Corneal ray tracing versus simulated keratometry for estimating corneal power changes after excimer laser surgery

Giacomo Savini, MD, Antonio Calossi, DipOptom, Massimo Camellin, MD, Francesco Carones, MD, Marco Fantozzi, MD, Kenneth J. Hoffer, MD

PURPOSE: To evaluate whether the refractive changes induced by excimer laser surgery can be accurately measured by corneal ray tracing performed by a combined rotating Scheimpflug camera–Placido-disk corneal topographer (Sirius).

SETTING: Private practices.

DESIGN: Evaluation of diagnostic test.

METHODS: This multicenter retrospective study comprised patients who had myopic or hyperopic excimer laser refractive surgery. Preoperatively and postoperatively, 2 corneal power measurements—simulated keratometry (K) and mean pupil power—were obtained. The mean pupil power was the corneal power calculated over the entrance pupil by ray tracing through the anterior and posterior corneal surfaces using Snell's law. Agreement between the refractive and corneal power change was analyzed according to Bland and Altman. Regression analysis and Bland-Altman plots were used to evaluate agreement between measurements.

RESULTS: The study evaluated 72 eyes (54 patients). The difference between the postoperative and preoperative simulated K values underestimated the refractive change after myopic correction and overestimated it after hyperopic correction. Agreement between simulated K changes and refractive changes was poor, especially for higher amounts of correction. A proportional bias was detected ($r = -0.77$; $P<.0001$), and the 95% limits of agreement (LoA) were $-0.15 -0.14 \times \pm 0.62$ diopters (D). The difference between the postoperative and preoperative mean pupil power showed an excellent correlation with the refractive change ($r^2 = 0.98$). The mean pupil power did not overestimate or underestimate the refractive change. The 95% LoA ranged between -0.97 D and $+0.56$ D.

CONCLUSION: Corneal ray tracing accurately measured corneal power changes after excimer laser refractive surgery.

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Until scanning-slit corneal topography and Scheimpflug imaging became available a few years ago, the posterior corneal curvature could not be measured in a clinical setting. Because manual and automated keratometers as well as computerized videokeratography devices could measure only the anterior corneal curvature, the total corneal power had to be calculated using a fictitious refractive index (ie, keratometric index) to convert the measured corneal radius of curvature into diopters (D) by means of a paraxial formula of spherical surfaces. The keratometric index (1.3315 to 1.3375, depending on the manufacturer) aims to calculate the power of a single refractive surface, which is meant to represent the anterior and posterior corneal surfaces, without knowing the actual curvature of the posterior corneal surface.

The corneal power derived with this method can be used to accurately calculate the intraocular lens (IOL) power in normal virgin eyes having cataract surgery.[1,2] However, after corneal photoablative refractive surgery, the alteration in the physiologic anterior-to-posterior corneal radius ratio makes the keratometric index and

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the resulting corneal power invalid.[3,4] Relying on the keratometric index leads to overestimation of corneal power after myopic ablations and underestimation after hyperopic treatments.[3,5] Studies[4,6–8] have shown that the keratometric index should be decreased according to the amount of myopic correction to avoid overestimation of corneal power, and vice versa in cases of hyperopic correction. Alternatively, corneal power should be adjusted according to 1 of the many formulas described over the past decade.[9–17]

The issue of corneal power calculation after refractive surgery is further complicated by the fact that keratometers (and corneal topographers providing simulated keratometry [K] values) measure a portion of cornea that does not include the pupillary central area. The measured area is limited to the portion of the cornea that reflects the keratometric targets. It is an annulus with a diameter that varies between approximately 2.0 mm and 4.0 mm and a width that varies between 0.1 mm and 0.4 mm according to the constructive characteristics of the keratometer and according to the measured surface curvature.[18,19] Any difference in corneal curvature between the central corneal area and the paracentral annulus where measurements are taken may result in the so-called radius error. Moreover, K and simulated K values do not take into account the change in asphericity caused by the laser ablation of the corneal surface, and this can be another source of error in corneal power estimation.[20] With modern large-optical zone lasers and optimized ablation profiles, this difference has little clinical relevance[21]; however, in cases with a small or decentered optical zone, it can significantly affect corneal measurements.[22]

A possible solution for corneal power estimation after any kind of corneal refractive surgery is ray tracing based on Snell's law. Ray tracing does not rely on any fictitious assumption (eg, the keratometric index and paraxial and spherical approximations). Rather, it uses the measured contours of both corneal surfaces and the actual indices of refraction of air, cornea, and aqueous. Previous studies[23–26] have shown that corneal power calculated by ray tracing can accurately reflect the refractive changes induced by the excimer laser.

The purpose of this study was to evaluate whether the refractive changes induced by myopic or hyperopic excimer laser surgery can be accurately tracked by ray tracing corneal power measurements performed using a rotating Scheimpflug camera combined with a Placido-disk corneal topographer (Sirius, Costruzione Strumenti Oftalmici). We also aimed to determine whether the simulated K value really does introduce bias when measuring corneal power after excimer laser surgery.

PATIENTS AND METHODS

This multicenter retrospective study comprised patients who had myopic or hyperopic photorefractive keratectomy (PRK), laser-assisted subepithelial keratectomy (LASEK), or laser in situ keratomileusis (LASIK). The study was performed in accordance with the ethical standards stated in the 1964 Declaration of Helsinki and approved by the respective local clinical research ethics committees. All patients provided informed consent.

Included were all patients operated on by 1 of 4 experienced surgeons (G.S., F.C., M.C., M.F.) between January 2012 and March 2013 for which the preoperative and postoperative refractions and corneal measurements by the Scheimpflug camera–Placido-disk topographer were available. Postoperative examinations had to be performed at least 3 months (for LASIK) or 6 months (for PRK and LASEK) after surgery. Refractive values were calculated at the corneal plane using a vertex distance of 12.0 mm. Preoperatively and postoperatively, cycloplegic refraction was obtained after tropicamide 1.0% was instilled twice 5 minutes apart.

Corneal Power Measurements

All eyes had corneal power measurements by the Sirius (version 2.6), a noninvasive system for measuring and characterizing the anterior segment. The scanning process acquires a series of 25 Scheimpflug images (meridians) and 1 Placido top-view image. The ring edges are detected on the Placido image so that height, slope, and curvature data are calculated using the arc-step method with conic curves. From the Scheimpflug images, profiles of the anterior cornea, posterior cornea, anterior lens, and iris are derived. Data for the anterior surface obtained from the Placido image and Scheimpflug images are merged using a proprietary method. All other measurements for internal structures (posterior cornea, anterior lens, and iris) are derived solely from Scheimpflug data.

Two corneal power measurements were obtained; that is, simulated K and mean pupil power. Simulated K was obtained by converting the measured radius into diopters using the standard 1.3375 keratometric refractive index. A modified simulated K value obtained with the corneal refractive index (ie, 1.376) was also studied. The combined Scheimpflug–Placido device, whose Placido disk projects 22 rings onto the cornea, calculates the simulated K value by averaging the sagittal curvature from the fourth to the eighth Placido rings of the flattest and steepest principal

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From the Studio Oculistico d'Azeglio (Savini), Bologna, the Department of Physics (Optics and Optometry) (Calossi), University of Florence, Florence, Sekal Microchirurgia Rovigo (Camelin), Rovigo, Carones Ophthalmology Center (Carones), Milan, and Studio Oculistico Fantozzi (Fantozzi), Pescia, Italy; the School of Optometry and Ophthalmology and Eye Hospital (Savini), Wenzhou Medical University, Wenzhou, Zhejiang, China; the Department of Ophthalmology (Hoffer), University of California, Los Angeles, and St. Mary's Eye Center, Santa Monica, California, USA.

Corresponding author: Giacomo Savini, MD, G.B. Bietti Foundation IRCCS, Via Livenza 3, Rome, Italy. E-mail: giacomo.savini@alice.it.

meridians. This zone has a variable diameter depending on the curvature of the cornea, and the principal meridians are 90 degrees away.

The mean pupil power is the mean corneal power over the entrance pupil calculated by ray tracing through the anterior and posterior corneal surfaces using Snell's law. For each point on the map, the angle of incidence is calculated relative to the anterior surface normal for incoming parallel rays. The angle of refraction is calculated using Snell's law, with $n_{air} = 1.0$ and $n_{cornea} = 1.376$. This angle of refraction is used to determine the nonparallel direction of incoming rays relative to the posterior surface normal and to calculate the angle of incidence for the posterior surface. A new angle of refraction is calculated for the posterior surface using Snell's law, with $n_{cornea} = 1.376$ and $n_{aqueous} = 1.336$. This final angle of refraction is used to calculate the intersection of the ray along the (0,0) axis, and the resultant equivalent focal length is used to determine the equivalent power for that point on the map. A diameter of 4.5 mm was arbitrarily chosen for all mean pupil power measurements to simulate vision under mesopic light conditions because of the relatively low mean age of patients. On this diameter, a polar matrix of 20 points × 50 points was sampled and weighted according to the Stiles-Crawford effect.

Because high repeatability has been reported for Sirius measurements,[27] the first corneal power measurement was used for clinical and statistical purposes if no artifacts related to blinking or tear film breakup were evident.

Surgical Technique

Each surgeon used a different technique and a different laser platform. Ablation was performed using 1 of the following excimer lasers: Allegretto Wave Eye-Q (400 Hz repetition rate, Wavelight Laser Technologie AG), EX-500 (Wavelight Laser Technologie AG), or Amaris excimer laser (Schwind Eye-Tech-Solutions GmbH and Co. KG). The surgical technique and the postoperative medications were the same as those previously described for PRK and LASIK.[24,28]

Statistical Analysis

Statistical analysis was performed using Excel software (Microsoft Corp.) and Medcalc for Windows software (version 12.7, Medcalc Software). The data showed that the measurement differences between matched pairs were normally distributed ($P = .7678$, Kolmogorov-Smirnov test) with a standard deviation (SD) of 0.39 D. When estimating the sample size for this study,[29] it was found that if the true difference in the mean measurement of matched pairs were 0.25 D, 36 pairs of patients would be required to be able to reject the null hypothesis that the response difference would be zero with a probability (power) of 0.95. The type I error probability associated with a test of this null hypothesis is 0.05. For patients who had bilateral surgery, both eyes were considered for statistical analysis. Because there was no correlation between the 2 eyes (correlation coefficient $r = 0.1490$, $P = .3858$), use of data in both eyes was appropriate.[30]

Agreement between the refractive change and the corneal power change was analyzed according to the method described by Bland and Altman.[31,32] Regression analysis and Bland-Altman plots were used extensively to evaluate the agreement between different clinical measurements. Bland-Altman plots allow one to determine whether there are systematic differences between the measurements (ie, fixed bias). The mean difference is the estimated bias, and the SD of the differences measures the random fluctuations around this mean. If the mean value of the difference differs significantly from 0 on the basis of a 1-sample t test, this indicates the presence of fixed bias. Also calculated were the 95% limits of agreement (LoA) for each comparison (mean difference ± 1.96 × SD), which tell how far apart measurements by 2 methods are more likely to be for most individuals.

Bland-Altman plots were also used to study possible relationships of the discrepancies between the measurements and the true value (ie, proportional bias). The existence of proportional bias indicates that the methods do not agree equally through the range of measurements; that is, the LoA will depend on the actual measurement. To evaluate this relationship formally, the difference between the methods was regressed on the average of the 2 methods. When a relationship between the differences and the true value was identified (ie, a significant slope of the regression line), regression-based 95% LoA were provided.[32]

RESULTS

Seventy-two eyes of 54 patients with a mean age of 35.4 years ± 9.6 (SD) were enrolled. The refractive change as the spherical equivalent (SE) at the corneal plane ranged from −10.00 to +5.25 D. Table 1 shows the surgical techniques, the laser platforms, and the mean correction for each subgroup of patients based on the surgical technique.

The difference between the postoperative and preoperative simulated K values underestimated the refractive change after myopic correction and overestimated it after hyperopic correction (Figure 1). Agreement between the simulated K changes and refractive changes was poor, especially for higher amounts of correction. A proportional bias was detected ($r = -0.77$; $P < .0001$), and the 95% LoA were −0.15 −0.14 × ±0.62 D (Figure 2). From this regression equation, the simulated K change values for the different corrections can be derived. For example, for a +4.00 D correction, the mean delta simulated K value is −0.70 ± 0.62 D; for a −6.00 D correction, the mean delta simulated K is +0.68 ± 0.62 D, and for a −10.00 D correction, the mean delta simulated K is +1.24 ± 0.62 D.

The difference between the postoperative and preoperative mean pupil power had an excellent correlation with the surgically induced refractive change ($r^2 = 0.98$). Figure 3 shows that, unlike the simulated K value, the mean pupil power did not overestimate the refractive change in post-hyperopic treated eyes and did not underestimate it in post-myopic treated eyes. There was a small bias (mean difference 0.20 D) that was statistically ($P < .0001$) but not clinically significant because it was lower than 0.25 D. The 95% LoA ranged between −0.97 D and +0.56 D (Figure 4).

Table 1. Descriptive statistics.

Parameter	Excimer Laser			Total
	Allegretto	Amaris	EX−500	
Eyes (n)	25	28	19	72
Surgical technique	PRK (n= 12); LASIK (n=13)	LASEK	LASIK	—
Refractive change (D)				
Mean ± SD	−4.51 ± 1.84	−2.00 ± 1.84	−2.83 ± 1.22	−3.09 ± 2.73
Range	−10.02, −1.96	−7.36, +5.24	−5.27, −1.59	−10.02, 5.24

LASEK = laser-assisted subepithelial keratectomy; LASIK = laser in situ keratomileusis; PRK = photorefractive keratectomy

Using a corneal refractive index of 1.376 (instead of the 1.3375 keratometric index), the difference between the postoperative and preoperative adjusted simulated K showed an excellent correlation with the surgically induced refractive change (r^2 = 0.98). Figure 5 shows that the adjusted simulated K did not overestimate the refractive change in post-hyperopic treated eyes and did not underestimate it in post-myopic treated eyes. Figure 6 shows that agreement between adjusted simulated K changes and refraction changes was good. A quite small proportional bias was detected (r = −0.30; P=.0109), and the 95% LoA were −0.16 −0.04 × ±0.69 D.

DISCUSSION

Corneal power overestimation after myopic excimer laser surgery is a well-known issue that occurs with any technology (manual and automated K, computerized videokeratography, and Scheimpflug imaging) when the keratometric index is used to convert radius measurements into dioptric power.[3,4,6,7,13,24,33] In contrast, corneal power underestimation occurs after hyperopic excimer laser surgery.[5] These errors arise as a consequence of the keratometric index, which requires a fixed ratio between the anterior corneal curvature and posterior corneal curvature and thus is made invalid once the excimer laser disrupts such a ratio by flattening or steepening the anterior corneal surface.[3,4] The altered corneal shape, which turns oblate after myopic excimer laser surgery and hyperprolate after hyperopic excimer laser surgery, further contributes to incorrect corneal power estimation. Unfortunately, the errors caused by the variation in asphericity and those caused by the changes in the ratio between the front corneal surface and back corneal surface always go in the same direction and tend to be additive.

Achieving the correct corneal power after excimer laser surgery is useful for at least 2 reasons. The first

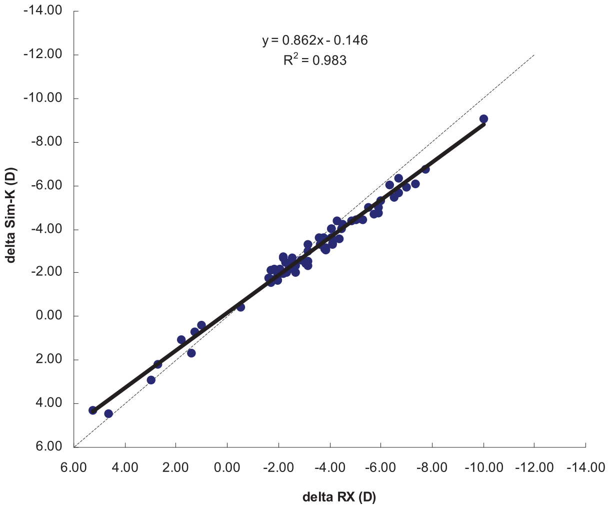

Figure 1. Linear regression between simulated K changes (delta Sim-K) and SE refractive changes (delta RX).

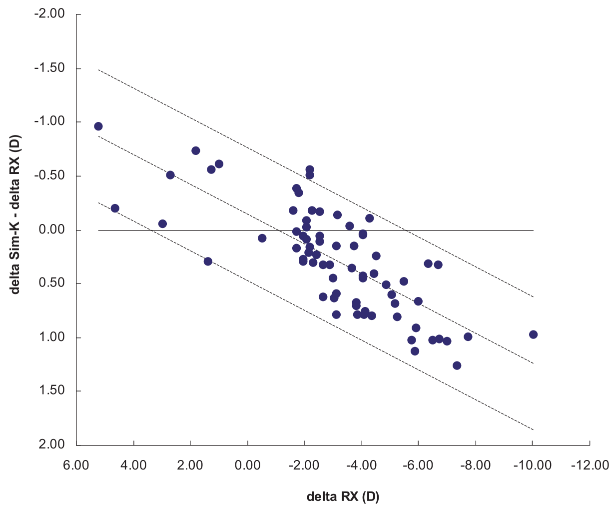

Figure 2. Bland-Altman plot showing low agreement between simulated K changes (delta Sim-K) and SE refractive changes (delta RX). Equations for regression-based 95% LoA are given because proportional bias was detected.

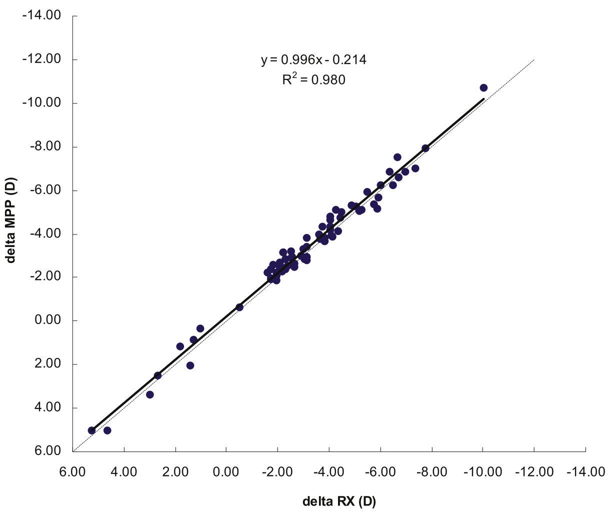

Figure 3. Linear regression between mean pupil power changes (delta MPP) and SE refractive changes (delta RX). The regression line is close to the equality line (---).

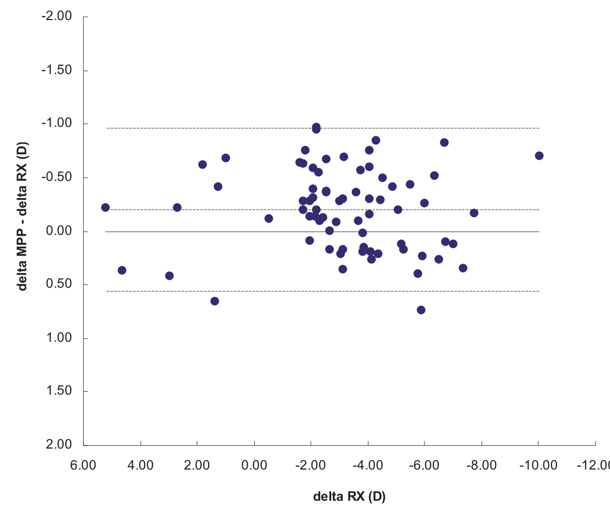

Figure 4. Bland-Altman plot showing quite good agreement between mean pupil power changes (delta MPP) and SE refractive changes (delta RX).

is to calculate the IOL power for cataract surgery. The second is to perform an objective follow-up of patients who have had refractive surgery. Several methods to adjust the corneal power in eyes with previous excimer laser surgery have been described and reviewed and compared in many studies.[12,13,16,33,34] Although they can lead to good results in patients having cataract surgery, calculating these values requires extra time because the measured values have to be entered into several formulas and can easily generate a wide range of corneal powers. In a previous theoretical comparison, for example, we reported that the calculated mean corneal power ranged between 35.97 D and 38.95 D.[13] Automatically calculated corneal power values that do not require adjustment would be a better option because ophthalmologists would not have to face the challenge of entering measured values into complex formulas and choosing a single calculated value from among several different values. Corneal ray tracing based on Snell's law seems a logical solution because it allows us to automatically calculate corneal power without relying on a fictitious index (eg, the keratometric index).[23–26] Moreover, it can take into account the optics of the real shape of the cornea[35] and can be computed on different diameters.

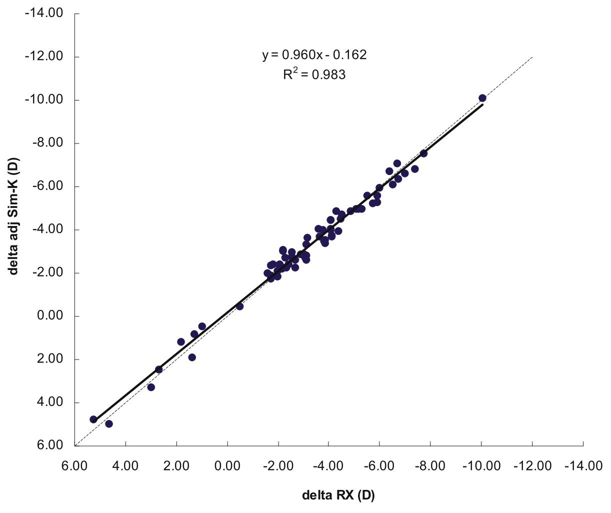

Figure 5. Linear regression between adjusted simulated K changes (delta adj Sim-K) and SE refractive changes (delta RX). The regression line is close to the equality line (---).

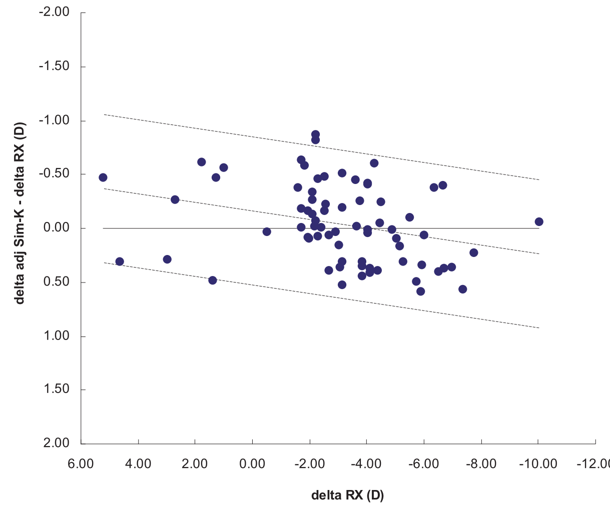

Figure 6. Bland-Altman plot showing good agreement between adjusted simulated K changes (delta adj Sim-K) and SE refractive changes (delta RX).

In this study, we enrolled a sample of post-myopic and post-hyperopic excimer laser surgery patients and evaluated the corneal power calculations offered by the Sirius, a rotating Scheimpflug camera combined with a Placido-disk based corneal topography. We found that the mean pupil power (ie, corneal power calculated by ray tracing) closely mirrored the refractive changes induced by surgery, with no proportional biases based on the amount of the correction. These findings confirm those previously achieved by other instruments based on scanning-slit corneal topography or Scheimpflug corneal topography[23–26] and show that an additional instrument can be relied on for this purpose. In contrast, the simulated K value underestimated corneal power after hyperopic laser surgery and overestimated it after myopic laser surgery. This is not surprising because several studies have reported this finding.[3–7,13,24] Neither were we surprised to observe that simulated K values could accurately reflect the surgically induced refractive changes once the corneal refractive index (1.376) was used instead of the keratometric index (1.3375), as previously reported by Mandell[36] and Gobbi et al.[37] However, it is mandatory to remember that the 1.376 index allows us to calculate the power of the anterior corneal surface only; thus, it can be used to assess the surgically induced refractive change but not to calculate the IOL power.

Regarding cataract surgery and IOL power calculation, before entering the mean pupil power value into any IOL power formula, the constants must be optimized. In a previous study,[1] in fact, we found that the A-constant was 118.10 for the mean pupil power compared with 118.60 for the simulated K value. Moreover, the mean pupil power with optimized constants should be entered into theoretical formulas modified according to the Aramberri double-K method.[38] Hence, using the mean pupil power without constant optimization and double-K formulas can easily lead to inaccurate IOL power calculation. Alternatively, specific software to calculate IOL power by ray tracing without relying on standard paraxial formulas are available.[39,40] Such software is included in the Sirius system and was recently shown to provide good results for IOL power calculation after myopic excimer laser surgery.[41]

The present study comprised patients enrolled at different centers where different laser platforms and techniques were used. Although this might seem a limitation, we believe that analyzing data from patients with different treatments reinforces our findings because it shows the Sirius Scheimpflug camera–Placido topographer can obtain accurate measurements over a wide range of treatments. Future studies are warranted to confirm that mean pupil power can obtain the expected results for IOL power calculation after cataract surgery in eyes with previous excimer laser refractive surgery.

In conclusion, in our study, corneal ray tracing provided by a rotating Scheimpflug camera combined with a Placido-disk corneal topographer accurately measured the corneal power changes after excimer laser refractive surgery. The calculated value can be used for IOL power calculation as well as in follow-up of patients having PRK, LASEK, or LASIK.

WHAT WAS KNOWN

- Simulated K values cannot provide accurate calculation of corneal power after excimer laser surgery because they underestimate dioptric changes after myopic treatments and overestimate them after hyperopic treatments.

WHAT THIS PAPER ADDS

- Corneal power measurements by ray tracing provided by a Scheimpflug camera combined with a Placido-disk corneal topographer accurately measured corneal power changes after myopic and hyperopic excimer laser surgery.

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