

Corneal Power Measurements Using Scheimpflug Imaging in Eyes With Prior Corneal Refractive Surgery

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ABSTRACT

PURPOSE: To evaluate the accuracy of central corneal power measurements by Scheimpflug imaging (Pentacam) for eyes that had corneal refractive surgery.

METHODS: This study comprised two groups: a pilot group of 100 eyes with prior hyperopic or myopic LASIK that did not have cataract surgery, and a test group of 41 eyes with prior radial keratotomy (RK) and cataract surgery. In the pilot group, Pentacam images and refraction were taken preoperatively and 3 months after LASIK. The historical method was used to compute the theoretical postoperative keratometry (K) -reading and then compared to the measured equivalent K-reading (EKR) from the Pentacam. The EKR is the same value measured by standard keratometry or topography on the front surface, adjusted for the effect of the back surface power difference from normal. In the test group of RK eyes, the postoperative refraction and EKR were measured 3 months after cataract surgery. The Holladay IOL Consultant Program was used to back-calculate the theoretical K-reading. The EKR measurements were then compared to the back-calculated corneal power.

RESULTS: The optimal zone sample size was determined to be 4.5 mm for the pilot group. The mean prediction error for this group was -0.06 ± 0.56 diopters (D) (range: -1.63 to $+1.34$ D). Using the 4.5-mm zone determined in the pilot group, the EKR value for the test group of 41 RK eyes had a mean prediction error of -0.04 ± 0.94 D (range: -1.84 to $+2.27$ D).

CONCLUSIONS: When historical refractive data are not available, Scheimpflug imaging with the Pentacam provides an alternative method of measuring the central corneal power in eyes that previously received corneal refractive surgery. [*J Refract Surg.* 2009;25:862-868.] doi:10.3928/1081597X-20090917-07

Corneal refractive surgery alters the central corneal power in ways that make accurate measurements problematic. Accurate corneal power measurements are critical in the calculation of intraocular lens (IOL) power for cataract surgery. For eyes with prior refractive surgery, a 1.00-diopter (D) error in the corneal power results in a 1.00-D error in the postoperative refraction.

Two methods are available for determining the refractive corneal power, direct and indirect. The direct methods (keratometry and topography) measure the front corneal radius of curvature and then calculate a refractive power using the standardized keratometric index (1.3375).¹ The problem with direct measurements is that after refractive surgery, the anterior corneal shape and ratio of the back to front corneal curvature have changed, making the reported corneal power invalid.^{2,3} To address this problem, the first indirect method was described in 1989 following radial keratotomy (RK). This method is known as the “historical method” and uses the keratometry (K) -readings before refractive surgery and the change in refraction to determine the theoretical power of the cornea.⁴ The problem with this method is the assumption that all refractive change is due to the cornea. This is not always true, especially for older patients in whom the refractive change may be partly due to the crystalline lens.⁵ Furthermore, following RK, diurnal variations in corneal power and a wide variation in optical zone sizes typically result in much larger refractive surprises than normal, unoperated corneas.⁶ Although LASIK and photorefractive keratectomy

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(PRK) have more consistent optical zones and refractions are much more stable than with RK, refractive surprises still occur.⁵

Several subsequent methods have been described over the past 19 years, using keratometry, topography, and tomography, which have led to improved results, but large refractive surprises have been reported.⁷⁻¹³ There are two primary reasons for these surprises. First, keratometers and topographers have a central scotoma that is not measured (due to the central location of the eyepiece or camera). For the standard manual keratometer, this area is 3.2 mm for a 44.00-D cornea. Topographers have a smaller scotoma (~1.6 mm), but still do not measure the central area. Second, the posterior radius of the cornea is not measured, and after all forms of corneal refractive surgery, there is no longer a physiologic ratio between the front and back corneal radii.^{14,15}

Tomography with Scheimpflug imaging has the advantage of measuring the entire central area of the cornea (ie, the camera is not central) as well as the posterior surface. The purpose of this study was to develop a method utilizing this additional information and report the mean error and standard deviation of this technique in patients who had undergone LASIK only (pilot group) and those in whom RK and cataract surgery were performed (test group).

PATIENTS AND METHODS

A chart review pilot study was first performed using 100 eyes from 55 patients aged <40 years, who had undergone LASIK with the VISX S4 laser (Abbott Medical Optics, Santa Ana, Calif) using 6.5- to 7.0-mm optical zones, 2.0-mm blends, iris registration, and pupil offset tracking. The spheroequivalent treatments ranged from +4.50 to -9.50 D. For each patient, prior to LASIK, the refraction was determined and Scheimpflug measurements were taken with the Pentacam (Oculus Optikgeräte GmbH, Wetzlar, Germany). Three months postoperatively, the patient's refraction and Scheimpflug measurements were repeated. In this pilot group, the historical method was used to determine the theoretical corneal power 3 months after refractive surgery. Because no patients had any sign of cataracts, and the maximum age in this study was less than 40 years, the chance of any lenticular changes occurring during this 3-month period would be remote. This theoretical historical method K-reading was used as the reference for the pilot group and compared to the equivalent K-reading (EKR).

The EKR on the Pentacam was designed to yield the same average value in a normal population as a keratometer or topographer using the standards established for these instruments.¹ In a specific patient, the

EKR will only differ by the effect of the power of the back surface from normal. The EKR is computed by first determining the average anterior radius and using the standardized keratometric index of 1.3375.* When the standardized keratometric index of refraction is used, with a 7.5-mm anterior corneal radius, the reported keratometric power would be 45.00 D $([1.3375-1.000]/0.0075)$. The average ratio of the back to front surface central radius is 0.818 ± 0.023 in normal eyes.¹⁶ In the pilot group of 100 LASIK eyes, the average ratio was similar at 0.822 ± 0.021 . For a 7.5-mm anterior radius, the front surface power (FSP) would be 50.133 D $([1.376 \pm 1.000]/0.0075)$ and the average back surface radius would be 6.165 mm (7.5×0.822) with a back surface power (BSP) of -6.488 D $([1.336 \pm 1.376]/6.165)$.

The equivalent power of this cornea would be 43.78 D $\{FSP+BSP-[(\text{central cornea thickness})/(\text{stromal index of refraction})] \times [FSP \times BSP]\}$ or $\{50.133-6.488-[(0.00055)/(1.376)] \times 50.133 \times [-6.488]\}$. The third term (thickness term) has a +0.13-D effect. Calculating the theoretical net index of refraction of the entire cornea using the front surface radius of 7.5 mm would yield 1.3283 $([\text{equivalent power} \times \text{front surface radius}] + 1 = 43.78 \times 0.0075 + 1)$. The empirically determined net index of refraction used in current IOL formulas ranges from 1.3215 to 1.3333, which is close to this theoretical value.¹

If the actual measured posterior radius in this example were flatter by 2 standard deviations, the ratio would be 0.843 $(0.822 + 0.021)$ and the posterior radius 6.323 mm (7.5×0.843) . The calculated average anterior radius from the measured posterior radius would be 7.692 mm $(6.323/0.822)$ and the calculated K-reading 43.88 D $([1.3375-1.000]/7.692)$, a keratometric difference of 1.12 D $(45.00-43.88)$. The FSP difference would be 1.25 D $(1.12/[(1.3375-1.000)/(1.376-1.000)])$, a difference of 0.13 D. The reported EKR would be 45.13 D $(45.00+0.13)$, accounting for the flatter than normal back surface, which would be less negative, increasing the overall power of the cornea. Having used the actual 2 standard deviations above the mean, it is evident that the EKR would differ from the standard K-reading by <0.13 D in 95% of the population of normal, unoperated corneas.

Following corneal refractive surgery, the variation in the back to front radius ratio is much greater

*In 1997, the American National Standards Institute (ANSI) and International Organization for Standardization (ISO) achieved a consensus to use 1.3375 as the standard keratometric index of refraction. Unfortunately, not all keratometers and topographers are in compliance, and users should confirm the index of refraction used on their device.¹

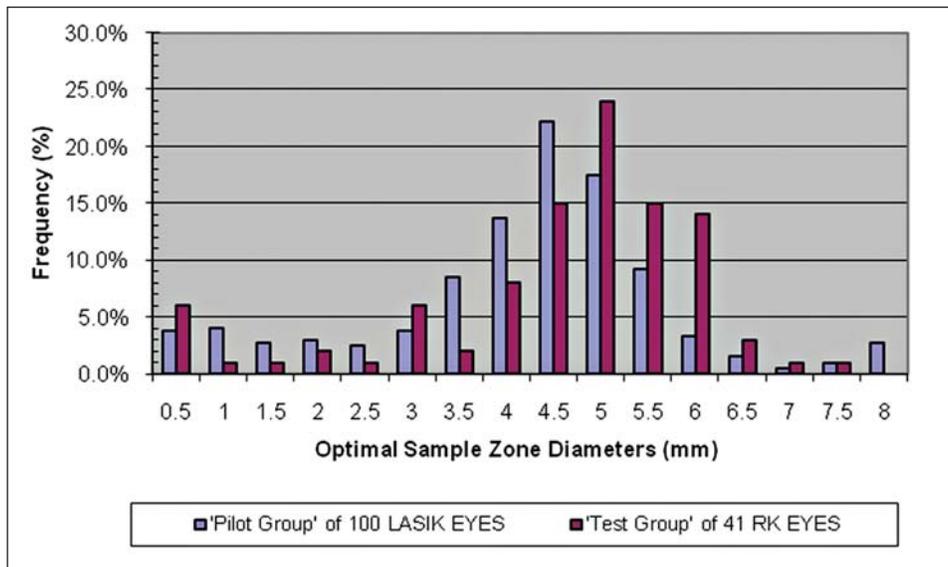


Figure 1. Frequency of the optimal sample zone diameter that yielded the best correlation with equivalent keratometry (K) -reading. The mode is 4.5 mm for the pilot group of 100 LASIK eyes and 5.0 mm for the test group of 41 radial keratotomy (RK) eyes, with a great deal of variation for both.

and causes a much greater error.^{2,3} To illustrate, if the patient above had a refraction of -10.00 D at the corneal plane, the historical method would yield a correct keratometric power of 35.00 D (45.00-10.00), which would be used in the IOL calculation. The actual measurement by the keratometer would be wrong at 36.02 D, as shown below.

Because PRK (and LASIK) only change the radius of the front surface, the FSP for a 7.5-mm radius must be determined, which is 50.13 D [(1.376-1.000)/0.0075]. The FSP must be reduced by 10.00 D at the corneal plane from 50.13 to 40.13 D (50.13-10.00) to achieve emmetropia.^{2,3} Using the stromal index of refraction of 1.376, we find the desired front radius for an FSP of 40.13 D must be 9.369 mm [(1.376-1.000)/40.13]. Although the keratometer measures the correct radius (9.369 mm), the reported K-reading using the keratometric index is 36.02 D [(1.3375-1.000)/0.00937]. The keratometric change is -8.98 D (36.02-45.00) versus the true change of -10.00 D. The error is a direct result of the difference in the keratometric and corneal stromal index of refraction. The ratio (scaling from FSP to keratometric power) is 0.8976 (1.3375-1.000)/(1.376-1.000), resulting in an underestimate of the true change in corneal power of 10.24%.

In this eye, the Scheimpflug can measure the back surface radius. For a 6.165-mm measured posterior radius, the normal anterior radius would be 7.500 mm (not the measured 9.369 mm). The calculated value for the K-reading would be 45.00 D [(1.3375-1.000)/0.0075]. The difference is -8.98 D (36.02-45.00) and scaling to FSP the change would be -10.00 D (-8.98/0.8976), a difference of 1.02 D. The reported EKR would be 35.00 D (36.02-1.02)—the same value as determined by the

historical method. Using the steps above, the relationships can be reduced to the following equation:

$$EKR(D) = \frac{n_c - 1}{r_{am}} + \frac{(n_k - 1)RAT_{bf}}{r_{pm}} \left(1 - \frac{1}{RAT_{kc}}\right)$$

where n_c = index of refraction of the corneal stroma = 1.3760; n_k = standardized keratometric index = 1.3375; r_{am} = measured anterior corneal radius (m); r_{pm} = measured posterior corneal radius (m); RAT_{bf} = normal ratio of back to front corneal radii = 0.822; and RAT_{kc} = ratio of change in keratometric versus front surface power = (1.3375-1.000)/(1.376-1.000) = 0.8976.

Substituting the constants above and simplifying, the computational formula is:

$$EKR(D) = \frac{376.0}{r_{am}(mm)} - \frac{31.65}{r_{pm}(mm)}$$

Using our example radii of 9.369 mm for r_{am} and 6.165 mm for r_{pm} , we find an EKR of 35.00 D.

Using the equation above, the EKR values were computed for each eye of the pilot group from 0.5- to 8.0-mm zones in 0.5-mm increments. The zone that yielded the best agreement with the historical method was considered the optimal sample zone size. A histogram of the optimal zone sizes is displayed in Figure 1.

The test group comprised 41 eyes from 29 patients who had previously undergone RK and cataract surgery. Three months after cataract surgery, the final refraction and EKR measurements were taken. Using the Holladay IOL Consultant Program (Holladay Consulting Inc, Bellaire, Tex), the back-calculated K-reading was determined. This back-calculation utilizes the

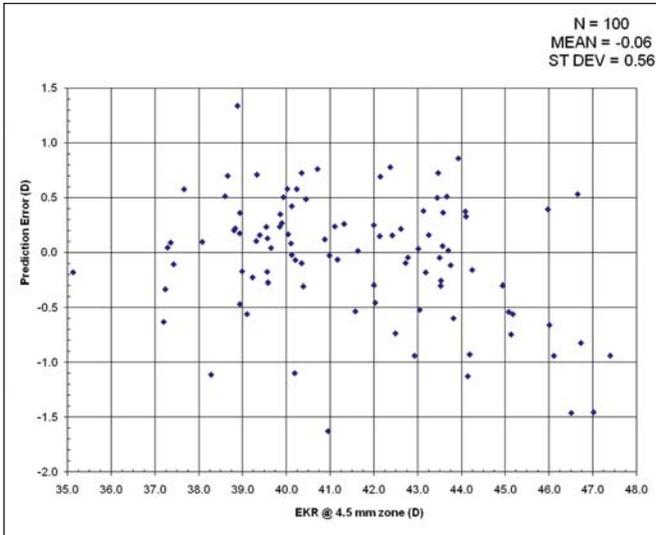


Figure 2. Pilot group of 100 LASIK eyes. Bland-Altman plot of the measured equivalent K-reading (EKR) for the 4.5-mm zone versus the theoretical calculated K-reading from the historical method.

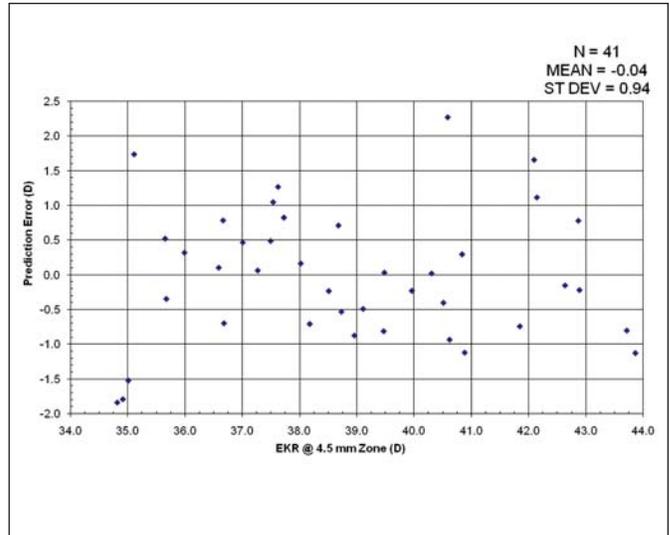


Figure 3. Test group of 41 RK eyes. Bland-Altman plot of the measured equivalent K-reading (EKR) for the 4.5-mm zone versus the theoretical back-calculated K-reading from the cataract surgical data.

lens constant, axial length, IOL power implanted, and final refraction to back-calculate the corneal power. The theoretical back-calculated corneal power was then compared with the measured EKR.

RESULTS

The optimal zone size for the pilot group is shown in Figure 1 and demonstrates that the 4.5-mm sample zone yielded the highest correlation when compared with the historical method K-reading. The EKR value was then fixed to a 4.5-mm zone and used to perform the statistical analyses for both the pilot and test groups.

The Bland-Altman statistical method was used to analyze the data.^{17,18} For the pilot group of 100 LASIK eyes, the EKR with a 4.5-mm value had a mean prediction error of -0.06 ± 0.56 D (range: -1.63 to $+1.34$ D) (Table 1, Fig 2). For the test group of 41 RK eyes, the EKR value had a mean prediction error of -0.04 ± 0.94 D (range: -1.84 to $+2.27$ D) (Table 1, Fig 3).

DISCUSSION

The standard deviation of measurements for normal, unoperated corneas obtained by keratometry, topography, and tomography is ~ 0.25 D.^{19,20} For the pilot group of 100 LASIK eyes, this standard deviation of the EKR was approximately twice normal, unoperated corneas (0.56 D) and for eyes with prior RK, the standard deviation is approximately four times normal (0.94 D). It should be noted that the pilot group of LASIK eyes did not undergo cataract surgery and using the historical method limits the source of error to corneal power alone. In the test group of RK eyes that underwent cataract surgery, using

TABLE 1

Bland-Altman Statistics of the Pilot Group of LASIK Eyes and Test Group of Radial Keratotomy Eyes

Prior Surgery (N)	Mean Deviation* (D)	SD (D)	Error Range (D)
LASIK (100)	-0.06	± 0.56	-1.63 to +1.34
RK (41)	-0.04	± 0.94	-1.84 to +2.27

SD = standard deviation, RK = radial keratotomy
**Difference of equivalent K-reading from calculated K from the history method for LASIK and back-calculated K for radial keratotomy.*

the back-calculated corneal power reflects the standard deviation of all parameters (corneal power, axial length, postoperative refraction, and lens constant) with cataract surgery.

In Figure 1, sample zone sizes from 0.5 to 8.0 mm were analyzed and the best sample zone size for the test group of RK eyes was slightly larger than the pilot group with a peak at 5.0 mm. Note that 4.5 mm is the mode for the pilot group and 5.0 mm for the test group, but there is a significant variation in both, ranging from 3.0 to 6.5 mm. In the lower left hand corner of Figure 4, the EKR distribution over the 4.5-mm zone is illustrated for an example RK eye, and in Figure 5, the EKR distribution is illustrated for an example LASIK eye. The variation in corneal power is 3 to 4 times greater over the same 4.5-mm zone for the RK cornea.

Previous results from various methods are shown in Table 2. The results vary significantly for each of

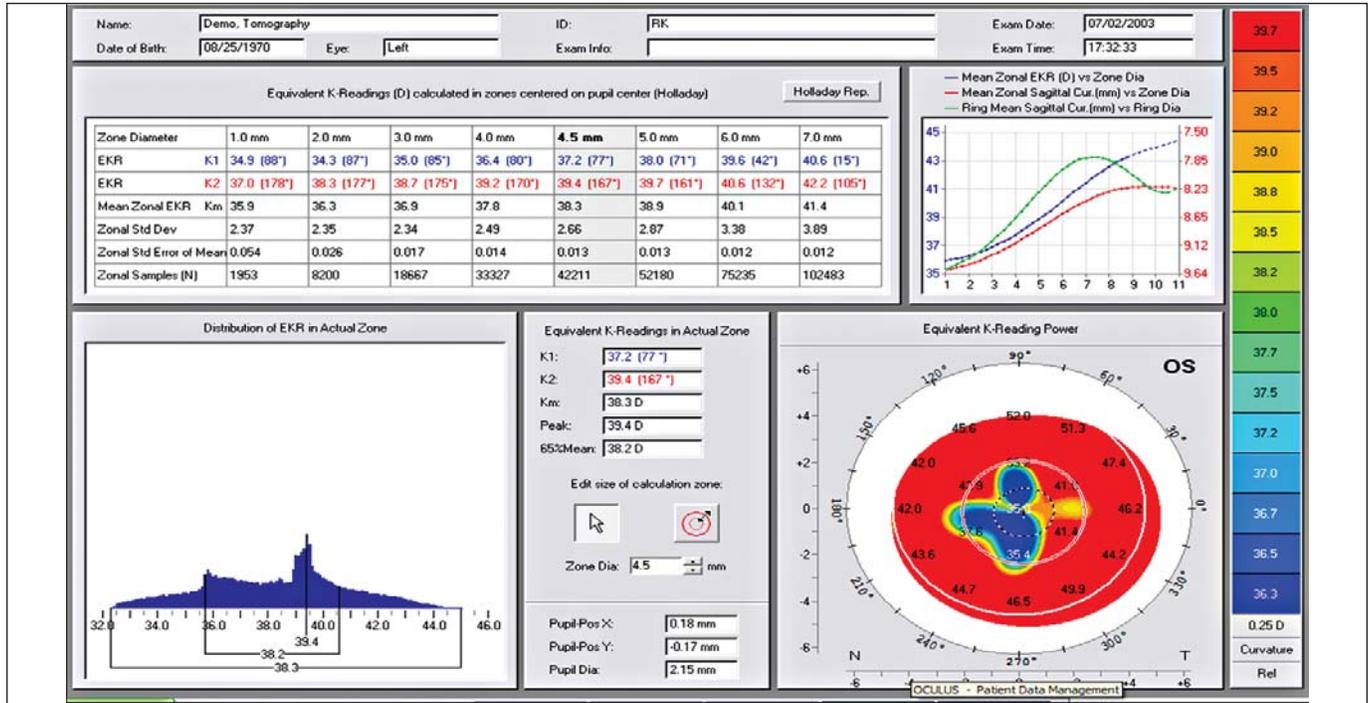


Figure 4. Detailed report of the equivalent K-reading (EKR) for an example radial keratotomy (RK) eye. The mean zonal value is shown in the table in the gray shaded central column under the 4.5-mm zone. There are ~42,000 points used to determine the mean value. The frequency distribution of powers over the 4.5-mm zone is shown in the lower left hand corner. Note the wide variation in the distribution EKR values (12.70 D, 32.30 to 45.00 D) over the 4.5-mm zone. The mean zonal EKR (D) (dashed blue line) versus the zone diameter is shown graphically in the upper right hand corner.

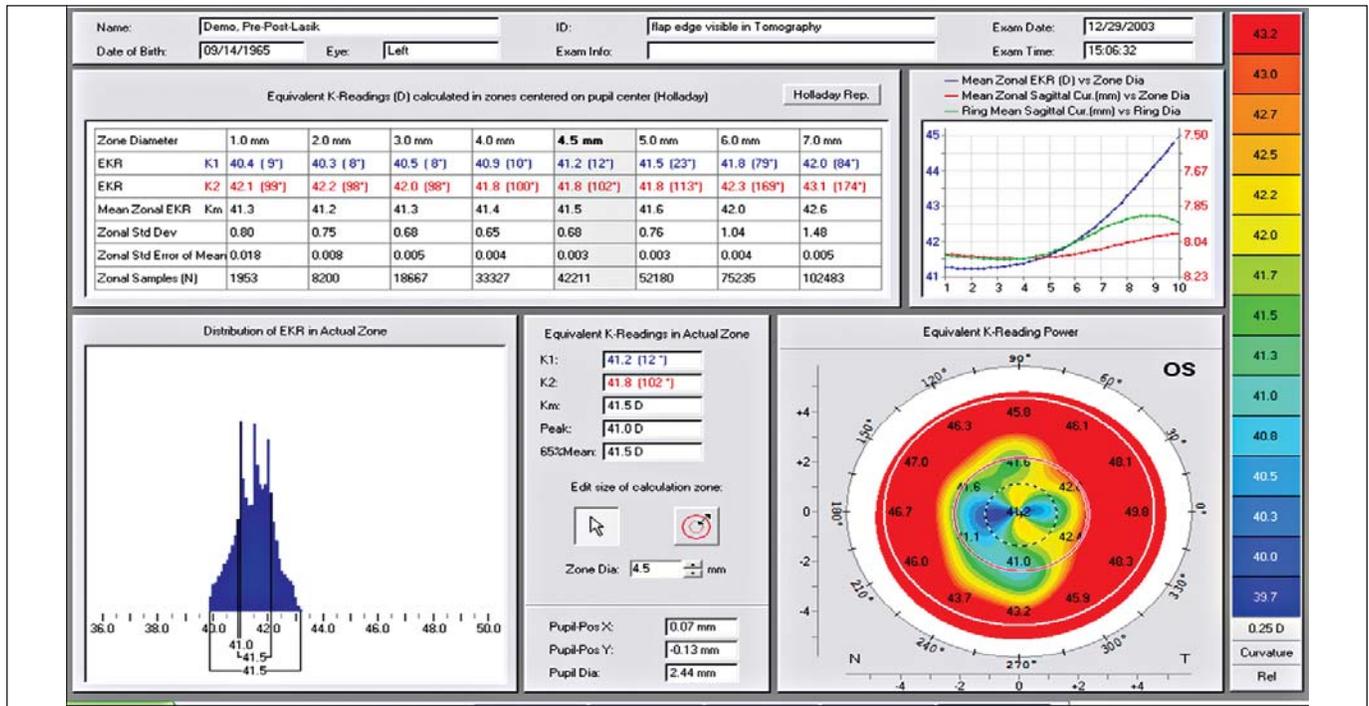


Figure 5. Detailed report of the equivalent K-reading (EKR) for an example LASIK eye. The mean zonal value is shown in the table in the gray shaded central column under the 4.5-mm zone. There are ~42,000 points used to determine the mean value. The frequency distribution of powers over the 4.5-mm zone is shown in the lower left hand corner. Note the smaller variation in the distribution of the EKR values (3.30 D, 39.90 to 43.20 D) over the 4.5-mm zone for the LASIK versus the RK eye. The mean zonal EKR (D) (dashed blue line) versus the zone diameter is shown graphically in the upper right hand corner.

TABLE 2
**Statistics of Other Studies Determining Central Corneal Power
 in Eyes With Prior Refractive Surgery**

Study	Prior Surgery (N)	Methodology	P Value	SD (D)*	Error Range (D)*
Walter et al ¹³	LASIK (9)	Authors' variation	NA	0.42	-0.63 to +0.75
Latkany et al ¹⁰	LASIK (21)	Historical K – cornea	>.05	1.76	-5.72 to +1.79
		Historical K – specs	>.05	1.59	-4.28 to +3.38
		Vertex	>.05	1.95	-1.78 to +5.42
		Back calculated	>.05	1.51	-1.56 to +1.13
		Average K	.009	2.36	-9.46 to +2.17
		Flat keratometry	.004	2.19	-8.57 to +1.33
		Gelender ⁸	LASIK (17)	Author's variation	NA
Masket & Masket ⁹	LASIK (30)	Authors' variation	NA	0.29	-0.75 to +0.50
Packer et al ¹¹	RK, CK, HK (20)	Authors' variation	NA	0.62	-1.49 to +1.03
		Authors' variation	NA	0.51	NA
		Authors' variation	NA	0.44	NA
		Authors' variation	NA	1.10	NA
Randleman et al ¹²	LASIK (10)	Authors' variation	NA	1.54	-2.25 to +2.25
		Manual K	NA	1.91	NA
		Refractive history	NA	2.01	NA
		Contact lens	NA	1.68	NA
		Videokeratography	NA	1.68	NA

RK = radial keratotomy, CK = conductive keratoplasty, HK = hexagonal keratotomy, LTK = laser thermal keratoplasty, NA = not available
 *Values in these columns can be compared to those listed in columns 3 and 4 of Table 1.

the methods. The standard deviations vary from 0.29 to 2.36 D in these studies, but the number of patients is small. Masket and Masket's study⁹ with 30 LASIK eyes, in which all of the perioperative data were known, yielded the lowest error on LASIK patients of 0.29 D followed by Walter et al¹³ of 0.42 D.

Our study confirms that when accurate perioperative refractive data are available, the historical method should always be calculated. In the absence of any corneal refractive surgery data, or when crystalline lens changes are present confounding the exact source of the refractive change, the directly measured EKR value provides an alternative method measuring the central corneal power prior to cataract surgery following refractive surgery. With a standard deviation of ± 0.94 D in the test group of RK eyes, targeting for plano would result in 67% within this tolerance and twice this value (± 1.88 D) for 95%; 5% of eyes would be more than 1.88 D from the target.

Patients with prior refractive surgery undergoing cataract surgery must be counseled regarding the risk of a secondary procedure to fine tune the IOL power, if an

intolerable refractive surprise occurs. Also, targeting for a mild amount of myopia (approximately -0.50 to -1.00 D) reduces the chance of a hyperopic surprise, which is much less desirable than an equal amount of myopia.

AUTHOR CONTRIBUTIONS

Study concept and design (J.T.H., W.E.H.); data collection (J.T.H., W.E.H.); interpretation and analysis of data (J.T.H., W.E.H., A.S.); drafting of the manuscript (J.T.H., W.E.H.); critical revision of the manuscript (J.T.H., W.E.H., A.S.); statistical expertise (J.T.H.)

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