Intraocular lens calculations status after corneal refractive surgery

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With the increasing number of keratorefractive surgical procedures, an increasing number of cataract surgeries in eyes after keratorefractive surgery is anticipated within a few decades. Although cataract extraction seems to be feasible without major technical obstacles, intraocular lens (IOL) power calculation turned out to be problematic. Insertion of the measured average K-readings (= "central corneal power" = keratometric diopters) after myopic radial keratotomy (RK), photorefractive keratectomy (PRK), or laser in situ keratomileusis (LASIK) into standard IOL power-predictive formulas commonly results in substantial undercorrection and postoperative hyperopic refraction or anisometropia. In this article, the major reasons for IOL power miscalculations (which are different for RK versus RRK/LASIK) are discussed based on model calculations and based on case series of cataract surgeries, methods for improved assessment of keratometric diopters as the major underlying problem are exemplary illustrated, and finally a clinical step-by-step approach to minimize IOL power miscalculations status after corneal refractive surgery is suggested. The "clinical history method" (*i.e.,* subtraction of the spherical equivalent [SEQ] change after refractive surgery from the original K-reading) should be applied whenever refraction and K-reading before the keratorefractive procedure are available to cataract surgeons. In addition, more than one modern third-generation formula (*e.g.,* Haigis, Hoffer Q, Holladay 2, or SRK/T) but not a regression formula (*e.g.,* SRK I or SRK II) should be applied and the highest resulting IOL power should be used for the implant. Curr Opin Ophthalmol 2000, 11:35–46

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Abbreviations

ACP	average central power
ELP	effective lens position
IOL	intraocular lens
LASIK	laser in situ keratomileusis
$Power_{ant}$	keratometric diopters of the anterior surface
PRK	photorefractive keratectomy
RK	radial keratotomy
SEQ	spherical equivalent
Sim-K	simulated keratometry value
SRK	Sounders-Retzlaff-Kraff
SRK/T	Sounders-Retzlaff-Kraff theoretical
TMS	topographic modeling system

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Patients who had refractive corneal surgery in the third or fourth decade of their lives and develop a cataract a few decades later expect excellent uncorrected visual acuity after cataract surgery just like after their previous radial keratotomy (RK), photorefractive keratectomy (PRK), or laser in situ keratomileusis (LASIK). Experience with eyes after RK that has been performed for a much longer period of time than PRK or even LASIK indicate that the insertion of the average keratometric readings into standard intraocular lens (IOL) power-predictive formulas commonly results in substantial undercorrection, predominantly in the early course after cataract surgery [1–4]. Refraction after cataract surgery following PRK may range from +0.25 D to +3.25 D of hyperopia despite aiming for emmetropia [5,6]. Hyperopic postoperative refraction or intolerable anisometropia may prompt disappointed patients to ask for a second intervention to remove and replace the lens implant. Awareness of this potential problem is the first step in preventing a surprise refractive result [7•].

Because the number of keratorefractive surgical procedures is expected to increase, an increasing number of cataract surgeries in eyes after keratorefractive surgery is anticipated. Therefore, timely development and testing of refined methods for accurate IOL power prediction after different types of refractive surgery is necessary [8]. Besides altered biomechanical behavior of the cornea, the problem may be caused by difficulties in measuring the axial length, difficulties in determining the average keratometric diopters, or the inaccuracy of certain IOL power formulas. No evidence shows that axial length measurement should be inaccurate after refractive surgery [9•,10•]. Thus, one may assume that the major problem lies in the difficulty to correctly determine the keratometric diopters to be entered into the IOL power calculation formulas. According to the American National Standards Institute (ANSI) and the recommendations of Roberts, the term corneal power ("average K") should no longer be used, and the term keratometric diopters be used to avoid confusion with optical diopters [11,12].

This article (1) assesses the validity of standard IOL power calculation after RK, PRK, and LASIK based on model calculations and published case series of cataract surgeries, (2) discusses the major reasons for IOL power miscalculations and emphasizes differences between RK and PRK/LASIK, and (3) illustrates potential methods (including a clinical step-by-step approach) for improvement of IOL power prediction after keratorefractive surgery.

Methods to assess keratometric diopters

Keratometry

Manual

Manual keratometry is the method on which IOL power calculation formulas were originally based. Keratometry evaluates only four points on two orthogonal meridians separated 3 mm to 4 mm on the paracentral cornea. This distance increases as corneal curvature decreases [2]. The corneal optics are assumed to be spherocylindrical. Thus, asphericity or asymmetry of corneal shape cannot be measured with standard keratometry. Manual keratometry probably represents the least accurate method because current instruments (*e.g.*, the Zeiss [Jena, Germany] and the Bausch & Lomb [Rochester, NY, USA] keratometers) make too many assumptions for corneas that have irregular astigmatism. Nevertheless, examiners can see the reflected mires and the amount of irregularity present. Seeing the mires does not help to get better measurements but allows observers to discount the measurement as unreliable [13].

Automated

In principle, automated keratometry is a simple keratometric technique that seems to be as accurate as but with less variability than manual keratometry in determining keratometric diopters for cataract surgery [14]. Automated keratometers may be more accurate than manual keratometers in corneas with small optical zones after RK (*i.e.*, < 3 mm) because they sample a smaller central area of the cornea (nominally 2.6 mm). The smaller the optical zone and the greater the number of RK incisions, the greater the probability and magnitude of error. This error occurs because the samples at 2.6 mm are close to the paracentral transition zone ("knee") after RK. After PRK or LASIK, automated keratometers accurately measure the front radius of the cornea because the transition areas are far outside the 2.6 mm-zone that is measured, but the derivation of keratometric diopters from radius of curvature is still incorrect.

Topography analysis

Videokeratography-derived keratometry-style readings

Using the Topographic Modeling System (TMS), the simulated keratometry value (Sim-K) is determined from the power of Placido mires 7, 8, and 9 of the videokeratoscope for 128 equally spaced meridians [15]. Measuring more than 5000 points over the entire cornea and more than 1000 points within the central 3 mm, topography analysis provides greater accuracy in determining the "power" of corneas with irregular astigmatism compared with keratometers, but the readership must be warned that Sim-K value derivation may vary among different topography units, and these values should be compared with the results of the keratometry unit individually applied before using them interchangeably.

Average central power

Maeda and Klyce [16] determined a new parameter, average central power (ACP), from the average of corneal powers inside of the region demarcated by the entrance pupil of the TMS-1 topography unit. Because the density of measured points with the videokeratoscope is highest in the central cornea and decreases toward the periphery, area-corrected "power" was used for compensation. This modified method is supposed to have major advantages over the classic Sim-K after RK with small optical zones, but not after PRK and LASIK.

Other similar values are provided by other topographic units. For example, the EyeSys unit (Premier Laser Systems; Irvine, CA, USA) has a display called the Holladay Diagnostic Summary, in which an analogous value, called the effective refractive power, is calculated [9•,17].

Pancorneal slit scanning topography

Using the Orbscan scanning slit-beam system (Orbtek; Salt Lake City, UT, USA), a three-dimensional location of several thousand points of the corneal and anterior chamber surfaces can be determined. Two scanning slit lamps project 40 calibrated beams onto the eye, angled at 45° to the left and to the right of the video camera axis, covering the whole cornea from limbus to limbus and overlapping in the central 5-mm zone. This system has the potential to provide topographic height and power maps of the anterior and posterior corneal surface and a corneal thickness profile, allowing a direct correlation of pachymetry and height data [18].

The accuracy of the Orbscan unit for posterior corneal curvature measurements has not been fully validated, but measuring the accuracy of an instrument on posterior curvature is not possible because the shape of these surfaces cannot be referenced. Discussions with authorities in this field revealed that, for many years, attempts failed to produce a "plastic anterior eye segment with realistic refractive indices and a well-defined posterior corneal curvature" to assess the validity of the Orbscan unit, but repeating the measurement of posterior keratometric diopters three times revealed a reliability coefficient of 0.96 (Cronbach's α), indicating at least a high reproducibility (*i.e.*, low test-retest variability) of this type of measurement [Seitz B *et al.*, Unpublished Data].

Model calculations after photorefractive keratectomy

In 31 eyes PRK for myopia (–1.5 to –8.0 D; mean, –5.4 ± 1.9 D) had been performed with the Meditec 193-nm

Table 1. Model calculations of keratometric diopters before and after PRK (–1.5 D to –8.0 D) [19••]

Keratometric diopters (D)	Keratometry (K) (Ophthalmometer H, Zeiss, Jena, Germany)	Simulated keratometry (Sim-K) (TMS-1, Tomey, Waltham, MA, USA)	Average central power (ACP) (TMS-1, Tomey, Waltham, MA, USA)
Preoperative	43.4 ± 1.0; 41.5 to 45.5	44.5 ± 1.0; 42.6 to 47.1	44.8 ± 1.1; 42.7 to 47.5
Postoperative measured	40.3 ± 1.4; 36.6 to 43.0	41.3 ± 1.5; 36.8 to 44.2	41.4 ± 1.5; 36.9 to 44.6
Postoperative calculated			
ΔPower of the anterior corneal surface*	39.9 ± 1.5; 35.6 to 42.7	40.9 ± 1.6; 35.6 to 44.0	41.1 ± 1.7; 35.8 to 44.5
ΔSEQ at the corneal plane†	39.2 ± 1.7; 35.9 to 42.2	40.3 ± 1.8; 36.6 to 44.1	40.6 ± 1.8; 37.1 to 44.6
ΔSEQ at the spectacle plane‡	38.9 ± 1.9; 34.9 to 42.1	39.9 ± 2.0; 35.6 to 43.7	40.2 ± 2.0; 36.1 to 44.1

*Calculated postoperative keratometric diopters according to the pre- to postoperative change of keratometric diopters of the anterior corneal surface (refractive index n = 1.376).
†Calculated postoperative keratometric diopters according to the pre- to postoperative spherical equivalent (SEQ) change corrected for vertex distance of 14 mm (*i.e.,* at the corneal plane).
‡Calculated postoperative keratometric diopters according to the pre- to postoperative spherical equivalent (SEQ) change without correction for vertex distance (*i.e.,* at the spectacle plane).

excimer laser (Zeiss; Jena, Germany) using a scanning slit mode. The optical zone ranged from 5.0 mm to 6.0 mm. After a mean follow-up of 16 months, ultrasonic biometry was performed in all patients with clear crystalline lenses to determine ultrasonic anterior chamber depth, lens thickness, and total length of the eye. Two different formulas (*i.e.,* SRK/T and Haigis) were used to calculate the power of a standard polymethylmetacrylate (PMMA) IOL for emmetropia using the measured and three types of calculated keratometric diopters. Theoretic postoperative ametropia after fictitious IOL implantation was calculated by entering the calculated keratometric diopters into the formulas but presetting the respective emmetropic IOL power values for *measured* keratometric diopters [19••].

Preoperatively and postoperatively, keratometric diopters as assessed by the Zeiss keratometer were significantly (≈ 1.0 D) smaller than keratometric diopters as assessed by TMS-1 topography analysis ($P < 0.001$; Table 1). No significant difference was found comparing Sim-K and ACP values of the topography system before and after PRK. After PRK, mean measured keratometric diopters were significantly greater (absolute difference, 0.4 D) than respective calculated values considering the preoperative to postoperative change of the anterior corneal surface ($P < 0.001$), which was significantly greater (absolute difference, 0.6–0.7 D) than calculated keratometric diopters considering the preoperative to postoperative SEQ change at the corneal plane ($P < 0.001$). The smallest keratometric diopters (absolute difference, 0.3–0.4 D) were achieved considering the preoperative to postoperative SEQ change at the spectacle plane ($P <$ 0.001; Table 1).

For both formulas, IOL power values using keratometer readings were significantly higher (more than 1 D) than IOL power values using topography analysis readings ($P < 0.001$). Overall, the Haigis formula resulted in somewhat greater IOL power values compared with the SRK/T formula, but the mean difference ranged at approximately 0.5 D, which was not found to be statistically significant. On average, the theoretically induced ametropia after fictitious IOL implantation may reach +1.0 D (maximum, +2.3 D) at the corneal plane and up to +1.4 D (maximum, +3.1 D) at the spectacle plane using the keratometer [19••]. Overestimation of keratometric diopters and underestimation of IOL power correlated significantly with the difference between the preoperative and postoperative SEQ (P = 0.001) and with the intended depth of PRK ablation (P = 0.004; Figs. 1 and 2).

Case reports of real cataract surgery after radial keratotomy, photorefractive keratectomy, and laser *in situ* keratomileusis

Despite hundreds of thousands of keratorefractive surgeries performed during the past few decades, only lim-

Figure 1. Correlation of the difference between calculated ("clinical history method") and measured keratometric diopters with the SEQ change after PRK (–1.5 to –8.0 D; R = 0.58, P = 0.001, N = 31)

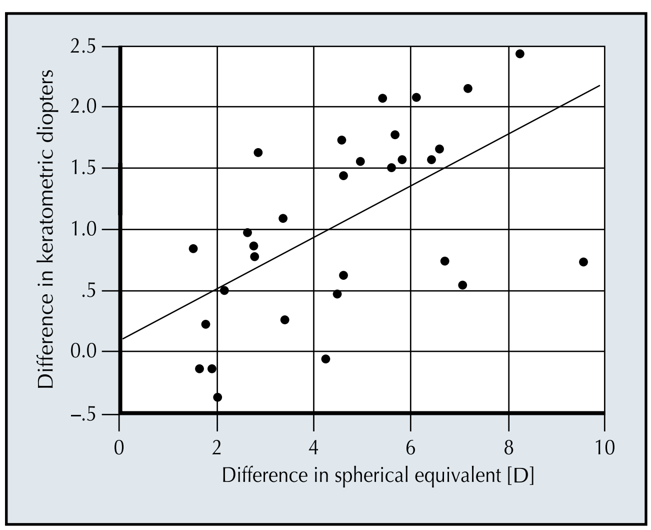
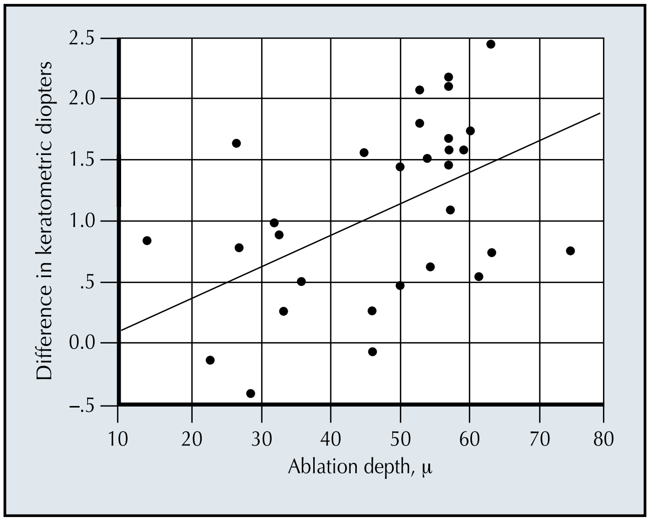


Figure 2. Correlation of the difference between calculated ("clinical history method") and measured keratometric diopters with the intended depth of ablation during previous PRK (–1.5 to –8.0 D, *R* = 0.51, *P* = 0.004, *N* = 31)



ited information about the results of cataract surgery status after corneal refractive surgery is available in the literature. Table 2 chronologically summarizes the outcome of these procedures and the main suggestions of the authors in terms of how to improve the IOL power prediction. All authors, with the exception of Gelender [20], who left the eye aphakic after extracapsular cataract extraction, agree that no major technical obstacles exist to phacoemulsification and IOL implantation after keratorefractive surgery. With the exception of articles by Lesher *et al.* [5] and Casebeer *et al.* [21], however, all investigators also agree that the use of the measured manual keratometry reading after RK or PRK/LASIK is inappropriate because it is most likely to leave patients hyperopic.

Earlier articles give quite exceptional recommendations (*e.g.*, using the 2-week K-reading after PRK [22] or using the current average K minus 1 D and averaging the results of Binkhorst and Holladay formulas, aiming for –0.75 D after RK [4]), but the newer publications converge to a simpler recommendation: Use refraction-derived K-reading at some stable time point after refrac-

Table 2. Published case reports (series) of real cataract surgery after keratorefractive surgery

First author	Year	Eyes, #	Refraction before refractive surgery (D)	Resulting ametropia (D) and VA	Suggestion for improved IOL power prediction; comments
Gelender [20]	1983	1	–2.50, 8-cut RK	+9.75, 20/20	No IOL implanted; soft contact lens correction
Markovits [1]	1986	1	–10.75, 32-cut RK	+0.25, 20/20	"IOL overplusing of 3 D"; very poor VA for 3 months
Koch [2]	1989	4	–12.5 to –1.6, 4- to 12-cut RK	+0.25 to +5.9, 20/20 to 20/15	Refraction-derived K + Holladay formula (not SRK II); flattening of the cornea by 1 to 6 D immediately after surgery, regressing partially over the next 1 to 3 months
Casebeer [21]	1993	1	n.a., T-hex	n.a.	"Preoperative workup did not require modification."
Lesher [5]	1994	1	–6.0, PRK	+0.5, n.a.	"Standard IOL calculation (automated K, SRK/T) successful."
Celikkol [3]	1995	4	–8.75 to –5.38, 8- to 10-cut RK	–0.50 to +2.75, 20/30 to 20/20	Mean power of ring 3 of TMS-1 topography system as K + Holladay formula; hard contact lens method unreliable
Siganos [22]	1996	1	–0.8, PRK	+3.4, 20/25	K-reading 2 weeks after PRK; do not apply SRK II
Lyle [4]	1997	10	–11.13 to –2.50 6- to 16-cut RK	–1.12 to +3.5, 20/50 to 20/20	Adjusted K (*i.e.,* current average K minus 1.0 D) + average Binkhorst and Holladay (not SRK II) aiming for –0.75 D
Kalski [6]	1997	4	–14.0 to –11.13, PRK	+0.25 to +3.25 n.a.	Refraction-derived K at the corneal plane + SRK/T or refraction-derived K at the spectacle plane + Holladay or SRK II
Bardocci [9•]	1998	1	n.a., 8-cut RK	+1.25, 20/20	"Effective Refractive Power" of Holladay's Diagnostic Summary (EyeSys) + SRK/T formula resulted in 2.5 D prediction error
Morris [10•]	1998	1	–7.0, PRK	+3.5, 20/30	Refraction-derived K + highest IOL power of Hoffer Q, Holladay, SRK/T; role of videokeratography unclear!
Speicher [23•]	1999	1	–18.0, decentered PRK	+4.0, 20/40	Refraction-derived K + third-generation formula (not SRK II)
Amm [24]	1999	1	–16.5, decentered LASIK	–3.1, n.a.	Refraction-derived K + third-generation formula (not SRK II)

D, diopters; RK, radial keratotomy; PRK, photorefractive keratectomy; LASIK, laser *in situ* keratomileusis; n.a., not available; VA, visual acuity; K, keratometric diopters.

tive surgery before index myopia occurs from a nuclear cataract and a modern third-generation IOL power prediction formula but not a regression formula. The situation is much more difficult in cases of prerefractive surgery keratometry and refraction being unavailable to cataract surgeons [6,9•,10•,23•,24].

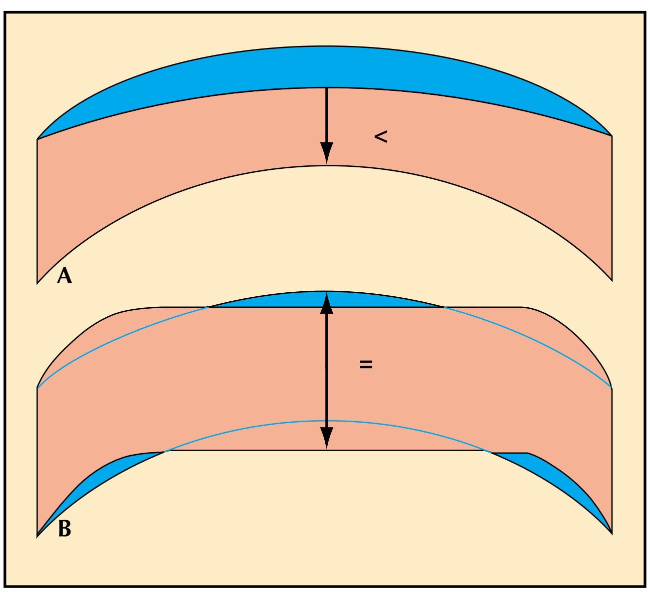
Reasons for intraocular lens power miscalculations

Principal approaches in refractive corneal surgery

During excimer laser PRK, selective removal of tissue across the anterior corneal surface results in a change of the anterior corneal curvature [25]. Although the central anterior surface of the cornea may become flatter (to treat myopia) or steeper (to treat hyperopia), the posterior surface is supposed to remain almost unchanged in uncomplicated cases (Fig. 3*A*), and the irregular astigmatism in the central 3-mm zone is usually minimal [26]. The same may be true for uncomplicated LASIK, in which direct flattening or steepening of the central anterior corneal surface is achieved by focal keratectomies under a plano hinged flap.

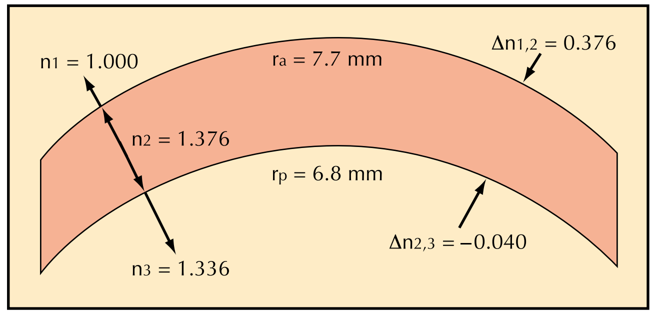
To correct myopia with RK, deep, radially orientated knife incisions are applied in the midperiphery of the cornea to induce midperipheral bulging of the cornea [27]. Indirectly, the central cornea becomes flatter. Because no tissue is removed, one may assume that the anterior and posterior surface of the cornea react in an analogous way [28–30] (Fig. 3*B*). While after PRK/LASIK the ratio between anterior and posterior curvature may increase markedly and the central corneal thickness decreases, this ratio and corneal thickness remains nearly unchanged after uncomplicated RK.

Figure 3. Changes of anterior and posterior corneal curvature after PRK/LASIK versus RK



A, Direct change of the central anterior corneal curvature after PRK/LASIK. Although the central anterior surface of the cornea becomes flatter, the posterior surface is supposed to remain almost unchanged. **B**, Indirect change of the central anterior corneal curvature after RK. Because no tissue is removed, the anterior and posterior surfaces of the cornea are assumed to react in an analogous way.

Figure 4. Refractive indices and curvature of the normal human cornea



Typically, the air/anterior surface interface *in vivo* (Δn = 0.376; r = 7.7 mm) effects positive keratometric diopters of approximately 49 D, and the posterior surface/aqueous humor interface (Δn = −0.04 = 1.336 − 1.376; r = 6.8 mm) effects negative keratometric diopters of approximately 6 D.

Determination of keratometric diopters

The main reason for underestimation of IOL power after keratorefractive surgery (*e.g.*, RK, PRK, and LASIK) lies in the inaccurate determination of keratometric diopters. Inaccurate determination of keratometric diopters has two major reasons: The first reason results from "irregularities" of the (para-) central anterior corneal surface, making the measurement of the anterior radius of curvature inaccurate. The second reason results from system-inherent inadequate calculation of keratometric diopters from correctly measured anterior radius of curvature values by keratometers and topographers. While the first reason applies primarily to eyes after RK (especially with small or decentered optical zones), the second reason applies primarily to eyes after PRK/LASIK.

Typically, the air/anterior surface interface *in vivo* (Δn = 0.376; r = 7.7 mm) effects positive keratometric diopters of approximately 49 D, and the posterior surface/aqueous humor interface (Δn = –0.04 = 1.336 – 1.376; r = 6.8 mm) effects negative keratometric diopters of approximately 6 D (Fig. 4). With keratometers and topography analysis systems currently in use, primarily the radius of curvature of the anterior surface of the (para-) central cornea is measured. The keratometric diopters are derived from radius of curvature using an "effective" refractive index *n* in a paraxial formula (Keratometric diopters [D] = (n – 1) / Radius of curvature [m]). "Effective" refractive indices of 1.3313 (*e.g.*, Zeiss keratometer, Haigis formula), 4/3 (*e.g.*, Holladay, SRK/T formula), 1.336 (*e.g.*, Hoffer formula), or 1.3375 (*e.g.*, Javal keratometer, TMS-1 topographer) have been used. Based on Gullstrand's model eye, such an effective refractive index characterizes the refraction of a fictitious single refractive lens representing the anterior and the posterior surface of the cornea [31–33••].

However, this "effective" refractive index is valid only as long as the proportion between radius of anterior and posterior surface of the cornea resembles that of the model eye. Because the distance between both refracting surfaces is reduced after PRK/LASIK, whereas the radius of the anterior surface is considerably increased, this historic method of calculating keratometric diopters from anterior radius of curvature becomes insufficient after PRK/LASIK [31–33••], which explains why the overestimation of keratometric diopters (and underestimation of IOL power) correlates significantly with the intended depth of ablation after myopic PRK [19••]. Although the application of an "effective" refractive index is the major reason for the inaccurate prediction of keratometric diopters, change of the asphericity from a prolate to an oblate shape in the optical zone after myopic PRK/LASIK (especially after procedures involving small optical zones); inadvertent multifocal power distribution, as in the case of "central islands"; or decentered treatment zones may result in an additional mismeasurement of the anterior radius of curvature.

After RK, the popular method of corneal power calculation using an "effective" refractive index usually gives fairly accurate long-term results, especially for optical zones of 4 mm and larger. After RK, mismeasurement of the anterior radius of curvature is the main reason for inadequate prediction of keratometric diopters [33••], perhaps because of the location of the keratometry mires (≈ 3 mm apart from each other). The area of the paracentral "knee" results in a measurement that is too steep. Because the entire cornea is flatter and the keratometry mires are located more peripherally, the keratometer measures an even more peripheral portion of the cornea, which further magnifies the difference between the K-reading and the central corneal curvature [2]. Thus, in RKs with optical zones of less than 3 mm, the accuracy of the predicted keratometric diopters is supposed to diminish [13]. The hyperopic shift as high as +4.00 D to +6.00 D and diurnal fluctuations in the early phase after cataract extraction in the RK eye most likely depend on mechanical instability allowing transient corneal swelling or even wound gaping to induce a pronounced but temporary central corneal flattening [2]. While these early effects after RK are supposed to be almost completely reversible, the systematic miscalculation of keratometric diopters after uncomplicated PRK/LASIK, in which mechanical stability of the cornea is not significantly decreased, may induce a persisting hyperopic ametropia after cataract extraction and IOL implantation.

Keratometers versus topography analysis systems

In a variety of clinical situations, keratometry may provide incomplete or misleading information. The use of videokeratography-derived K-values has been suggested to be superior to standard keratometry for determination of IOL power in eyes with abnormal or surgically altered corneal surfaces, *e.g.,* in eyes with keratoconus, in eyes with other types of irregular corneal astigmatism, and after RK [3,34–37]. Typically, excellent keratometry mires can be acquired after PRK/LASIK. Thus, corneal topography analysis does not seem to be necessary to get satisfactory information on corneal curvature after PRK/LASIK. In addition, keratometric diopters, as assessed by topography analysis, may be significantly greater than the respective value as assessed by a keratometer, resulting in increased IOL power underestimation, especially after PRK for high myopia [6,19••].

Seitz *et al.* [19••] found that before and after PRK, keratometric diopters as measured by the Zeiss keratometer were significantly smaller than those as measured by the TMS-1. The mean difference was approximately 1 D, depending on the absolute value. Strong evidence from several studies on test surfaces and human corneas indicates an inherent tendency of videokeratographs to measure steeper than keratometers. Hannush *et al.* [38] found that the Bausch & Lomb keratometers generally read lower values, and the CMS (the precursor model of the TMS-1), higher values than calibrated steel spheres. These findings are well in keeping with experiences in eyes after penetrating keratoplasty in studies by Seitz *et al.* [39•] and Karabatsas *et al.* [40], in which the Zeiss keratometer typically measured keratometric diopters and corneal astigmatism approximately 1 D on average smaller than the TMS-1 topographer. A minor aspect concerning this problem may be the different "effective" refractive indices used by different devices as discussed earlier. Obviously, topography analysis reflects the manifest refractive change after PRK without a major error only when the "real" corneal refractive index of 1.376 is used with a parameter assessing the "effective refractive power" over the pupil [17,41].

Nevertheless, topography analysis using ACP seems to be useful after RK with small optical zones [13]. Even more reliable values may be achieved by recording and averaging the central power at multiple (para-) central points using the cursor of the topography system. If surgeons use keratometry (instead of topography analysis) as a routine for their IOL power calculation formulas, they must be aware of the relative level (*i.e.,* systematic error) of the keratometry and topography units they use.

Intraocular lens power prediction formulas

Calculation of IOL power in cataract surgery is based on measurements of "corneal power"or radius of curvature; axial length; and estimation of postoperative anterior chamber depth, which has been termed effective lens position (ELP) more recently [42]. Several formulas are used to calculate IOL power. They can be classified as empiric regression formulas (most popular is the Sanders-Retzlaff-Kraff formula) with (*e.g.*, the SRK/T) or without (*e.g.*, the SRK I and II) the inclusion of additional terms accounting for nonlinearity [43,44] or theoretic optical formulas (*e.g.*, those of Haigis, Holladay, or Hoffer) [45–47].

Five variables exist in such a formula: (1) the IOL power, which is generally chosen as the dependent variable; (2) the keratometric diopters ("average K"), which is the most crucial variable after refractive corneal surgery; (3) the axial length, which is measured by A-scan sonography or by optical means; (4) the ELP; and (5) the target refraction, which typically ranges between −2 D and 0 D. The calculation of the resulting spectacle correction for a given IOL is typically based on a vertex distance of 12 mm or 14 mm. The only variable that cannot be measured preoperatively is ELP. The improvements in IOL power calculations over the past 30 years are mainly a result of improving the predictability of ELP [42,48] by additional measurement of horizontal white-to-white corneal diameter, preoperative anterior chamber depth, and lens thickness because the anterior segment dimensions often are not proportional to the axial length [49,50].

The prediction error of the third-generation formulas (*e.g.*, the Haigis [45], Holladay [46], Hoffer Q [47], and the SRK/T formulas [43,44]) was found to be largely unaffected by variations in axial length and keratometric diopters [48,51–53], but Bardoccio and Lofoco [9•] reported that the Hoffer Q formula resulted in approximately 1 D higher IOL power than the SRK/T formula in a myopic eye after RK. In contrast, the empiric SRK I and II formulas were less predictive in long and short eyes because they make too many assumptions in terms of a "normal eye morphology," so that they are inaccurate in long or short eyes or in flat or steep corneas. Implant power prediction errors increase when a flat cornea is paired with an axial myopic eye, *e.g.*, after PRK/LASIK [48,51–53].

Future developments

Experience shows that patients may ask for cataract surgery in centers other than those where the refractive procedure was performed. Thus, the preoperative K-reading and the exact amount of refractive correction may not be available. For these patients, surgeons might take into account the keratometric diopters of the anterior and posterior corneal curvature separately after PRK/LASIK, which can be achieved by means of slit scanning topography [18,54]. Nevertheless, refractive surgeons might consider giving their patients a wallet card indicating their preoperative keratometric reading, preoperative refraction, and postoperative refraction at some stable time point (*e.g.*, after 6 months) to allow for the application of the "clinical history method" [55–57].

An additional approach to adjust K-readings after PRK/LASIK (if no data on the status of the eye before refractive surgery are available) is to apply multiple regression analysis comparing the corrected keratometric diopters to the measured values and to the SEQ change in many cases. Thus, correction of keratometric diopters after PRK/LASIK may be realized by entering the measured value into an empiric quadratic regression formula [58]. Certainly, such a theoretic approach must be refined after data from more actually performed cataract operations become available. In cases of inaccurate or difficult preoperative ultrasound biometry, IOL power may be estimated after intraoperative retinoscopy in aphakic, highly myopic eyes [59].

No definite statement can be made concerning IOL power calculation in patients with intracorneal rings, but reversing the keratorefractive effect by timely removal of the ring before assessment of keratometric diopters might be a valid option, especially in face of the multiple reports about "complete" reversibility of the refractive effect after ring removal.

One case report suggests that IOL power calculation after hexagonal keratotomy, which may result in disastrous complications and is widely abandoned today [60], does not require a modified workup [21]. No publications on IOL power calculations after hyperopic PRK or LASIK exist, but one may hypothesize that the "clinical history" method overcomes this problem.

Examples of methods for improved assessment of keratometric diopters

For the subsequent examples illustrating different methods of assessment of keratometric diopters, the following measurements are given:

1) Preoperative measured K: 42.00 D at 0° and 44.00 D at 90° → mean preoperative K: 43.00 D
2) Preoperative refraction (at the spectacle plane): −8.00 D − 1.0 D × 0°
3) Intended PRK correction: −8.00 D spherical
4) Postoperative measured K: 36.50 D at 0° and 37.50 D at 90° → mean postoperative K: 37.00 D
5) Postoperative measured radius of anterior curvature: 9.08 mm at 0° and 8.83 mm at 90°
6) Postoperative refraction (at the spectacle plane): 0.00 D − 1.0 D × 0°

Clinical history methods

Spherical equivalent change

The SEQ change method was first published for eyes after RK by Guyton [55] and Holladay [56] in 1989 and later termed the clinical history method by Hoffer [57]. It involves subtracting the SEQ change induced by the refractive procedure from the keratometric diopters measured before refractive surgery. The stabilized refraction after the refractive surgical procedure must be measured before any myopic shift from nuclear sclerotic cataracts has occurred. The SEQ change may be calculated at the corneal plane with—which is theoretically correct—or at the spectacle plane without correction for vertex distance (14 mm).

Spherical equivalent change at the spectacle plane

The preoperative to postoperative SEQ change at the spectacle plane (ΔSEQ_{sp}) is subtracted from the mean preoperative K-reading [2]. This method results in the lowest K-reading compared with all of the other methods shown.

Step 1:

Calculate the SEQ at the spectacle plane (SEQ_{sp}) preoperatively and postoperatively.

$$SEQ_{sp} = \text{sphere} - (0.5 \cdot \text{cylinder})$$

Preoperative $SEQ_{sp} = -8.00\ D - (0.5 \cdot 1.00\ D) = -8.50\ D$

Postoperative $SEQ_{sp} = 0.00\ D - (0.5 \cdot 1.00\ D) = -0.50\ D$

Step 2:

Calculate of the change in refraction at the spectacle plane.

ΔSEQ_{sp} = Postoperative SEQ_{sp} – Preoperative SEQ_{sp}

$\Delta SEQ_{sp} = -0.50\ D - (-8.50\ D) = 8.00\ D$

Step 3:

Calculate the corrected postoperative keratometric diopters at the spectacle plane.

Mean postoperative K = Mean preoperative K – ΔSEQ_{sp}

Mean postoperative K = 43.00 D – 8.00 D = **35.00 D**

Spherical equivalent change at the corneal plane

The preoperative to postoperative SEQ refraction change at the corneal plane (ΔSEQ_{co}) is subtracted from the mean preoperative K-reading.

Step 1:

Calculate the SEQ at the corneal plane (SEQ_{co}) preoperatively and postoperatively.

$$SEQ_{co} = SEQ_{sp} / [1 - (0.014 \cdot SEQ_{sp})]$$

Preoperative SEQ:

$SEQ_{co} = -8.50\ D / [1 - (0.014 \cdot (-8.50\ D)] = -7.60\ D$

Postoperative SEQ:

$SEQ_{co} = -0.50\ D / [1 - (0.014 \cdot (-0.50\ D)] = -0.49\ D$

Step 2:

Calculate of the change in refraction at the corneal plane.

ΔSEQ_{co} = Postoperative SEQ_{co} – Preoperative SEQ_{co}

$\Delta SEQ_{co} = -0.49\ D - (-7.60\ D) = 7.11\ D$

Step 3:

Calculate the corrected postoperative keratometric diopters at the corneal plane.

Mean postoperative K = Mean preoperative K – ΔSEQ_{co}

Mean postoperative K = 43.00 D – 7.11 D = **35.89 D**

Change in anterior surface K readings

The preoperative to postoperative change of keratometric diopters of the anterior corneal surface is subtracted from the mean preoperative K-reading. The keratometric index *n*, which must be accounted for with this method, varies between devices (*e.g.*, 1.3313 for Zeiss keratometer, 1.3375 for Javal keratometer or TMS-1 topographer) [19].

Step 1:

Calculate the keratometric diopters of the anterior surface ($Power_{ant}$) preoperative and postoperatively.

$$Power_{ant} = \text{Measured keratometric diopters} \cdot [(1.376 - 1.000) / (n - 1.000)] = \text{Measured keratometric diopters} \cdot 1.135 \text{ (for } n = 1.3313)$$

Preoperative $Power_{ant} = 43.00\ D \cdot 1.135 = 48.81\ D$

Postoperative $Power_{ant} = 37.00\ D \cdot 1.135 = 42.00\ D$

Step 2:

Calculate the change in anterior surface keratometric diopters.

$\Delta Power_{ant}$ = Preoperative $Power_{ant}$ – Postoperative $Power_{ant}$

$\Delta Power_{ant} = 48.81\ D - 42.00\ D = 6.81\ D$

Step 3:

Calculate the corrected postoperative keratometric diopters.

$$\text{Mean postoperative K} = \text{Mean preoperative K} - \Delta\text{Power}_{ant}$$

$$\text{Mean postoperative K} = 43.00\ \text{D} - 6.81\ \text{D} = \mathbf{36.19\ D}$$

Hard contact lens method

The hard contact lens method determines the difference between the manifest postoperative refraction with and without a plano hard contact lens of known base curve and subtracts this difference from the base curve [56,57]. This method has been questioned in cataractous eyes after RK [3] and has not been validated for eyes after PRK/LASIK.

Step 1:

Determine the patient's refraction by trial lenses and calculate SEQ_{sp} without contact lens.

$$SEQ_{sp} = 0.00\ \text{D} - (0.5 \cdot 1.00\ \text{D}) = -0.50\ \text{D}$$

Step 2:

Place a plano hard contact lens with known base curve on the cornea and reassess the spherical refraction. If the SEQ does not change with the contact lens in place, the patient's cornea must have the same "power" as is indicated by the base curve of the contact lens. A hyperopic or myopic shift with the contact lens indicates that the cornea is stronger or weaker than the base curve of the contact lens.

Postoperative refraction with contact lens with a base curve of 8.7 mm (= 37.00 D) = −1.50 D.

Step 3:

Calculate the change in refraction.

$$\Delta SEQ = \text{Refractive shift} - \text{Postoperative SEQ}$$

$$\Delta SEQ = -1.50\ \text{D} - (-0.50\ \text{D}) = -1.00\ \text{D}$$

Step 4:

Calculate the postoperative mean keratometric diopters.

$$\text{Mean postoperative K} = \text{Base curve of contact lens} + \Delta SEQ$$

$$\text{Mean postoperative K} = 37.00\ \text{D} + (-1.00\ \text{D}) = \mathbf{36.00\ D}$$

Consideration of posterior corneal curvature

To accurately determine the total keratometric diopters of the cornea, the keratometric diopters of the anterior and the posterior surface of the cornea must be known. The contribution of central corneal thickness (Power_{ant} · Keratometric diopters of the posterior surface · Corneal thickness [m]) has been shown to be less than 0.1 D [61]. Thus, this term may be neglected for clinical purposes.

Consideration of posterior corneal curvature without actual measurement

The first step in this direction is to calculate the Power_{ant} from radius of curvature or measured keratometric diopters using the real refractive index of the cornea *in vivo* (n = 1.376) and add −5.9 D, which is the theoretic posterior surface "power" according to Gullstrand's model eye, or add −6.2 D, which has been found to be the "real" mean keratometric diopters of the human posterior surface *in vivo* as assessed by slit scanning topography technique [54]. In this study enrolling 263 normal participants, Seitz *et al.* [54] found neither a correlation with age nor a significant difference between female and male subjects, but this study disclosed a wide interindividual variability in posterior surface keratometric diopters ranging from −2.1 D to −8.5 D. Therefore, adding only the mean value of the posterior surface keratometric diopters to the anterior surface keratometric diopters may effect a considerable error in a given patient.

Step 1:

Calculate the Power_{ant} from postoperatively measured keratometric diopters. The keratometric index *n*, which must be accounted for with this method, varies between devices (*e.g.*, 1.3313 for Zeiss keratometer, 1.3375 for Javal keratometer or TMS-1 topographer).

$$\text{Power}_{ant} = \text{Measured keratometric diopters} \cdot [(1.376 - 1.000) / (n - 1.000)] = \text{Measured keratometric diopters} \cdot 1.135\ (\text{for } n = 1.3313)$$

$$\text{Postoperative Power}_{ant} = 37.00\ \text{D} \cdot 1.135 = 42.00\ \text{D}$$

or

Calculate the Power_{ant} from postoperatively measured radius of anterior curvature.

$$\text{Power}_{ant}\ [\text{D}] = [(1.376 - 1.000) / \text{Radius of curvature in steep meridian [m]} + (1.376 - 1.000) / \text{Radius of curvature in flat meridian [m]}] / 2$$

$$\text{Postoperative Power}_{ant}\ (0.376 / 0.00908 + 0.376 / 0.00883) / 2 = 42.00\ \text{D}$$

Step 2:

Add the keratometric diopters of the posterior surface to the $Power_{ant}$, neglecting the term accounting for corneal thickness.

Mean postoperative K = 42.00 D + (–5.9 D) = **36.10 D**

or

Mean postoperative K = 42.00 D + (–6.2 D) = **35.80 D**

Consideration of posterior corneal curvature with actual measurement

Modern slit scanning topography devices allow for the measurement of the posterior curvature of the cornea, thus potentially further improving accuracy.

Step 1:

Calculate power of the anterior surface from postoperatively measured corneal power.

$$Power_{ant} = 37.00\ D \cdot 1.135 = 42.00\ D$$

Step 2:

Measure the real *in vivo* posterior keratometric diopters of the cornea, *e.g.*, –6.31 D.

Step 3:

Add the keratometric diopters of the posterior surface to the $Power_{ant}$, neglecting the term accounting for corneal thickness.

Mean postoperative K = 42.00 D + (–6.31 D) = **35.69 D**

Clinical step-by-step approach

1) Ensure that patients have realistic expectations just like you do before every refractive surgery procedure.
2) Ensure that the refraction is stable (after refractive surgery and before cataract surgery).
3) Discuss the desired target refraction. Aiming for –1.0 D seems to be a good compromise. Trying to produce monovision in patients who have never experienced this condition may cause intolerable anisometropia and may require further surgery.
4) Perform corneal topography analysis in all patients to assess the amount of irregular astigmatism and asphericity.
5) If keratometric diopters and refraction before refractive surgery are well known, use the "clinical history method" considering the change of SEQ refraction at the corneal plane before cataract evolution after RK and PRK/LASIK. If those values are not known for sure, surgeons should use the respective calculations at the spectacle plane to "be on the safe (*i.e.*, myopic) side." Some experts in this field even recommend the use of the SEQ change at the spectacle plane as a routine and to add another one or two diopters to the resulting IOL power, being sure to avoid any potential undercorrection.
6) If keratometric diopters but not refraction before refractive surgery are known, use the change in anterior surface K-readings after PRK/LASIK.
7) If preoperative keratometric diopters and refraction are not known and the visual acuity is 20/80 or better, try the hard contact lens method after RK [13,57].
8) If preoperative keratometric diopters and refraction are not known and visual acuity is less than 20/80 or plano hard contact lenses are not available, use ACP or the average keratometric diopters at multiple (para-) central cursor points of the topography analysis after RK, but use refined calculation of keratometric diopters from radius of anterior and posterior corneal surface after PRK/LASIK.
9) Use more than one modern third-generation formula (*e.g.*, Hoffer Q, Holladay 2, SRK/T, or Haigis) but not a regression formula (*e.g.*, SRK I or SRK II) to calculate the IOL power and choose the highest value for the implant [10•,57].
10) The first days after cataract surgery following RK, patients may experience a significant hyperopic shift similar to the first postoperative days following their RK because of corneal edema. These patients may also exhibit diurnal fluctuations of refraction soon after cataract surgery. No lens exchange should be contemplated until the refraction has stabilized (*i.e.*, 1–3 months). To account for potentially occurring persistent long-term flattening, 0.5 D might be added to IOL after RK [2].
11) Following PRK and LASIK, early hyperopic shift or diurnal fluctuations are usually not present after cataract surgery. In most cases, the stability of the cornea makes these cases no different than patients who have had no previous keratorefractive surgery.

Conclusions

Major reasons for the underestimation of IOL power are different after RK versus PRK/LASIK. Conventionally measured keratometric diopters (also called K-reading, average K, and central corneal power) to be entered into IOL power calculation formulas have to be corrected to avoid hyperopia after cataract surgery with lens implantation. The "clinical history method" should be applied whenever refraction and keratometric diopters before the keratorefractive procedure are available to cataract surgeons after PRK and PRK/LASIK. If preoperative keratometric diopters and refraction are not known, ACP of topography analysis may be used after RK, but refined calculation of keratometric diopters from radius of anterior and posterior corneal surface should be used after PRK/LASIK. The results of more than one applicable method for correction of conventionally measured keratometric diopters should be compared, and the lowest most reliable K-reading should be used. In addition, more than one third-generation formula should be applied and the highest resulting IOL power should be used for the implant. In all instances, cataract surgeons must ensure that corrected keratometric diopters are not wrongly reconverted within the IOL power calculation formula used [33••].

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