction was back-calculated using the stable post-cataract surgery refraction and implanted IOL power. Using the optimum IOL power, the predicted IOL power error and the resultant refractive error with each method were calculated and compared.

RESULTS: The Holladay 2 FlatK method was most accurate for IOL power calculation, followed by the Holladay 2 PCI-K, ASCRS-Min, Wang-Koch-Maloney, ASCRS-Average, Shammas No-History, Haigis-L, and ASCRS-Max. Statistically significant differences were observed between Holladay 2 FlatK and Holladay 2 PCI-K ($P<.05$), Wang-Koch-Maloney and ASCRS-Average ($P<.05$), and Haigis-L and ASCRS-Max ($P<.01$). No statistically significant differences were observed between the Holladay 2 PCI-K, ASCRS-Min, and Wang-Koch-Maloney or between the ASCRS-Average, Shammas No-History, and Haigis-L (both $P>.05$).

CONCLUSIONS: The Holladay 2 FlatK method provided the most accurate IOL power in eyes without previous myopic laser surgery data. If the Holladay IOL Consultant Program is unavailable, the ASCRS methods can be used; the ASCRS-Min represents the most accurate method.

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Today, millions of post-refractive surgery patients have reached an age at which they develop senile cataract.[1] Cataract surgery is more challenging in patients who have had refractive surgery than in those who have not had refractive surgery because post-refractive surgery patients have higher visual expectations after cataract surgery and intraocular lens (IOL) power calculation is more difficult and less accurate.[2,3]

There are 3 main sources of prediction error in IOL calculation after refractive surgery; that is, the corneal radius measurement error, the keratometer index error, and the IOL power calculation method error.[4] Over the past decade, more than 20 methods[3,5–16] have been devised to improve the accuracy of IOL power calculation in eyes with previous refractive surgery. These methods can be divided into 2 groups: (1) those that require the previous refractive surgery information and (2) those that use current biometry only.[17] Historically, the clinical history method[6] had been considered the gold standard of determining corneal power after laser refractive surgery. However, the clinical history method requires pre-refractive keratometry (K) readings and pre-refractive and final

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stable post-refractive manifest refraction, which are often not available or are of questionable accuracy due to the use of older imaging technologies at the time of the refractive surgery. In addition, the outcomes of the clinical history method differ greatly depending on which vergence method is used, whether refractions are vertex corrected, and whether the Aramberri double-K adjustment is applied.[2,8,9,11,12,18] Furthermore, potential nuclear sclerosis and/or progressive axial myopia at the time of refractive surgery can result in a biased calculation.[12,19] Because of these unavoidable limitations of the clinical history method and methods that require clinical history data,[7,10,11] several newer methods that require only current measurements have been developed in recent years. These include the Shammas No-History, Haigis-L, and Wang-Koch-Maloney methods, and they have been shown to have better accuracy overall than traditional clinical history methods.[9,14,16,20,21]

At present, surgeons can perform IOL power calculations for post-refractive surgery patients without previous refractive data using several software programs. The 2 most popular are the Holladay IOL Consultant Program[A] and the American Society of Cataract and Refractive Surgery (ASCRS) IOL Power Calculator.[B] However, despite the availability of the above-mentioned methods and software programs, clinicians are sometimes still at a loss when trying to decide which method would generate the most accurate IOL power.

The purpose of this study was to compare the accuracy of the methods provided by the above 2 popular IOL calculation software packages, to gain insight on the strength and weakness of each method, and to provide useful guidelines for selecting the best method for IOL calculations in eyes without previous refractive surgery data. We confined our current study to eyes with previous myopic corneal refractive surgery.

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PATIENTS AND METHODS

This retrospective study included eyes that had myopic laser in situ keratomileusis (LASIK) or photorefractive keratectomy (PRK) 8 to 14 years ago and subsequently had cataract surgery from January 2011 to March 2012 at the Wang Vision Cataract and LASIK Center, Nashville, Tennessee. The exclusion criteria included eyes with corrected distance visual acuity (CDVA) worse than 20/100 before cataract surgery; CDVA worse than 20/32 after cataract surgery; and a history of intraocular disease, other ocular surgeries, ocular trauma, or intraoperative complications during refractive or cataract surgery. In addition, patients with systemic disease known to affect vision were excluded.

All cataract surgeries were performed by the same surgeon (M.W.) using the same technique of temporal clear corneal incision and phacoemulsification. The preoperative examinations related to IOL power calculation included manifest refraction, keratometry (K) readings measured with the partial coherence interferometry (PCI) (IOLMaster, version 5.4.3.0002, Carl Zeiss Meditec AG), rotating Scheimpflug imaging (Pentacam, version 1.15, Oculus, Inc.), corneal topography (Atlas, version 3.0.0.39, Carl Zeiss Meditec AG), lens thickness (Lenstar, LS900, Haag-Streit International), axial length (AL), anterior chamber depth (ACD), and white-to-white (WTW) distance (corneal horizontal diameter); the last 3 parameters were measured with the PCI device. The preoperative target refraction was determined by the surgeon's experience and the patient's visual needs. Preoperative parameters were entered into the Holladay IOL Consultant Program[A] and the ASCRS IOL Power Calculator[B] to calculate IOL power. All previous clinical history data, such as preoperative corneal power and pre-refractive and post-refractive surgery refractions (before the onset of cataract), were unavailable. The surgeon selected the IOL power to be implanted based on his judgment in terms of the target refraction and the IOL powers predicted by these methods.

Methods Used for Intraocular Lens Power Calculation

Holladay IOL Consultant Program (version 2011.0410) The Holladay 2 formula (unpublished) is displayed on the Holladay IOL Consultant Program software.[A] It was developed based on the Holladay 1 formula and is a fourth-generation formula. The Holladay IOL Consultant Program requires 7 variables (WTW, K readings, ACD, lens thickness, patient's age, preoperative refraction, and AL) and the target refraction to calculate IOL power. For post-refractive surgery eyes without previous data, there is an option to enter an adjusted K value, which can be determined by the rigid trial contact lens method, current measurements, or the surgeon-entered K value.

The following 2 Holladay IOL Consultant Program methods were analyzed in this study.

1. *Holladay 2 PCI-K.* This method uses the Holladay 2 formula. The current average K measured by the IOLMaster device is input to calculate the IOL power.
2. *Holladay 2 FlatK.* This method uses the Holladay 2 formula. The lowest average K value selected from 3 keratotomy measuring devices (IOLMaster, Pentacam, Atlas) is input as the surgeon-entered K value to calculate IOL power. In this study, the lowest average K value from the IOLMaster average K readings, Pentacam equivalent

K readings, and Atlas 0.0 to 3.0 mm ring average K readings were used.

American Society of Cataract and Refractive Surgery Intraocular Lens Power Calculator (version 4.1)

Following are the ASCRS IOL power calculator methods that use current pre-cataract surgery data:

1. *Wang-Koch-Maloney*. This method was developed based on the modified Maloney formula using converted anterior central corneal power from corneal topography.[9] To cover more points over the central ablated area, the mean annular corneal power, determined by Atlas 0.0 to 3.0 mm measurements, is used as follows:

$$\text{Adjusted corneal power} = 1.114 \times (\text{Atlas 0 to 3}) - 5.59$$

2. *Shammas No-History with Regression Analysis*.[20] This method calculates the post-LASIK or PRK corneal power by adjusting the measured post-LASIK or PRK K values. In the IOL calculator,[9] the Atlas 0.0 to 3.0 mm ring average K value is used as the post-LASIK or PRK K-value as follows:

$$\text{Adjusted corneal power} = 1.14 \times \text{post} - \text{LASIK/PRK K} - 6.8$$

3. *Haigis-L*.[14] This algorithm modifies the measured corneal radius (R_{meas}) of curvature by the IOLMaster based on regression analysis and then determines the corrected corneal radius of curvature (R_{corr}) and calculates IOL power using the regular Haigis formula as follows[22]:

$$\text{Rcorr} = 331.5/(-5.1625 \times \text{Rmeas} + 82.2603 - 0.35)$$

4. *American Society of Cataract and Refractive Surgery-Average*. This method uses the mean IOL power of predicted IOL power with all ASCRS IOL power calculator methods available (except ASCRS-Maximum [Max] and ASCRS-Minimum [Min]).
5. *American Society of Cataract and Refractive Surgery-Minimum*. This method chooses the lowest IOL power among the predicted IOL power with all ASCRS IOL power calculator methods available (except ASCRS-Average and ASCRS-Max).
6. *American Society of Cataract and Refractive Surgery-Maximum*. This method chooses the highest IOL power among the predicted IOL power with all ASCRS IOL power calculator methods available (except ASCRS-Average and ASCRS-Min).

Computing Methods for Intraocular Lens Power Prediction Error and Refractive Prediction Error

Using the IOL power calculation software, with an optimized lens constant taken from the User Group for Laser Interference Biometry web site[C] (optimized constants for the Zeiss IOLMaster) and the target refraction after cataract surgery, the predicted IOL power for each method was calculated. The surgeon selected the IOL power to be implanted depending on his judgment and the patient's need. The stable manifest refraction at the spectacle plane after cataract surgery was obtained 3 to 6 months postoperatively. The IOL power prediction error was computed as the difference between the predicted IOL power using a particular method and the back-calculated ideal IOL power based on the target refraction, with positive values indicating an overpredicted IOL power and hence a myopic refractive outcome. For back-calculation, as in the method described by Feiz et al.[7] and later adopted by other authors,[16] the assumption was that 1.00 diopter (D) of IOL prediction error produces 0.70 D of refractive error at the spectacle plane.

Statistical Analysis

All statistical tests were performed using Graphpad Prism software (version 5.0, Graphpad Prism Software, Inc.). All the data transformations (square root) of absolute IOL power prediction error and absolute refractive prediction error were performed for passing the Shapiro-Wilk normality test (alpha = 0.05). Then a paired t test and 1-way analysis of variance were used to analyze the differences between methods in IOL power prediction error and refractive prediction error. A paired t test also was used to analyze the difference in K readings measured with 3 instruments. The percentages of eyes within certain refractive prediction errors were compared using the chi-square test and Fisher exact test. A P value less than 0.05 was considered statistically significant.

RESULTS

Patients Demographics

Sixty-two eyes of 33 patients were retrospectively analyzed. Table 1 shows the patients' demographics. Seventeen eyes had PRK, and 45 eyes had LASIK. The mean interval between refractive surgery and cataract surgery was 9.3 ± 2.6 years. Five IOL types were implanted as follows: 55 eyes Crystalens AO (Bausch & Lomb), 2 eyes Tecnis ZMB00 (Advanced Medical Optics, Inc.), 2 eyes Acrysof SN60WF (Alcon Laboratories, Inc.), 2 eyes EC3-PAL (Aaren Scientific, Inc.), and 1 eye Tecnis Z9003 (Advanced Medical Optics, Inc.).

Table 1. Patient demographics.

Parameter	Mean ± SD	Range
Age (y)	61.27 ± 6.79	43, 76
Pre-cataract MRSE (D)	−0.65 ± 1.48	−5.50, 1.25
Axial length (mm)	25.98 ± 1.55	23.29, 30.47
ACD (mm)	3.46 ± 0.31	2.92, 4.25
White-to-white (mm)	12.26 ± 0.49	11.40, 12.83
Lens thickness (mm)	4.53 ± 0.44	4.13, 4.97
IOL power implanted (D)	19.81 ± 1.96	16.50, 25.00

ACD = anterior chamber depth; IOL = intraocular lens; MRSE = manifest refraction spherical equivalent; White-to-white = corneal horizontal diameter

Table 2. Target refraction before cataract surgery versus MRSE after cataract surgery.

	Arithmetic (D)		Absolute (D)	
Parameter	Mean ± SD	Range	Mean ± S D	Range
Preop refraction target	−0.24 ± 0.47	−1.50, 0.75	0.40 ± 0.35	0.00, 1.50
Postop MRSE	−0.39 ± 0.72	−1.75, 1.75	0.65 ± 0.49	0.00, 1.75
Postop MRSE off target	−0.15 ± 0.65	−1.25, 1.50	0.53 ± 0.41	0.00, 1.50

MRSE = manifest refraction spherical equivalent

Table 3. Keratometry measurement by 3 instruments in 62 eyes.

Instrument	Mean K (D) ± SD	Frequency as Lowest K, n (%)
Rotating Scheimpflug imaging	40.08 ± 2.58	33 (53.23)
Partial coherence interferometer	40.20 ± 2.44	17 (27.42)
Corneal topographer (0.0–3.0 mm	40.53 ± 2.40	12 (19.35)

K = keratometry

Pre-Cataract Surgery Target Refraction Versus Post-Cataract Surgery Actual Refraction

Table 2 shows pre-cataract surgery target refraction and post-cataract manifest refraction spherical equivalent (MRSE). The mean postoperative period was 4.5 months (range 3 to 6 months).

Preoperative Keratometry Determination Methods

Table 3 shows the difference in K readings measured with 3 instruments. There were statistically significant differences between the K readings of the rotating Scheimpflug device and the corneal topographer ($t = 3.308$, $P < .01$) and between the PCI device and the corneal topographer ($t = 2.873$, $P < .01$). No statistically significant difference was seen between the rotating Scheimpflug device and the PCI device ($t = 1.964$, $P = .0541$). Of the 3 devices, the K reading provided by the rotating Scheimpflug device was most frequently chosen as the lowest K. The differences in the frequency of being chosen as the lowest K reading between the rotating Scheimpflug device and the PCI device and between the rotating Scheimpflug device and the corneal topographer was statistically significant ($P < .01$, Fisher exact test). There was no statistically significant difference between the PCI device and the corneal topographer ($P > .05$, Fisher exact test).

Table 4. Frequency of the 3 independent methods (using no previous refractive surgery data) displayed on ASCRS IOL Power Calculator chosen as the ASCRS-Min or ASCRS-Max.

	Frequency, n (%)	
Method	ASCRS-Min	ASCRS-Max
Wang-Koch-Maloney	34 (54.84)	5 (8.06)
Shammas No-History	21 (33.87)	8 (12.90)
Haigis-L	7 (11.29)	49 (79.03)

ASCRS = American Society of Cataract and Refractive Surgery

Frequency of the Result of Each ASCRS Intraocular Lens Power Calculator Methods Being Chosen as the ASCRS-Min or ASCRS-Max

Table 4 shows how often each of the 3 independent ASCRS IOL Power Calculator methods (using no previous refractive surgery data) produced the lowest IOL power (ASCRS-Min) or the highest IOL power (ASCRS-Max). Of the 3 independent methods, the Haigis-L produced the highest IOL power most frequently (79.03% of the time) and the Wang-Koch-Maloney produced the lowest IOL power most frequently (54.84% of the time).

Intraocular Lens Power Prediction Error

Table 5 shows the mean absolute IOL power prediction errors calculated using all 8 methods. The Holladay 2 FlatK produced the lowest mean absolute error (MAE) in IOL power prediction. There was

Table 5. Mean absolute errors in IOL power prediction and refractive prediction in 62 eyes.*

	Mean Absolute Error (D) ± SD	
Method	In IOL Power Prediction	In Refractive Prediction
Holladay 2 FlatK	0.83 ± 0.35	0.70 ± 0.29
Holladay 2 PCI-K	0.92 ± 0.34	0.77 ± 0.29
ASCRS-Min	0.93 ± 0.45	0.78 ± 0.37
Wang-Koch-Maloney	0.94 ± 0.48	0.79 ± 0.40
ASCRS-Average	1.00 ± 0.42	0.84 ± 0.35
Shammas No-History	1.01 ± 0.40	0.85 ± 0.33
Haigis-L	1.10 ± 0.44	0.92 ± 0.37
ASCRS-Max	1.15 ± 0.41	0.96 ± 0.34

ASCRS = American Society of Cataract and Refractive Surgery; IOL = intraocular lens; PCI-K = keratometry measured with partial coherence interferometry

*Primary data transformation (square root) was done for passing Shapiro-Wilk normality test

Table 6. Arithmetic errors in IOL power prediction and refractive prediction in 62 eyes.

	Arithmetic Error (D)			
	In IOL Power Prediction		In Refractive Prediction	
Method	Range	Median	Range	Median
Holladay 2 FlatK	−3.37, 2.42	−0.29	−1.69, 2.36	0.20
Holladay 2 PCI-K	−3.37, 1.51	−0.71	−1.06, 2.36	0.50
ASCRS-Min	−5.27, 2.69	0.45	−1.88, 3.69	−0.31
Wang-Koch-Maloney	−5.27, 2.73	0.51	−1.91, 3.69	−0.36
ASCRS-Average	−3.64, 2.97	0.74	−2.08, 2.55	−0.52
Shammas No-History	−4.81, 2.69	0.74	−1.88, 3.37	−0.52
Haigis-L	−1.31, 3.60	1.25	−2.52, 0.92	−0.87
ASCRS-Max	−1.31, 3.60	1.26	−2.25, 0.92	−0.88

ASCRS = American Society of Cataract and Refractive Surgery; IOL = intraocular lens; PCI-K = keratometry measured with partial coherence interferometry

Table 7. Percentage of eyes within certain refractive prediction error.*

	Percentage		
Method	Within ±0.5 D	Within ±1.0 D	Within ±2.0 D
Holladay 2 FlatK	58	90	98
Holladay 2 PCI-K	44	84	98
ASCRS-Min	53	74	−94
Wang-Koch-Maloney	50	68	90
ASCRS-Average	45	66	97
Shammas No-History	45	71	94
Haigis-L	40	68	90
ASCRS-Max	27	56	89

ASCRS = American Society of Cataract and Refractive Surgery; PCI-K = keratometry measured with partial coherence interferometry
*Precondition: assuming that 1.0 D of IOL prediction error produces 0.7 D of refractive error at the spectacle plane[14]

a statistically significant difference in the MAE results between the Holladay 2 FlatK method and the Holladay 2 PCI-K method (t = 2.283, $P<.05$). The Holladay 2 PCI-K, ASCRS-Min, and Wang-Koch-Maloney methods gave the second lowest MAEs with no statistically significant differences between them (F = 0.035, $P>.05$). This was followed by the ASCRS-Average, Shammas No-History, and Haigis-L methods (F = 1.132, $P>.05$); there was a statistically significant difference in the MAE results between the Wang-Koch-Maloney method and the ASCRS-Average method (t = 1.941, $P<.05$). The ASCRS-Max gave the highest MAE of all 8 methods. The difference in the MAE result between the Haigis-L method and the ASCRS-Max method was statistically significantly different (t = 3.481, $P<.01$).

The median arithmetic errors in IOL power prediction (Table 6) had negative values with both Holladay IOL Consultant Program methods, indicating that these 2 methods underestimate IOL power. In contrast, the median arithmetic errors were positive using the remaining 6 ASCRS IOL power calculator methods, indicating that these 6 ASCRS IOL power calculator methods tend to overestimate the IOL power.

Refractive Prediction Error

Table 5 shows the mean absolute refractive prediction errors using the 8 methods. Assuming a fixed relationship between the IOL power error and the refractive error (Absolute refractive prediction error = Absolute IOL power prediction error × 0.7), the results of the mean absolute refractive prediction error mirrored those of the mean absolute IOL power prediction error.

The median arithmetic error in refractive prediction (Table 6) has positive values using the 2 Holladay IOL consultant program methods, indicating a slight postoperative hyperopic shift. In contrast, the median arithmetic errors in refractive prediction had negative values with all 6 ASCRS IOL power calculator methods, indicating a slight postoperative myopic shift.

Percentage of Eyes Within a Certain Refractive Prediction Error

Table 7 shows that the Holladay 2 FlatK, Holladay 2 PCI-K, and ASCRS-Min methods produced the highest percentages (74% to 90%) of eyes within ±1.00 D of the refractive prediction error followed by the other 5 methods (56% to 68%) (χ^2 = 24.54, $P<.01$). The ASCRS-Max method produced the least reliable result, having the lowest percentage of eyes within ±0.50 D, while the other 7 methods had relatively higher percentages (40% to 58%) of eyes within ±0.50 D (χ^2 = 14.89, $P<.05$). All 8 methods had higher percentages of eyes (89% to 98%) within ±2.00 D (χ^2 =10.70, $P>.05$).

DISCUSSION

To our knowledge, this is the first comprehensive study comparing the accuracy of the methods of IOL power calculation offered by the 2 most popular software packages for post-myopic refractive eyes without previous refractive surgery data.

The first software, the Holladay IOL Consultant Program,[A] provides a platform for the Holladay 2 formula and all third-generation theoretical formulas (SRK/T, Hoffer-Q, Holladay 1). The Holladay 2 formula, available since 1998, is considered by some to be one of the most accurate theoretical formulas for average eyes as well as for unusual eyes, such as those with excessively shorter or longer ALs, or with extreme flat or steep corneas.[23-25] In addition, previous refractive surgery data are not essential for the Holladay 2 formula to calculate IOL powers for post-laser refractive surgery patients. Differing from the third-generation theoretical 2-variable formulas, which underestimate the effective lens position (ELP) in post-refractive surgery eyes by using the currently measured corneal power, the Holladay 2 formula uses the following 7 variables to predict the ELP: K reading, AL, WTW, ACD, lens thickness, age, and refraction. Furthermore, for post-refractive surgery eyes without previous data, the prediction of the Holladay 2 can be optimized by entering an adjusted K value, which can be chosen from the rigid trial contact lens method, current measurements, or a surgeon-entered K value.

The second software, the ASCRS IOL Power Calculator,[B] was developed by Warren E. Hill, MD, Li Wang, MD, PhD, and Douglas D. Koch, MD, and first reported by Wang et al.[16] in 2010. With regard to post-myopic excimer surgery eyes, the ASCRS IOL Power Calculator provides surgeons with different IOL power selections using 5 to 8 methods that require all or partial previous clinical data and 3 to 4 additional methods that require only current data.

In this study, the IOL calculation accuracy of 8 methods (Holladay 2 PCI-K, Holladay 2 FlatK, Wang-Koch-Maloney, Shammas No-History, Haigis-L, ASCRS-Average, ASCRS-Min, and ASCRS-Max) were analyzed and compared. Our results show that of these 8 methods, the Holladay 2 FlatK provided the most accurate prediction for IOL power calculation with the smallest mean absolute IOL prediction error (0.83 ± 0.35 D), the smallest refractive prediction error (0.70 ± 0.29 D), the smallest variances, and the greatest percentage of eyes within ±0.50 D (58%) and ±1.00 D (90%) of the refractive prediction error. In 2009, 2 benchmark standards were proposed by the British National Health Service (NHS) for virgin cornea cataract surgeries; that is, 55% of the eyes should be within 0.50 D of the target spherical equivalent and 85% within 1.00 D.[26] Although in this study we analyzed post-refractive surgery eyes (rather than virgin eyes) whose IOL power calculations are inherently less accurate, our results using the Holladay 2 FlatK method exceeded both NHS benchmarks.

In comparison with published literature, our MAE results in IOL power prediction and the percentage of eyes within ±0.50 D and ±1.00 D of the refractive prediction error using the 3 independent ASCRS IOL power calculator methods (Wang-Koch-Maloney, Shammas No-History, and Haigis-L) seem to be a bit worse than in the studies by Wang et al.[16] and Haigis.[14] Factors that account for these differences may include: (1) the smaller sample size in our study (62 eyes/33 patients) compared with Wang et al.[16] (72 eyes/57 patients) and Haigis[14] (187 eyes); (2) the IOL constants we used were not personalized but were taken directly from the optimized constants for the IOLMaster device; (3) the mean age of our patients was 61.27 ± 6.79 years, older than that in Wang et al.[16] (58 ± 8 years) or in Haigis[14] (58.1 ± 8.5 years), which may have affected the accuracy of the postoperative MRSE readings in our study because older patients tend to have more significant ocular surface issues and less reliable refraction.

Another difference between our study and Wang et al.'s study[16] is that in the latter, the ASCRS-Min method and ASCRS-Max method were not evaluated, presumably because these methods are not independent. In our study, we decided to include these 2 related methods for analysis because we presumed that even though they are not independent methods, they produced useful clinical references in predicting IOL power. In fact, our study found that of the 6 methods displayed on the ASCRS IOL Power Calculator software, the ASCRS-Min gave the best outcome, yielding the lowest MAE and the highest percentage of eyes within ±0.50 D and ±1.00 D of the refractive prediction error. We also found that the ASCRS-Max method gave the worst outcome with the highest MAE. With regard to refractive prediction error, our data show negative median arithmetic values in refractive prediction errors with all 6 ASCRS IOL Power Calculator methods, indicating a myopic prediction trend. *Hence, of the* 6 ASCRS IOL Power Calculator methods, choosing the IOL power predicted by the ASCRS-Min method may be the ideal choice because it will lower the amount of myopic shift from the target refraction.

In evaluating the 2 most accurate methods found in this study (ie, Holladay 2 FlatK and Holladay 2 PCI-K), the Holladay 2 FlatK achieved better accuracy in IOL power prediction than the Holladay 2 PCI-K, and the difference between them was statistically significant (t = 2.283, $P<.05$). The only variable between the Holladay 2 FlatK and Holladay 2 PCI-K is the actual K value used. While the Holladay 2 FlatK uses the lowest average K value chosen from IOLMaster average K, the Pentacam equivalent K readings, and the Atlas (0.0 to 3.0 mm ring) average K, the Holladay 2 PCI-K uses the IOLMaster average K directly. The results in the present study show that the Pentacam equivalent K readings provided lower average K values (t = 3.308, $P<.01$) than the Atlas average K (0.0 to 3.0 mm). Similar findings were also reported by Borasio et al.[13] and Doménech et al.[27] In our study, although the mean K values were not significantly different between the Pentacam equivalent K readings and the IOLMaster average K (t = 1.964, P = .0541), the

Pentacam equivalent K readings were chosen as the flat K more frequently (33 times [53.23%]) than the IOLMaster average K (17 times [27.42%]) and the difference in these frequencies was statistically significant ($P < .01$, Fisher exact test). This result is similar to that obtained by Elbaz et al.[28] in a study of the mean interdevice differences in K values for the rotating Pentacam device versus the IOLMaster device.

It is generally recognized that the keratometry measurement error is a main source of prediction error in IOL calculation after refractive surgery. We believe that the Pentacam device offers relatively the most accurate K values in eyes with previous laser refractive surgery because it directly measures the curvatures of both the anterior and posterior corneal surfaces and provides topographies with wider diameters. The Pentacam equivalent K readings value was computed by taking into account the refractive effect, anterior/posterior radius of curvatures, and refractive indices of the cornea. On the other hand, the Atlas and IOLMaster systems only measure the anterior corneal K readings using topographic or keratometric principles with the curvature of the posterior cornea assumed to mirror that of the anterior cornea. With post-refractive corneas, this mirroring relationship between the anterior corneal surface and posterior corneal surface is no longer present. Hence, in post-refractive surgery eyes, it is essential to independently and directly measure both the anterior corneal surface and particularly the posterior corneal surface to accurately determine the total corneal power. In fact, in 1 of Holladay et al.'s prior studies,[15] they also recommend using equivalent K readings from the Pentacam device when accurate historical refractive data are not available. Another advantage of the Pentacam device is that it is able to provide wider diameter topography due to its temporally located camera, which prevents a shadow from the nose. We believe that this may give more accurate results than the Atlas corneal topographer, in which the nasal shadows are often present.

With regard to the arithmetic errors in refractive prediction with the 8 methods, the Holladay 2 FlatK (median +0.20 D) and Holladay 2 PCI-K (median +0.50 D) methods show positive values, indicating that the Holladay 2 formula is most likely to result in a slightly hyperopic shift in eyes without previous myopic laser surgery data. Hence, choosing the lowest average K value for the Holladay 2 formula, namely using Holladay 2 FlatK, may be the best strategy because it will lower the amount of hyperopic shift from the target refraction.

Similar to our findings that the flattest (lowest) K may be the best K to use, Latkany et al.[10] also found that the accuracy of IOL power prediction was improved using the flat K value. They compared the accuracy of IOL power prediction using the flat K (the flattest K value measured manually or by topography), the K value derived from the clinical-history methods, and the average K (average K value measured manually), and found that IOL power prediction with the flat K (-1.72 ± 2.19 D) was better than that with the K value derived from the clinical history methods (-1.76 ± 1.76 D) or average K (-2.32 ± 2.36 D). Note that our study using the Holladay 2 FlatK appeared to yield more accurate IOL power prediction than the Latkany et al.'s study.[10] We believe that this could be due to the formula error in the third-generation SRK/T formula that they used as well as the keratometry measurement error from the manual keratometer used in their study.

The present study focused on no-history methods because previous refractive surgery data are often unavailable. Even if they are available, they are based on measurements taken using older instruments many years ago. In fact, McCarthy et al.,[29] showed that the accuracy of IOL power prediction using the Holladay 2 formula (with the clinical history method adjusted K) was worse than the accuracy using the Shammas no-history method and the Haigis-L method, both of which do not use previous history data. In 2010, Wang et el.[16] showed that ASCRS IOL Power Calculator methods using surgically induced refraction (Masket formula, adjusted Atlas corneal topography 0.0 to 3.0 mm, adjusted effective refractive power, and modified Masket) and methods using no previous data (Wang-Koch-Maloney, Shammas, and Haigis-L) gave better results than methods using whole clinical history data (clinical history, Feiz-Mannis, Corneal Bypass). Their results reconfirmed that the newer no-history methods were more accurate than methods using whole clinical history data.

Our study provides the first comprehensive evaluation of the accuracy of all methods of IOL power prediction offered by the Holladay IOL Consultant Program and the ASCRS IOL Power Calculator software packages for patients without previous refractive surgery data. It also compared rotating Pentacam K readings with those of the Atlas corneal topographer and the IOLMaster in eyes with previous myopic laser refractive surgery and assessed the frequency at which each of them was chosen as the lowest K. Because we did not develop any of these methods and also have no financial relationship with any company manufacturing the instruments used, we have no inherent bias toward any of the methods or instruments used.

Limitations of this study include the limited sample size and that eyes with a history of hyperopic LASIK, PRK, or radial keratotomy were not studied.

In conclusion, when previous refractive surgery data are unavailable, the IOL power prediction with the Holladay 2 FlatK method seems to be the most accurate of the methods offered by the Holladay IOL Consultant Program and ASCRS IOL Power Calculator platforms. With regard to the measurement of keratometry, the Pentacam equivalent K readings appear to offer the lowest values in eyes with previous myopic laser surgery and may possibly be the most accurate of the 3 popular keratometry measuring devices. If the Holladay IOL Consultant Program is unavailable, the ASCRS-Min method appears to provide the next best choice for IOL power prediction. A larger prospective study is needed to verify our results.

WHAT WAS KNOWN

- Intraocular lens calculations after laser refractive surgery are less predictable than that with virgin corneas.
- There are unavoidable limitations to IOL power prediction methods that use whole clinical history data.
- Several methods that require only current measured values have been developed to determine the IOL power for patients without previous refractive surgery data.
- No comprehensive comparison has been performed of the accuracy of those methods displayed on the Holladay IOL Consultant Program and ASCRS IOL Power Calculator software packages for patients without previous refractive surgery data.

WHAT THIS PAPER ADDS

- The Holladay 2 FlatK method provided the most accurate IOL power prediction for the post-myopic laser correction patients without previous refractive data.
- The Pentacam equivalent K readings provided the lowest K value and is used most frequently in the Holladay 2 FlatK method for IOL calculations in eyes with previous myopic laser refractive surgery.
- Coupled with the result of IOL calculation formula comparison, the Pentacam device produced the most accurate K readings of the 3 popular keratotomy-measuring devices.
- If the Holladay IOL Consultant Program is unavailable, among the ASCRS IOL power calculator methods, the ASCRS-Min method appears to provide the next best choice for IOL power prediction in eyes without previous myopic laser surgery data.

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Theoretical analysis of wavefront aberration caused by treatment decentration and transition zone after custom myopic laser refractive surgery

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PURPOSE: To analyze the induced wavefront aberrations caused by treatment decentration and transition zone after custom myopic laser refractive surgery.

SETTING: Refractive Surgery Center, Tianjin Eye Hospital & Eye Institute, Tianjin Medical University, Tianjin, China.

DESIGN: Cohort study.

METHODS: Wavefront aberration data from potential refractive surgery candidates were used. Based on the preoperative wavefront aberrations, the custom ablation profile was computed. Then, the influence of treatment decentration and especially that of the transition zone on induced wavefront aberrations was studied. The impact of angle mismatch on induced aberrations was analyzed.

RESULTS: Data from 117 eyes (77 patients) were analyzed. The transition zone played a significant role in the influence of decentration on the induced aberrations in refractive surgery. Induced coma and spherical aberration increased rapidly as the lateral translation increased, and coma was significantly larger than other Zernike aberration terms. The induced aberrations from decentration with oblique incidence in the laser ablation profile were less than in the actual laser ablation process for slight subclinical decentration. The induced aberrations were not closely related to the subclinical unmatched angle from eye cyclotorsion. The induced aberrations from lateral translation were correlated with the position vector. The transition zone was designed to smooth the transition from the optical zone to the untreated cornea, and it mainly dominated induced coma and spherical aberration.

CONCLUSION: To achieve the best postoperative visual performance, the effect of the transition zone in refractive surgery should be taken into account, especially for scotopic pupils.

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To deliver a custom correction, it is important to understand the types and magnitudes of wavefront aberrations induced by treatment decentration. Custom corneal ablations to correct refractive errors can be based on whole-eye wavefront aberrations and corneal topography. Topography-guided ablations aim to treat irregularities in corneal elevation in addition to the refractive errors of defocus and astigmatism.[1] Alternatively, wavefront-guided ablations aim to address the wavefront aberrations in the entire eye in addition to the refractive errors.[2] Based on the clinical refraction and whole-eye wavefront aberrations, the ablation profile of a wavefront-guided treatment in an ablation zone can be obtained.[3]

Pupil-center shift and eye cyclotorsion are inevitable in corneal refractive surgery. Patients are supine in refractive surgery, yet they are seated at the preoperative examination. A low to moderate amount of eye cyclotorsion has been found in the transition from the seated to supine position.[4] In addition, treatment decentration in refractive surgery has been observed in several studies, and the results indicate that centration errors have an important influence on induced aberrations. Wang and Koch[5] found that the mean pupil centroid shift was 0.29 mm during wavefront-guided corneal ablation and that the centration error induced 4.9 times, 2.8 times, and 8.7 times higher values of total aberration, lower-order aberrations

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