Intraocular Lens Power Calculation after Myopic Refractive Surgery

Theoretical Comparison of Different Methods

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Objective: To evaluate the reliability of different methods developed to calculate intraocular lens (IOL) power after corneal refractive surgery.

Design: Retrospective observational case series.

Participants: Preoperative and postoperative data of all eyes that underwent myopic excimer laser surgery in a private practice (Centro Salus, Bologna, Italy) between 1999 and 2004 were reviewed.

Intervention: The following methods were analyzed: videokeratography, clinical history, Shammas' refraction-derived and clinically derived methods, Rosa's correcting factor, Ferrara's variable refractive index, separate consideration of anterior and posterior corneal curvature (with and without preoperative data), Feiz–Mannis' formula and nomogram, and Latkany's regression formulas (based on both average and flattest postrefractive surgery keratometry). The Holladay 1 formula was used for eyes with an axial length between 22 and 24.49 mm and the SRK-T for eyes longer than 24.49 mm. Double-K formulas were also evaluated, when applicable. Each IOL power determined with these methods was compared to a benchmark value, calculated using the preoperative axial length and corneal power and aiming for the preoperative spherical equivalent.

Main Outcome Measure: Mean error in IOL power prediction.

Results: Ninety-eight eyes of 98 patients were analyzed. The double-K clinical history method, Feiz–Mannis' formula, double-K method based on separate consideration of anterior and posterior corneal curvature (with and without preoperative data), and both Latkany's regression formulas were the only methods resulting in a mean IOL power not statistically different ($P>0.05$) from the benchmark used for comparative purposes.

Conclusions: When prerefractive surgery data are available, IOL power should be calculated using the double-K clinical history method. Alternative choices may be represented by the Feiz–Mannis' formula, Latkany's regression formulas based on average and flattest postrefractive surgery keratometry, and the double-K method based on separate consideration of anterior and posterior corneal curvatures. A variant of the latter can be used to calculate IOL power when prerefractive surgery data are not available. Further prospective studies based on patients undergoing phacoemulsification after refractive surgery are needed to validate the results of this theoretical comparison. *Ophthalmology 2006;113:1271–1282 © 2006 by the American Academy of Ophthalmology.*

Intraocular lens (IOL) power calculation after corneal refractive surgery is one of the most challenging aspects in cataract surgery today. When performed on eyes that have undergone either myopic photorefractive keratectomy (PRK) or laser in situ keratomileusis (LASIK), keratometry and computerized videokeratography (VKG) fail to provide a correct measurement of the dioptric corneal power and tend to underestimate corneal flattening by overestimating the K-reading. This leads to a falsely low IOL power, which causes an undesirable hyperopic refraction in previously myopic patients.[1–3] Several methods have been developed to provide accurate measurements of corneal power so that surgeons may reasonably predict postoperative refraction. Some of these methods have already been clinically tested in small case series including a limited number of patients who developed cataract after LASIK or PRK.[2,4–9] Such cases are relatively rare; most patients who have undergone excimer laser surgery over the past 15 years are still young, and it will take some time before clinical studies can be performed on larger samples. In the meanwhile, the data from the large numbers of patients who have undergone corneal refractive surgery can be used to assess which is the best method, from a theoretical point of view, to achieve emmetropia in the event of cataract surgery and IOL implantation.

This study aims to compare some of the most promising methods developed for this purpose, namely, the clinical history method,[10] Shammas' refraction-derived and clinically derived keratometric values,[11] the correcting factor by Rosa,[12] the variable refractive index by Ferrara,[13] both the

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formula and the nomogram by Feiz–Mannis,[14] the separate consideration of anterior and posterior corneal curvatures method as reviewed by Speicher,[15] and the regression formulas (based on both average and flattest keratometry after refractive surgery) developed by Latkany.[9]

Materials and Methods

Data Source

With institutional review board approval of Centro Salus, Bologna, Italy, we retrospectively analyzed the preoperative and postoperative data of all patients who underwent either myopic PRK or LASIK by 1 of the 3 authors in a private eye clinic (Centro Salus, Bologna, Italy) between 1999 and 2004. Patients were asked to discontinue wearing contact lenses for at least 1 month before the last refractive evaluation, which was carried out the week before surgery. In all cases, surgery was performed using the Nidek EC-5000 (Nidek Co. Ltd, Gamagori, Japan) excimer laser; for LASIK, a Bausch & Lomb Hansatome microkeratome (Claremont, CA) was used to create the flap. All patients underwent a thorough preoperative ophthalmic examination, including cycloplegic refraction, VKG by means of the TMS-2 Topography System (Tomey, Erlangen, Germany) and axial length measurement (performed by ultrasonic contact biometry with standardized A-scan echography [Ultrascan, Alcon, Fort Worth, TX]). Patients were enrolled in this study only if they had best spectacle-corrected visual acuity of 20/25 or better (both preoperatively and postoperatively) and postoperative VKG performed at least 1 month after PRK and 2 weeks after LASIK. To exclude cases with refractive errors caused by irregular and delayed wound healing, regression, and unexpected overcorrection or undercorrection, we investigated only the eyes with a postoperative manifest refraction within ±0.25 diopters (D) of emmetropia (the analysis of eyes with higher postoperative spherical equivalent is the topic of another ongoing study).

Methods for Calculating the Correct Corneal Power

Corneal refractive power after LASIK/PRK was calculated using the following methods in all patients.

1. VKG-derived simulated keratometry reading (Sim-K): Sim-K was assessed by means of the TMS-2 topography system using the power of Placido mires 7, 8, and 9 of the videokeratoscope for 128 equally spaced meridians.[16]
2. Clinical history method: Postoperative corneal power was obtained by subtracting the refractive change (calculated at the corneal plane) induced by surgery from the preoperative K readings.[10,17] The refractive change was determined once refraction had stabilized after corneal surgery.
3. Refraction-derived corrected keratometric value (Kc.rd): According to this method, which Shammas derived from the clinical history method, the corneal power is the result of the formula Kc.rd = $K_{post}(-0.23\times CRc)$, where K_{post} is the actual keratometry reading and CRc is the amount of myopia corrected at the corneal plane.[11]
4. Clinically derived corrected keratometric value (Kc.cd): This method (also developed by Shammas from the historical method) calculates the corneal power by means of the following equation: Kc.cd = 1.14 $K_{post}-6.8$, where K_{post} is the actual keratometry reading.[11]
5. Correcting factor method by Rosa et al[12]: The postoperative radius, as measured by VKG, is multiplied by a correcting factor that varies between 1.01 and 1.22 according to the axial length of the eye. The dioptric corneal power is then obtained by the formula (1.3375−1)/corrected radius.
6. Theoretical variable refractive index (TRI): As recently proposed by Ferrara et al,[13] the change in the corneal refractive index after excimer laser surgery is correlated to the axial length; such a correlation is expressed by the formula TRI = $-0.0006\times(AL\times AL)+0.0213\times AL+1.1572$, where AL is axial length. Corneal power (P) can be calculated using the formula $P = (TRI-1)/r$, where r is the corneal curvature in meters.[13]
7. Separate consideration of anterior and posterior corneal curvature: This method is based on the assumption that the total refractive power of the cornea (P) can be calculated by adding the power of the anterior (P_a) and posterior (P_p) corneal surfaces, as shown in the formula $P = P_a + P_p = (n_2 - n_1)/r_1 + (n_3 - n_2)/r_2$, where n_1 is the refractive index of the air (= 1), n_2 is the refractive index of the cornea (= 1.376), and n_3 is the refractive index of the aqueous humor (= 1.336).[15] Both preoperatively and postoperatively, the power of the anterior corneal surface (P_a) can be obtained by multiplying the VKG corneal power by 1.114 (corresponding to 376/337.5), as proposed by Mandell and later adopted in practice by Maloney.[4,18] Hence, P_a = Sim-K × 1.114. Knowing the power of the anterior corneal surface allows us to calculate, prior to surgery, the power of the posterior corneal surface (P_p) as the difference between the total and the anterior surface corneal powers, as shown in the formula P_p. = P_a − P = (Sim-K × 1.114) − Sim-K. Applying this method to our sample, we determined the posterior corneal surface power to be −4.98±0.17 D (range, −4.54 to −5.58 D). To measure the total corneal power after excimer laser surgery we have 2 options: (a) if the preoperative VKG is available, and thus the posterior corneal surface can be calculated, the postoperative power of the anterior corneal surface may be added to the power of the posterior corneal surface (which is assumed not to be significantly altered by surgery), as expressed by the formula P = postop $P_a + P_p$ = postop Sim-K × 1.114 + (preop Sim-K × 1.114 − preop Sim-K); (2) if the preoperative VKG is not available, thus precluding calculation of the posterior corneal surface power, the latter is substituted by a mean value such as −4.98 D. The resulting formula is P = postop $P_a + P_p$ = postop Sim-K × 1.114 − 4.98.

Calculated K-readings were entered in the single and double-K Holladay 1 and SRK-T formulas to determine the IOL power for emmetropia (A-constant 118.4).[19,20] The former were chosen for average length eyes (22–24.49 mm), the latter for longer eyes (>24.49 mm).[21] Finally, IOL power was also calculated by means of both the Feiz–Mannis formula and nomogram,[14] and by means of the regression formulas described by Latkany et al,[9] based on both the average and flattest postrefractive surgery keratometry readings (in this case we did not use Javal readings, as in the original work, but VKG values, because the former were not always available).

Choice of the Benchmark for Comparison

All these data required a benchmark for comparison. Back-calculated IOL values (such as those generated by the Holladay IOL consultant program) would be the most logical benchmark to employ. They have been used for this purpose in some clinical studies,[6] but cannot be adopted in theoretical comparisons like our own, where no patients have actually been implanted with an IOL. In the past, such theoretical studies have used the clinical history

Table 1. Corneal Power as Measured Using the Different Methods Analyzed

VKG	Clinical History	Shammas Rd-K	Shammas Cd-K	Rosa	Ferrara	A+PCC^{wpd}	A+PCC^{npd}
39.21 ± 2.10	38.95 ± 2.27	37.99 ± 2.47	37.80 ± 2.45	36.86 ± 2.77	35.97 ± 3.14	38.60 ± 2.40	38.60 ± 2.30

A+PCC^{npd} = separate consideration of anterior + posterior corneal curvatures (no preoperative data); A+PCC^{wpd} = separate consideration of anterior + posterior corneal curvatures (with preoperative data); Cd-K = clinically derived keratometry; Rd-K = refraction-derived keratometry; VKG = videokeratography.
All data are presented as mean values±SD.

method as the benchmark for comparison[11,22,23] because this was previously reported to provide the highest accuracy. Recent evidence, however, suggests that even the clinical history method can lead to erroneous IOL power calculation.[4–7] It has been suggested that the best benchmark might be the IOL power as determined by standard calculation techniques with K-readings and axial length measurements performed before excimer laser surgery.[11] We made such calculations and set the amount of preoperative myopia (at the spectacle plane with 12 mm vertex distance) as the target for refraction. We considered the IOL power obtained by this method to be equivalent to the power of the natural crystalline lens, sharing the assumption made by Rosa et al[12] in developing their formula (e.g., patient with preoperative spherical equivalent = −5.50 D, axial length = 26.83 mm, target refraction = −5.50D; according to SRK-T the IOL power is 20.32 D; this is the IOL power that would maintain the patient's natural refraction and should thus have the same value as his or her crystalline lens; the same IOL power is expected not to change the refraction in a patient that achieved emmetropia following excimer laser surgery and must later undergo phacoemulsification and IOL implantation).

Primary Outcome Measure. The difference between the IOL power calculated using each of these methods and the benchmark value was defined as the mean error and was considered the main outcome. The value derived was negative if the IOL power was lower than the natural crystalline lens power and positive if it was higher.

To validate this approach, we calculated the power of the natural crystalline lens in the 9 cases reported by Aramberri[19] and compared these values to the IOL power that, according to his study, would have resulted in emmetropia. As expected, we did not find any significant difference between the 2 measurements (20.41±3.58 D vs. 20.43±3.55 D; P = 0.96, Mann–Whitney test for nonparametric data).

Secondary Outcome Measure. Linear regression analysis was performed to assess to what extent the attempted correction by PRK or LASIK may have influenced the error in IOL power prediction by the most accurate methods.

Statistical Analysis

Unless otherwise indicated, all data are expressed as the mean ± standard deviation. Repeated measures of analysis of variance were performed to compare mean values such as corneal power or IOL power generated by the different methods. Because some groups did not show a Gaussian distribution, the Friedman test with Dunn's multiple comparisons posttest was adopted (this is a nonparametric test that compares ≥3 paired groups).

Linear regression was used to assess the correlation between the amount of refractive change (taken as the independent variable) and the error in IOL prediction generated by each method (taken as the dependent variable).

$P<0.05$ was considered statistically significant. All statistical tests were performed using GraphPad InStat version 3a for Macintosh (GraphPad Software, San Diego, CA). For patients who had bilateral surgery, only the first operated eye was considered for statistical analysis.

Results

Ninety-eight eyes of 98 patients who had undergone either PRK or LASIK to correct myopia met the inclusion criteria and were enrolled in the present study. Patients' mean age was 33.7±8.6 years; before corneal surgery, the spherical equivalent ranged between –1.13 and –11.38 D (mean, −5.18±2.21 D), Sim-K between 39.86 and 48.93 D (mean, 43.77±1.53 D), and axial length between 22.15 and 28.44 mm (mean, 25.4±1.14 D). Fifty-four of the patients (55.1%) had received PRK and 44 (44.8%) LASIK. Postoperative assessment was performed 116±74.3 days after PRK and 122±96.4 days after LASIK.

Table 1 reports the postoperative corneal power as calculated using the different methods. VKG provided the highest mean corneal power (39.21±2.10 D), whereas Ferrara's variable refractive index method resulted in the lowest (35.97±3.14 D). The comparison among the corneal powers determined by each method disclosed a statistically significant difference ($P<0.0001$). Both methods of separate consideration of anterior and posterior corneal curvatures (with and without preoperative data) calculated the mean corneal powers closest to that provided by the clinical history method, which is usually considered the standard approach under these circumstances. Dunn's posttest further confirmed that these methods were the only ones that did not generate significantly different corneal powers compared to the clinical history method.

The mean power of the natural crystalline lens, calculated on the basis of the prerefractive surgery data and aiming at the original spherical equivalent, was 21.7±1.59 D. Because VKG was the method that gave the highest corneal power, it also calculated the lowest IOL power, as shown in Table 2. Again, a statistically significant difference among all the different methods was observed ($P<0.0001$), with double-K formulas always providing a higher mean IOL power than their single-K counterpart.

Methods Requiring Prerefractive Data

Among all methods, the double-K clinical history gave the theoretically most accurate IOL power, as evidenced by the lowest mean arithmetical (−0.06±0.18 D) and absolute error (0.13±0.14 D) in relation to the natural crystalline lens power. Differences from the IOL power for theoretical emmetropia ranged between –0.66 and 0.91 D and 96.9% of eyes would have received an IOL with a power within ±0.5 D of the power of the natural crystalline lens. The Feiz–Mannis formula achieved the second-best result with a mean arithmetical error of −0.25±0.31 D, a mean absolute error of 0.27±0.29 D, 86.7% of eyes with a computed IOL power within ±0.5 D of the theoretically emmetropic IOL power and 13.2% of eyes potentially becoming hyperopic owing to IOL power underestimation. Fair results were achieved with the double-K

Table 2. Intraocular Lens Power as Measured

	VKG		Clinical History		Shammas Rd-K		Shammas Cd-K		Rosa	
	SK	*DK*	*SK*	*DK*	*SK*	*DK*	*SK*	*DK*	*SK*	*DK*
IOL power (D) (mean ± SD)	19.69±1.72	21.21±1.74	19.98±1.52	21.6±1.59	20.86±1.67	22.76±1.91	21.09±1.65	23.05±1.75	22.13±1.33	24.43±1.51
ME* (mean ± SD)	−1.97±1.14	−0.45±0.77	−1.68±0.78	−0.06±0.18	−0.8±0.79	1.10±0.74	−0.57±1.03	1.39±0.76	0.46±1.02	2.76±1.03
Error range	− 4.98 0.36	−3.41 1.29	−3.72 −0.29	−0.66 0.91	−3.23 0.89	−1.18 3.10	−3.61 1.42	−1.62 3.07	−2.63 3.20	0.24 5.63
MAE (mean ± SD)	1.98±1.13	0.68±0.58	1.68±0.78	0.13±0.14	0.88±0.71	1.13±0.69	0.87±0.79	1.43±0.70	0.91±0.65	2.76±1.03
% within ±0.5 D	6.1	46.0	4	96.9	36.7	20.4	38.7	7.1	28.5	1
% with IOL underestimation > 0.5 D	93.9	44.9	95.9	1	60.2	1	46.9	1	16.3	0
% with IOL overestimation > 0.5 D	0	9.1	0	2	3	78.6	7.1	91.9	55.1	99

Cd-K = clinically derived keratometry; D = diopters; DK = double-K formula; MAE = mean absolute error (in relation to the benchmark value; formula; VKG = videokeratography.
*Negative values indicate an IOL power lower than the natural crystalline lens power; positive values indicate an IOL power higher than the natural

method of separately considering the anterior and posterior corneal curvatures (with preoperative data), which produced a low mean error in IOL power calculation but a higher standard deviation (0.37±0.78 D) and absolute error (0.68±0.54), and Latkany's regression formulas based on average and flattest postrefractive surgery keratometry, which provided a relatively low mean absolute error (respectively 0.04±0.61 D and −0.21±0.57 D) but a higher absolute error (respectively 0.47±0.38 D and 0.48±0.37 D). The Feiz–Mannis nomogram produced less accurate results, calculating an IOL power within ±0.5D of the natural crystalline lens in 45.9% of cases. This method may carry a higher risk of myopia, because it overestimated IOL power (mean error 0.64±0.68 D) in most cases. The refraction-derived method by Shammas showed the lowest accuracy among the methods requiring preoperative data; it achieved a slightly higher percentage of eyes within ±0.5 D of the emmetropic IOL power when the single-K formula was adopted; using the double-K formula with this method would theoretically cancel the risk of postoperative hyperopia, although a considerable number of excessively myopic eyes should be expected (in 78.6% of cases the IOL power would be overestimated by an amount >0.5 D compared to the benchmark).

Methods That Do Not Require Prerefractive Data

Among the formulas proposed to calculate the IOL power when prerefractive surgery data are not available, the separate consideration of anterior and posterior corneal curvature with the double-K formula and fixed value of −4.98 D for the posterior corneal curvature provided the most accurate result. It showed a mean error of 0.28±0.76 D in IOL power calculation and a mean absolute error of 0.64±0.49 D and the computed IOL power was within ±0.5 D of the theoretically emmetropic IOL power in 48.9% of eyes. Shammas' single-K clinically derived method produced less accurate results, calculating an IOL power within ±0.5D of the natural crystalline lens in 40.8% of eyes. This method may carry a higher risk of postoperative hyperopia, because it underestimated the IOL power in the majority of eyes (mean error −0.57±1.03 D).

A lower percentage of eyes within ±0.5 D of the emmetropic IOL was achieved by other methods, such as those devised by Rosa and Ferrara; these yielded a lower mean arithmetical error when the single-K formula was adopted (0.46±1.02 D and 1.29±1.06 D, respectively) and predicted an excessively high IOL power when the double-K formula was used (mean arithmetical error: 2.76±1.03 D and 3.87±1.28 D, respectively). With single-K formula, the rate of eyes with a computed IOL power within ±0.5 D of the theoretically emmetropic IOL power was 28.5% and 14.2%, respectively, for Rosa's and Ferrara's methods.

Given the considerably high mean error in IOL power prediction generated by some methods, we repeated the Friedman test with Dunn's multiple comparisons posttest after excluding the methods producing the highest mean absolute error: single-K VKG, single-K clinical history, Rosa's double-K correcting factor, Ferrara's double-K variable refractive index, and both single-K methods of separate consideration of anterior and posterior corneal curvatures. The analysis of the methods theoretically providing the most accurate predictions revealed that only the following did not significantly differ from the benchmark for comparison:

- Double-K clinical history
- Separate consideration of anterior and posterior corneal curvatures with preoperative data and double-K formula
- Separate consideration of anterior and posterior corneal curvatures without preoperative data and with double-K formula
- Feiz–Mannis' formula
- Both Latkany's regression formulas

Therefore, these 6 methods can be considered the most reliable.

To study the possible influence of the preoperative spherical equivalent on the performance of each method, we performed a linear regression analysis to assess to what degree the error in IOL power prediction generated by the most accurate methods was related to the amount of refractive correction obtained by PRK or LASIK. The results are listed in Table 3. Most methods revealed a positive correlation, meaning a tendency to underestimate IOL power in eyes with higher preoperative myopia (Figs 1–4). Conversely, a negative correlation, meaning a likely overestimation of IOL power in eyes with higher preoperative myopia, Using the Different Methods

Ferrara		Anterior + Posterior Corneal Curvatures (with Preoperative Data)		Anterior + Posterior Corneal Curvatures (No Preoperative Data)		Feiz–Mannis Formula	Feiz–Mannis nomogram	Latkany (Average Keratometry)	Latkany (Flattest Keratometry)
SK	*DK*	*SK*	*DK*	*SK*	*DK*				
22.95±1.10	25.53±1.43	20.24±1.70	21.94±1.83	20.24±1.66	21.94±1.74	21.42±1.58	22.30±1.86	21.70±1.72	21.45±1.69
1.29±1.06	3.87±1.28	−1.42±1.01	0.37±0.78	−1.42±1.04	0.28±0.76	−0.25±0.31	0.64±0.68	0.04±61	−0.21±0.57
−1.48	0.16	−4.35	−2.17	−4.45	−2.76	−1.31	−0.98	−2.05	−2.38
4.77	7.51	0.67	2.34	0.60	2.34	0.25	2.65	1.52	1.16
1.42±0.87	3.87±1.28	1.45±0.96	0.68±0.54	1.45±0.99	0.64±0.49	0.27±0.29	0.73±0.58	0.47±0.38	0.48±0.37
14.2	1	15.3	50	11.2	50	86.7	45.9	64.2	62.2
4.1	0	84.7	13.2	87.8	14.2	13.2	2	13.2	22.4
79.6	99	52	78.6	1	35.7	0	52	22.6	13.4

ME = mean arithmetic error (in relation to the benchmark value); Rd-K = refraction-derived keratometry; SD = standard deviation; SK = single-K

crystalline lens power.

was observed with the double-K refraction-derived method by Shammas and the Feiz–Mannis nomogram (Fig 5). The double-K clinical history, both double-K methods of separate consideration of anterior and posterior corneal curvatures, and both Latkany's regression formulas were the only ones that seemed neither to overestimate or underestimate IOL power in relation to preoperative refraction.

Discussion

Keratometry and VKG are inaccurate in eyes that have undergone PRK or LASIK because the standardized value for the corneal index of refraction (1.3375) used in both devices to convert the anterior radius of curvature to an estimate of the refractive power of the entire cornea is no longer valid.[1] Therefore, predicting the correct IOL power in these eyes is problematic. An increasing number of methods have been proposed to achieve emmetropia. Ophthalmologists facing this challenge still do not know which is the best formula; few studies have reported the results of IOL implantation in such eyes and in all cases only a small number of patients were analyzed.[2,4–9] Moreover, some of the formulas proposed have yet to be tested and compared. Our study aimed to determine, from a theoretical point of view, the most reliable method for predicting postoperative refraction among 11 possible alternatives: (1) Sim-K generated by standard VKG; (2) the clinical history method; (3) Shammas' refraction-derived method; (4) Shammas' clinically derived method; (5) Rosa's correcting factor; (6) Ferrara's variable refractive index; (7) the Feiz–Mannis formula; (8) the Feiz–Mannis nomogram; (9) the separate consideration of anterior and posterior corneal curvatures method; (10) Latkany's regression formula based on the average postrefractive surgery keratometry reading; and (11) Latkany's regression formula based on the flattest postrefractive surgery keratometry reading.[9–15] The contact lens overrefraction method, despite being well-documented in the literature, was not considered in this study because of its intrinsic limitations (possible influence of nuclear scle-

Table 3. Correlation Factors Obtained by Means of a Linear Regression Analysis Performed to Assess the Relationship Between Refractive Change Induced by Excimer Laser and the Error in Intraocular Lens Prediction

	Correlation Coefficient (*r*)	Statistical Significance (*P*)
Methods requiring prerefractive surgery data		
Double-K VKG	0.4598	<0.0001
Double-K clinical history	0.09869	NS
Single-K refraction-derived method	0.6328	<0.0001
Double-K refraction-derived method	−0.3665	0.0002
Feiz-Mannis formula	0.5710	<0.0001
Double-K method based on separate consideration of anterior and posterior corneal curvatures (with preoperative data)	−0.1674	NS
Latkany's regression formula (average keratometry)	0.1127	NS
Latkany's regression formula (flattest keratometry)	−0.0071	NS
Feiz-Mannis nomogram	−0.4326	<0.0001
Methods not requiring prerefractive surgery data		
Single-K clinically derived method	0.7338	<0.0001
Rosa's single-K method	0.4494	<0.0001
Ferrara's single-K method	0.2809	0.0051
Double-K method based on separate consideration of anterior and posterior corneal curvatures (no preoperative data)	0.1550	NS

NS = not significant; VKG = videokeratography.

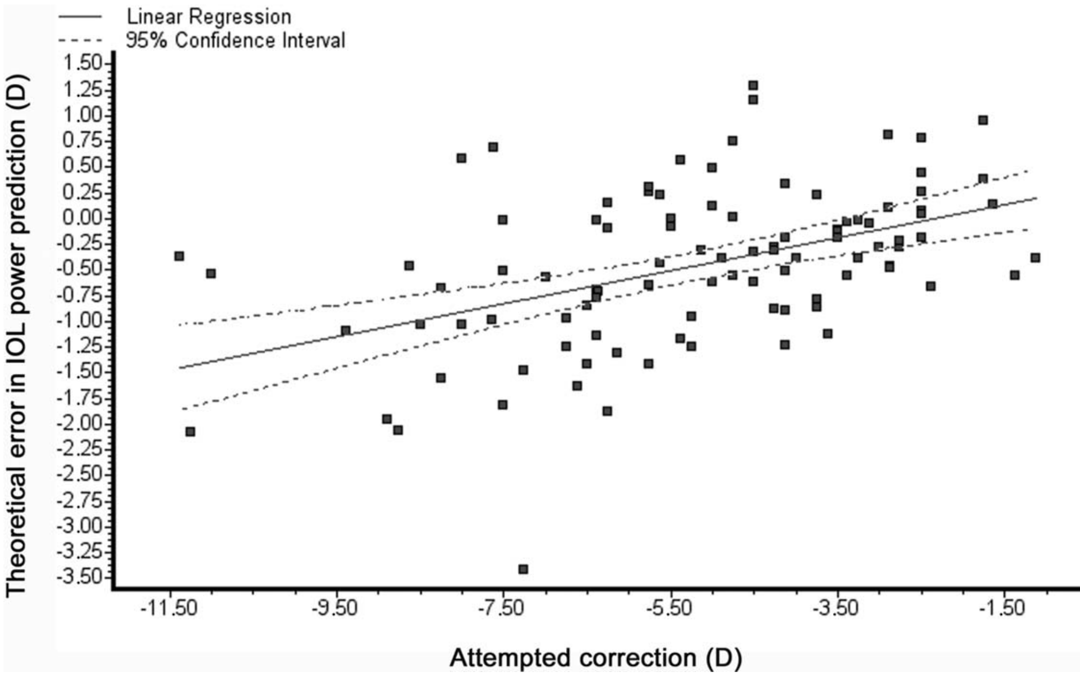

Figure 1. Linear regression shows a significant correlation ($r = 0.4598$) between the mean error in intraocular lens (IOL) power prediction based on double-K VKG and the preoperative spherical equivalent. D = diopters.

rosis on refraction and the impossibility of accurately measuring refraction when visual acuity is below 20/80) and the retrospective nature of this report, which ruled out the possibility of reexamining and testing all of the patients. Additional pitfalls of the contact lens overrefraction method that further support our decision to exclude it from the present analysis have been described by Haigis.[24]

Some advantages and disadvantages of the methods theoretically having the best predictive power are summarized in Table 4.

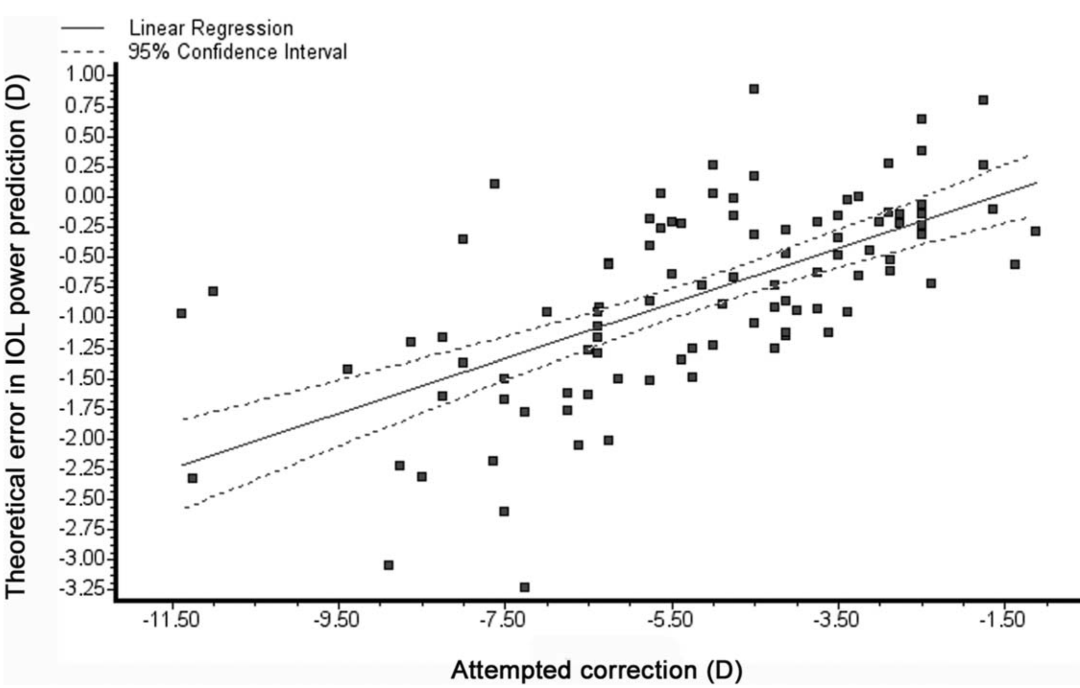

Figure 2. Linear regression shows a significant correlation ($r = 0.6328$) between the mean error in intraocular lens (IOL) power prediction by means of Shammas' single-K refraction-derived method and the preoperative spherical equivalent. D = diopters.

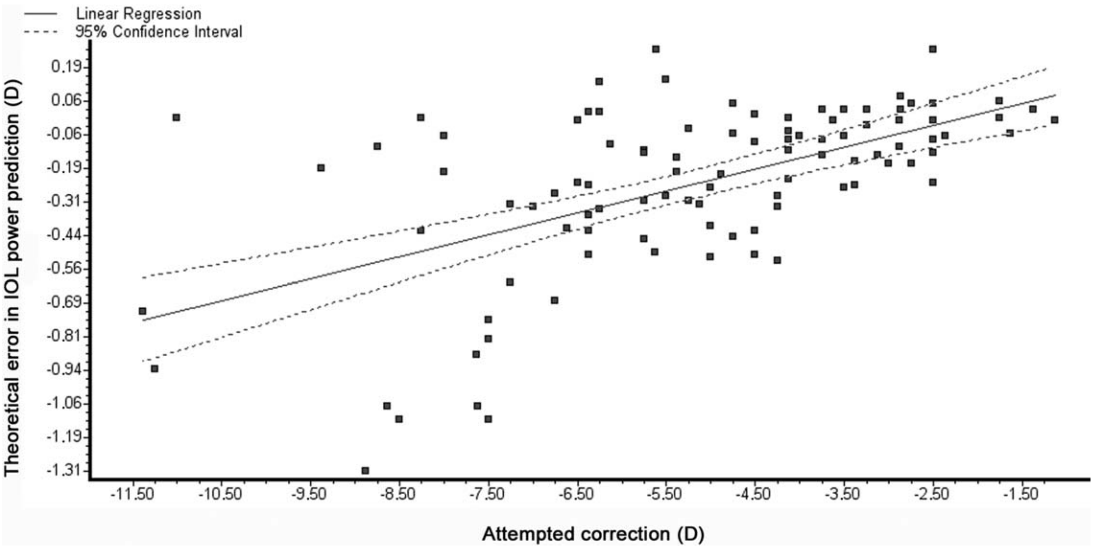

Figure 3. Linear regression shows a significant correlation ($r = 0.5710$) between the mean error in intraocular lens (IOL) power prediction by means of the Feiz–Mannis formula and the preoperative spherical equivalent. D = diopters.

Methods Requiring Prerefractive Data

Our data, based on an analysis of 98 eyes, suggest that the double-K clinical history method provides the highest accuracy in predicting postoperative emmetropia, as is demonstrated by the fact that 96.9% of the eyes would receive an IOL whose power is within ±0.5 D of the IOL power for theoretical emmetropia. This result confirms the well-known notion according to which clinical history can be considered a highly reliable method to assess corneal power after corneal refractive surgery.[1,2,9,22] The remarkable performance of the double-K clinical history method is consistent with the results reported by Aramberri[19] when he first described this method and further validates his findings. Moreover, the double-K method enhances the precision of the clinical history method calculated at the corneal plane, which is optically correct,[25] so that the correction at the spectacle plane (traditionally adopted to prevent hyperopic results)[9] is no longer necessary. Another theoretical advantage of the clinical history method is the lack of correlation with the amount of refractive change induced by LASIK or

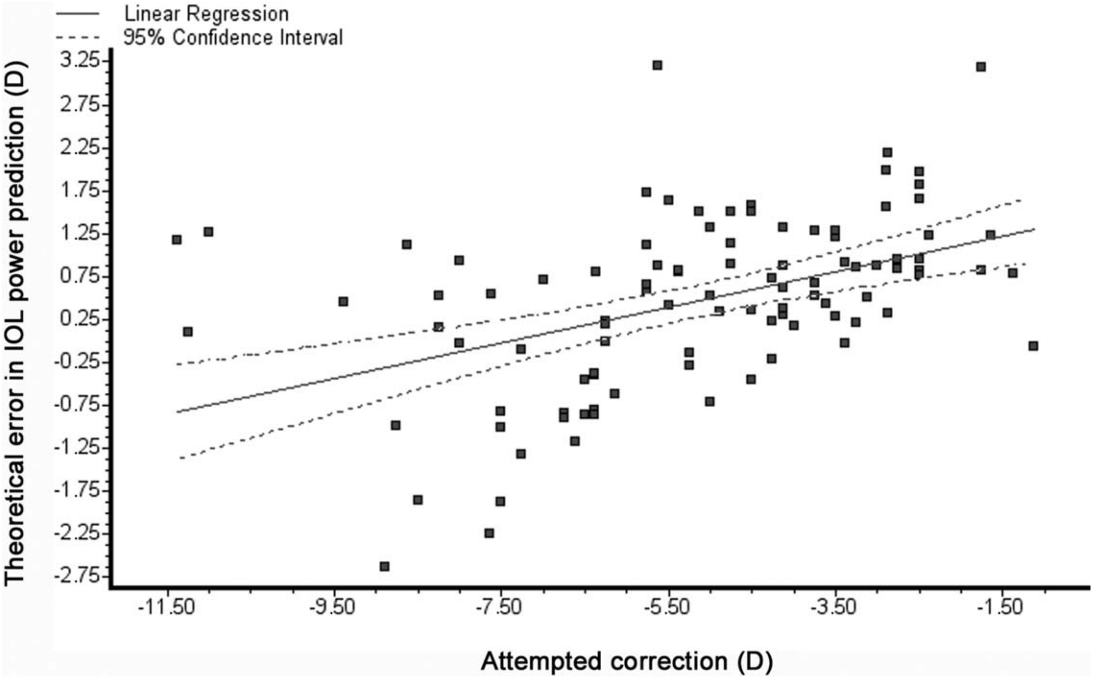

Figure 4. Linear regression shows a significant correlation ($r = 0.4494$) between the mean error in intraocular lens (IOL) power prediction by means of Rosa's correcting factor and the preoperative spherical equivalent. D = diopters.

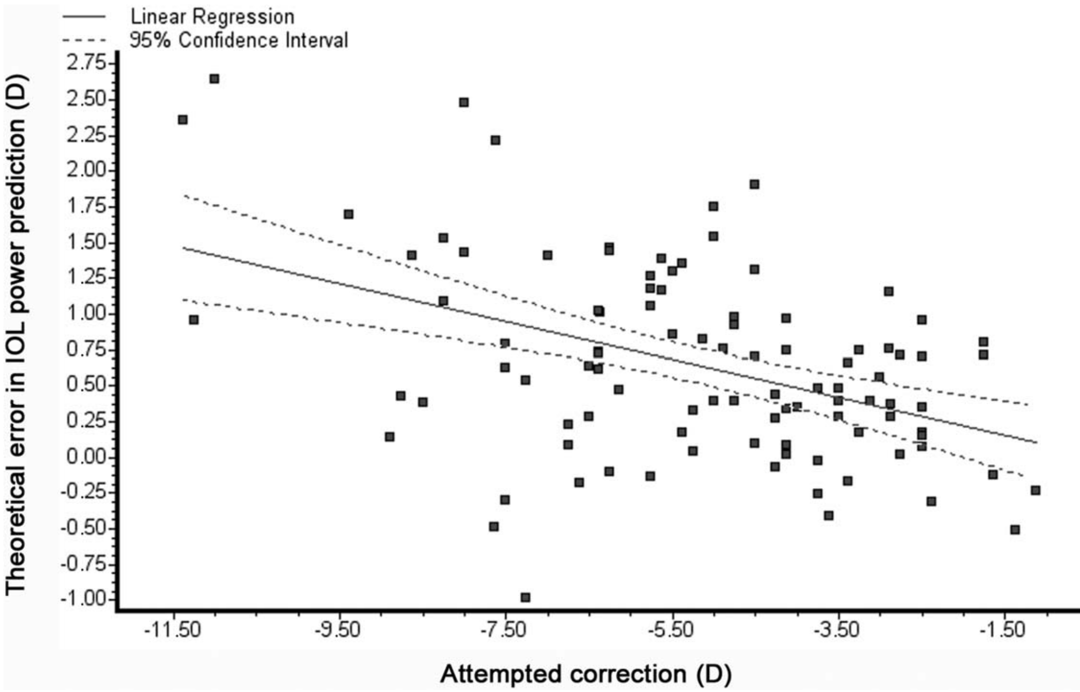

Figure 5. Linear regression shows a negative correlation ($r = -0.4326$) between the mean error in intraocular lens (IOL) power prediction by means of the Feiz–Mannis nomogram and the preoperative spherical equivalent. D = diopters.

PRK; hence, a good result can also be expected in eyes that have undergone refractive surgery for high myopia. Unfortunately, the clinical history method also has some drawbacks that may lead to significant mistakes in IOL calculation (such errors are commonly reported in a number of papers, above all where the double-K method was not adopted).[4–7] Not only does it require the presurgical K-readings and the amount of attempted correction (information that is often lacking), but it is also highly vulnerable to bad data; its predictive power, for example, may be seriously affected by nuclear sclerosis–induced or axial length progression myopia, which can significantly change the post-LASIK/PRK refraction and render the calculation invalid. Therefore, if the pre-LASIK/PRK corneal power is available, the most logical solution might be to use this value to calculate the IOL power targeting for the subject's natural myopia, as we did to generate the benchmark for comparison in the present study.

As far as the other methods requiring availability of pre-PRK/LASIK data are concerned, the Feiz–Mannis formula also gave IOL powers close to the benchmark values (87.7% of eyes within ±0.5 D), even if a slight theoretical IOL underestimation occurred in most eyes. This formula may be considered as an alternative choice to the double-K clinical history method, as confirmed by the fact that no statistically significant differences could be detected between the mean arithmetical errors in IOL power calculated by the last 2 methods. This result is consistent with previous findings of Wang et al,[4] whose study showed the Feiz–Mannis formula to yield a mean IOL prediction error compared with that of the double-K clinical history method, albeit with higher variance. One advantage of the Feiz–Mannis formula over the clinical history method is that it does not require post-LASIK/PRK refraction data, which may be influenced by the same factors mentioned for the clinical history method. A potential drawback of the Feiz–Mannis formula, as evidenced by linear regression analysis, is a higher risk of IOL underestimation (and subsequent hyperopia) in eyes with higher preoperative myopia.

Separate consideration of anterior and posterior corneal curvatures was advocated by Seitz et al[26] in 2000 and later reviewed by Speicher,[15] who accurately reported the required formulas. When preoperative data were used, this method gave good results in 50% of eyes, where the IOL power would have been within ±0.5 D of the IOL power for theoretical emmetropia on condition that the double-K formula was adopted. IOL overcorrection by more than 0.5 D with consequent myopia would have occurred in more than one third of eyes, and IOL underestimation by more than 0.5 D with consequent hyperopia would have occurred in only 13.2% of eyes (but in no case would the error have reached 1 D). A noteworthy advantage of this method is that it does not require preoperative refraction data or stable postoperative refraction; the preoperative K-readings suffice on their own. This method has never been evaluated by other studies, so no comparison is possible. The fairly good results are not surprising, however, because the corneal power generated by this method was the closest to that calculated based on clinical history.

Both of Latkany's regression formulas may be useful when the myopic spherical equivalent is the only preoperative value we know.[9] These formulas may provide reliable results in a large percentage of patients and should not carry the risk of IOL underestimation in eyes with higher preop-

Table 4. Advantages and Disadvantages of the Most Accurate Methods Developed to Calculate Intraocular Lens Power After Myopic Excimer Laser Surgery

Method	Advantages	Disadvantages
Methods requiring prerefractive surgery data		
Double-K clinical history	• Best predictability • No correlation with attempted correction	• Need for prerefractive surgery data • Vulnerability to bad data
Feiz-Mannis formula	• Good predictability • No need for post-LASIK/PRK refraction data	• Need for prerefractive surgery data • Risk of IOL underestimation in eyes with higher preoperative myopia
Double-K method based on separate consideration of anterior and posterior corneal curvatures	• Fair predictability • Prerefractive surgery keratometry value = only required datum • No correlation with attempted correction	• Need for prerefractive surgery data
Latkany's method (average or flattest keratometry)	• Fair predictability • Prerefractive surgery spherical equivalent = only required datum • No correlation with attempted correction	• Need for prerefractive surgery data
Feiz-Mannis nomogram	• Prerefractive surgery spherical equivalent = only required datum	• Low predictability • Risk of IOL power overestimation
Single-K Shammas' refraction-derived method		• Need for prerefractive surgery data • Low predictability
Methods that do not require prerefractive data		
Double-K method based on separate consideration of anterior and posterior corneal curvatures	• Best predictability (among methods with no prerefractive data) • No correlation with attempted correction	• Risk of IOL power overestimation
Single-K Shammas' clinically derived method	• No need for prerefractive surgery data	• Low predictability
Rosa's and Ferrara's single-K methods	• No need for prerefractive surgery data	• Low predictability

IOL = intraocular lens; LASIK = laser in situ keratomileusis; PRK = photorefractive keratectomy.

erative myopia. As they have been described only recently, however, there are no studies confirming their effectiveness.

As regards the Feiz–Mannis nomogram, this may calculate an IOL power close to that for achieving emmetropia in almost half of eyes. However, considerable deviations from the benchmark value for emmetropia may still occur; about 52% of patients would be myopic as a result of an IOL power 0.5 D higher than needed. This result seems in agreement with those reported by Randleman et al,[6] where IOL power calculated using the Feiz–Mannis nomogram was higher than the IOL power for emmetropia in the majority of patients. More consistent results might be achieved if the nomogram were refined by analyzing a larger number of eyes (only 19 eyes were included in the original paper) and if it could also be adjusted for 0.5 D changes in refraction induced by refractive surgery.

A lower predictability in IOL power calculation may be achieved with Shammas' refraction-derived method, whose formula depends on a strict correlation between the amount of refractive correction at the corneal plane and the overestimation of corneal power by VKG compared to the clinical history method.[11] According to Shammas, such a difference is 0.23±0.11 D for each diopter of refractive change induced by excimer laser. We reanalyzed that correlation to understand whether the low predictability might be explained by it. Our data confirmed a similar, albeit weaker correlation ($r = -0.4409$, $P<0.0001$), but also showed a high degree of variability due to the fact that in 33 out of 98 eyes (33.6%) the Sim-K obtained by VKG was slightly lower (rather than higher) than the corneal power calculated using the clinical history method (mean underestimation, −0.26±0.24 D). As a consequence, the relationship between the error in corneal power calculation by VKG and the amount of myopic correction ranged between −0.41 and +0.29 D, with a mean value of 0.04±0.11 D. This variability is likely to account for the poor prediction performance of the refraction-derived method. Again, there are no clinical studies to confirm these findings in patients who underwent phacoemulsification and IOL implantation after corneal refractive surgery.

Surprisingly, in one third of eyes, the corneal power measured by VKG was lower than the value obtained by the clinical history method; this result seems to contradict most published papers. Actually, such a contradiction is less evident if we consider that (1) the difference was always <1 D and ranged between 0.01 and 0.5 D in 26 out of 33 cases (78.8%); (2) a careful review of the literature revealed to us that previous studies had already reported similar data in a minority of patients.[1,5,6,22,27] Further studies are needed to elucidate why and when VKG may not overestimate corneal power after excimer laser surgery.

Methods That Do Not Require Prerefractive Data

When neither the original K-readings nor the corrected amount of myopia are known, we can choose among Shammas' clinically derived method, Rosa's correcting factor, Ferrara's variable refractive index, and the method based on the separate consideration of anterior and posterior corneal curvature (using a fixed value of –4.98 D for the posterior corneal surface power).

The double-K method based on separate consideration of anterior and posterior corneal curvatures yielded the highest rate of eyes with a mean arithmetical error < 0.5 D (50%). This seems to represent the best choice when preoperative data are not known; not only does it provide the highest rate of theoretical emmetropia and the lowest rate of theoretical hyperopia, but also the lowest mean arithmetical and absolute error. In addition, it was the only method among those not requiring preoperative data that generated a mean IOL power that did not show statistically significant differences with the benchmark for comparison. Finally, it appeared neither to overestimate or underestimate IOL power in relation to preoperative refraction. A considerable rate of postoperative myopia may be expected; in 35.7% of cases, the IOL power would have been overestimated by >0.5 D, whereas the IOL power would have been underestimated by >0.5 D in only 14.2% of eyes. This variant of the method based on separate evaluation of both corneal curvatures is very similar to Maloney's method, recently evaluated by Wang et al.[4] In his method, Maloney used a mean power of –4.9 D for the posterior corneal curvature; interestingly, such a value is very close to the mean value that we calculated in our own sample (−4.98 D). Different results, however, have been obtained: the good IOL power predictability suggested by our own findings contrasts, in fact, with the mean IOL power underestimation observed by Wang et al,[4] even when the double-K formula was used. Following Wang et al's suggestion, we also tried to calculate the IOL power using a modified value of –6.1 D for the posterior corneal curvature (data not reported), but in this case a considerable IOL overestimation resulted. It is not clear whether such a discrepancy depends on the theoretical nature of the present study (as opposed to the clinical nature of Wang et al's study), the different instrument used for VKG, the more central keratometric value used with Maloney's method (as opposed to Placido's mires 7, 8, and 9 used in our study) or the larger size of the sample we analyzed.

Shammas' clinically derived method provided an acceptable rate of theoretical emmetropia (40.8%) when the single-K formula was adopted. Unfortunately, a considerable percentage of patients could theoretically be left hyperopic because of IOL power underestimation (>0.5 D in 46.9% of cases and >1 D in 30.6% of cases).

It is worth highlighting that our results do not perfectly agree with those reported in the original paper.[11] Although Shammas et al[11] found almost perfect coincidence between the mean corneal power generated by their method and that calculated by the clinical history method, in our series the mean corneal power was significantly lower when using the clinically derived method (37.80±2.45 vs. 38.95±2.27, $P<0.0001$). A possible explanation for this discrepancy may lie in the main limit of Shammas' clinically derived method; namely, its lack of correlation with the amount of attempted correction, as the authors themselves acknowledge. Even though it has been shown that the amount of error in IOL prediction is directly related to the entity of myopic correction, the formula used in this method ($Kc.cd = 1.14\ K_{post} - 6.8$) relies simply on the postoperative Sim-K and fails to consider preoperative refraction. As a consequence, the higher the refractive correction achieved by excimer laser, the greater the likelihood of IOL power underestimation, as confirmed by the linear regression for the single-K clinically derived method ($r = 0.7338$).

Rosa's correcting factor may represent another interesting option when preoperative data are not available. It gave a low mean corneal power, resulting in a mean IOL power overestimation of 0.46±1.02 when the single-K formula was used. The risk of postoperative hyperopia with this method seems low (16.3% of eyes with a IOL power underestimation >0.5 D); a myopic outcome may be expected in >50% of patients. This result partially confirms what Rosa et al[12] reported in their original paper, where the single-K clinical history method underestimated the IOL power compared to their method. The main limit of this method is that the correction factor varies with the axial length of the eye, which is only an indirect measure of the refractive change induced by surgery. As a consequence, the precision of this method is poor, for example, in the case of very long eyes requiring a low amount of refractive correction owing to a naturally flat cornea.

Among the formulas we compared, Ferrara's method calculated the lowest corneal power. This produces the highest IOL power and, as a consequence, the highest degree of myopic refraction after IOL implantation (such an outcome would be further reinforced by application of the double-K formula). A high degree of variability in relation to the benchmark value might also be expected, with a difference in IOL power ranging between −1.48 and +4.77 D for the single-K formula and between +0.16 and +7.51 D for the double-K formula. Hence, it is our impression that the variable refractive index method needs further refinement before its clinical application can be safely recommended. The discrepancy between this approach, as described by Ferrara, and the expected IOL power for emmetropia probably derives from the assumption that the variable refractive index changes according to the axial length of the eye. As we pointed out previously when discussing Rosa's correction factor, this is only partly true, because the refractive index of the cornea is a function of the corneal curvature and this, in turn, is modified by the amount of refractive correction, which is not always proportional to the axial length. Consequently, very long eyes that receive a low correction because of an originally flat cornea would be implanted with an excessively powerful IOL (e.g., male with 28.38-mm-long eye, pre-LASIK Sim-K of 39.86 D and attempted correction of −5.62 D; the variable refractive index method would give a 23.23/25.94 D IOL for the single-/double-K formula, compared to a theoretical 18.46 D IOL for emmetropia). However, it should be remembered that Ferrara et al (as well as Rosa) derived the TRI from keratometry, whereas our study was based on VKG readings.

We made several further assumptions in the design of our study, and these warrant review as possible sources of error or limitation. First, given the theoretical nature of the

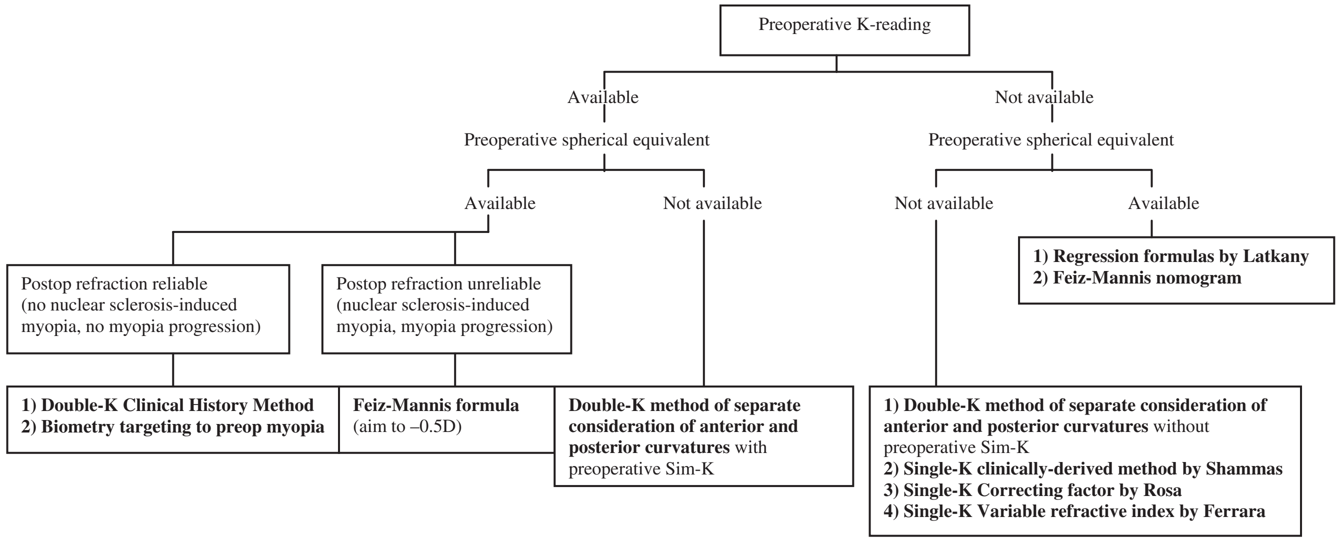

Figure 6. The decision tree illustrates the various options for calculating intraocular lens power after myopic refractive surgery by excimer laser. D = diopters; Sim-K = simulated keratometry.

analysis, our results need to be confirmed by clinical studies performed on patients who undergo phacoemulsification and IOL implantation. Second, we used as the benchmark for comparison a value (the IOL power calculated before LASIK/PRK, aiming for the preoperative myopia) that is considered likely to give an accurate prediction but has never been validated on patients. Moreover, such a method implies that neither the lens thickness nor the axial length (as measured by ultrasound biometry) change as a consequence of LASIK or PRK. To our knowledge, there is no definitive evidence that these parameters are modified by refractive surgery; however, caution is suggested, because recent studies using optical biometry (which may suffer from irregularities of the corneal surface after refractive surgery) have provided contradictory data about axial length.[28,29] Third, further investigations are needed to assess whether our findings can be applied to patients where laser surgery resulted in overcorrection or undercorrection, because these cases were not included in the present study. Fourth, we did not measure postoperative cycloplegic refraction, which in some cases may significantly differ from manifest refraction; such a difference may lead to different results in the formulas (such as in the clinical history method) where postoperative refraction is required. Fifth, we did not have VKG values measured by the EyeSys Corneal Analysis System and could not calculate the effective refractive power, which has already been reported to be one of the best parameters for obtaining K-readings in eyes that have undergone corneal refractive surgery.[4] Sixth, we could not directly measure the curvature of the posterior corneal surface, which would have allowed us to calculate the true optical power of the cornea according to the thin lens formula.[30] Finally, IOL power calculations in our study were performed using the axial length values obtained by contact biometry; in clinical practice, it probably would be more appropriate to rely on immersion biometry.

In conclusion, we can make the following recommendations when calculating IOL power in eyes that achieved emmetropia by myopic PRK or LASIK (Fig 6).

- If the Sim-K values before corneal surgery, the exact refractive change, and the stabilized refraction after corneal surgery are known, the double-K clinical history method is the preferred choice. Future studies will assess if it is also possible to rely on the power of the natural crystalline lens, used as the benchmark for comparison and calculated as described in the Methods section.
- If preoperative Sim-K and refraction are known, but postoperative refraction is not reliable, the best alternative option may be the Feiz–Mannis formula.
- If only the preoperative Sim-K is available (and not the preoperative spherical equivalent), the double-K method based on separate consideration of anterior and posterior corneal curvatures could be the best choice.
- If only the preoperative myopic spherical equivalent is known, Latkany's regression formula, based on either the average or flattest keratometry reading, may represent the most reliable option. The results of the Feiz–Mannis nomogram may be alternatively considered.
- When both the preoperative myopic spherical equivalent and Sim-K are unknown, the first choice should be the double-K method based on separate consideration of anterior and posterior corneal curvature, using a fixed value of –4.98 D for the posterior corneal power. It seems wise to compare the IOL power generated by this method to the IOL power generated by 3 additional methods: Shammas' single-K clinically derived method, Rosa's single-K correcting factor method and Ferrara's single-K variable refractive index method.

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