65 IOL Power Calculation After Corneal Refractive Surgery

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Introduction

Central corneal curvature is a fundamental variable in the intraocular lens (IOL) power calculation process. Its modification by corneal refractive surgery (CRS) will affect both measurement accuracy and measurement performance within calculation formulas, leading to an IOL power prediction error. The residual refractive error is usually hyperopic after myopic refractive surgery and myopic after hyperopic refractive surgery [1]. The calculation process needs to be adjusted to reduce or eliminate the induced error.

Corneal Refractive Surgery

The cataract surgeon must know the different techniques that have been performed through the years and their impact on corneal anatomy and optical properties. Many of them are no longer used, but the patients who underwent them demand now refractive lensectomy or cataract surgery. These techniques modify, by definition, the anterior corneal surface: flattening to correct myopia and steepening to correct hyperopia. The effect will be asymmetrically applied in two orthogonal meridians to correct astigmatism.

– LASIK and PRK: Excimer laser is used to eliminate tissue from the cornea by photoablation. In LASIK, a lamellar flap is cut and lifted, giving access to the stromal layer where the ablation is performed. In PRK, there is no need for corneal cutting as the laser is applied directly on the stromal surface after epithelium removal. Posterior corneal surface is not affected by surgery.
– SMILE: Tissue is eliminated by intrastromal resection by means of a femtosecond laser. Posterior corneal surface is not affected as well as in excimer techniques.
– RADIAL KERATOTOMY (RK): A variable number of radial cuts performed with a diamond knife produce central anterior and posterior corneal flattening with the aim of correcting myopia. A relevant feature is effect progression many years after surgery in certain cases.
– HEXAGONAL KERATOTOMY: Similar to the previous technique, but with an hexagonal pattern instead of a radial one, in order to

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J. Aramberri et al. (eds.), *Intraocular Lens Calculations*, Essentials in Ophthalmology,
https://doi.org/10.1007/978-3-031-50666-6_65

induce central anterior and posterior corneal steepening to correct hyperopia.

- THERMOKERATOPLASTY AND CONDUCTIVE KERATOPLASTY: Both techniques were used to correct hyperopia. Heat was delivered focally to portions of cornea producing central anterior corneal steepening
- INTRACORNEAL RING SEGMENTS (ICRS): Two ring segments were implanted in the corneal stroma to produce central corneal flattening to correct myopia. There might be some alterations of posterior corneal surface.
- CORNEAL INLAYS: Synthetic intracorneal lenticular implants that steepen the anterior corneal surface to correct hyperopia.
- INTRACOR: This technique produced a central anterior corneal slight steepening to correct presbyopia by means of intrastromal annular cuts with a femtosecond laser.

The effect of these surgeries on the anterior and posterior corneal surfaces must be known in order to calculate properly the IOL power (Fig. 65.1). The keratometric power can be different despite similar topographic patterns (Fig. 65.1a and b).

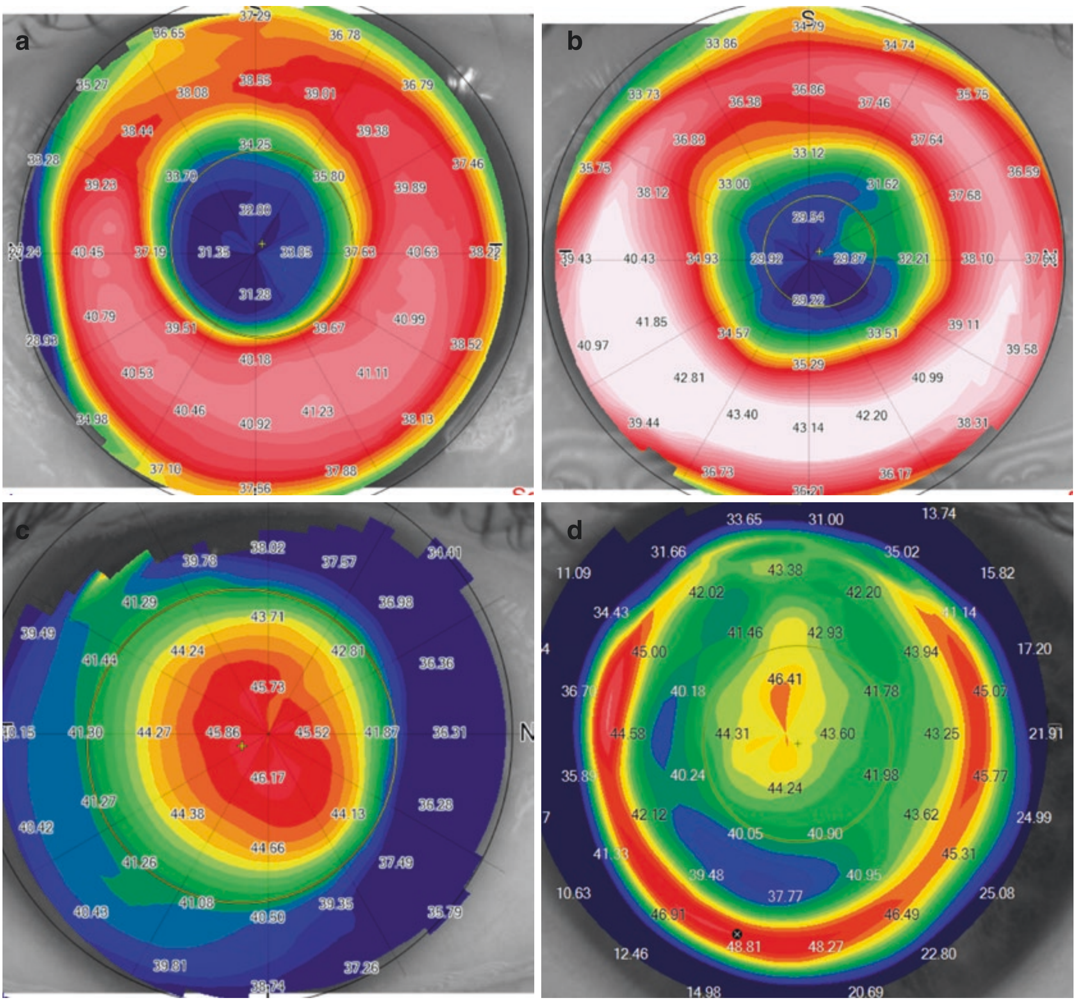


Fig. 65.1 (**a**) LASIK-M. (**b**) RK. (**c**) LASIK-H. (**d**) Intracorneal ring segments (Intacs)

Sources of Error

Three different sources of error can be identified in the IOL power calculation process after CRS. Sometimes they shift the refraction in the same direction and sometime signs cancel out: Effective lens position (ELP) prediction error, corneal radius measurement error, and corneal power calculation error [2].

– **ELP prediction after corneal refractive surgery:**

After CRS K value has been modified while anterior segment anatomical dimensions remain unchanged. Therefore, the physical position of the implant after IOL surgery, distance to cornea and retina, is not affected by CRS and ELP value should be the same as without CRS. However, IOL power formulas that use K value as predictor of ELP will be driven to error: after any cornea flattening surgery, e.g., LASIK-M, PRK-M, and RK, the formula will underestimate ELP with a subsequent underestimation of IOL power. This will shift postoperative refraction towards hyperopia. After any cornea steepening surgery, e.g., LASIK-H or PRK-H, the formula will overestimate ELP and IOL power, producing a myopic effect on refraction (Fig. 65.2).

Well-known formulas that use K in this way: Holladay 1 and 2, Hoffer Q, SRK/T, Olsen, Barrett Universal II, Kane, and EVO. It must be highlighted that Haigis formula is not affected by this problem since K is not used as ELP predicting variable (Table 65.1).

It should be pointed out that not all algorithms are equally affected. Hoffer Q formula bases the ELP prediction on a curve formula and decreases the ELP shortening effect as a function of K, leading to a lower ELP underestimation than SRK/T and Holladay 1 [3]. That's why this formula produces less hyperopia after myopic CRS as several authors have proved [4, 5] (Fig. 65.3).

The induced error magnitude is proportional to the dioptric correction of the CRS, potentially achieving up to 2–2.50 D of IOL power error (approximately 1.4–1.75 D in spectacle plane) after 10–12 D myopic corrections.

– **Corneal power calculation error:**

Most theoretical IOL power calculation formulas are thin lens analytical vergence formulas. Corneal total power (K or Sim K) is an essential variable calculated from the anterior corneal radius of curvature measured by keratometry or topography applying the formula

$$K = \frac{n2 - n1}{r}$$

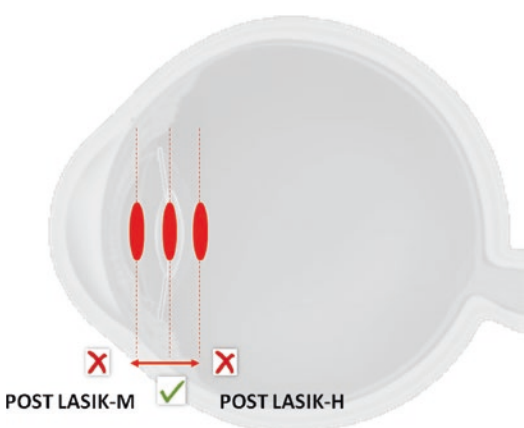


Fig. 65.2 After myopic laser, ELP is underestimated, smaller cornea-IOL distance, and after hyperopic laser ELP is overestimated

Table 65.1 ELP predicting variables of different theoretical formulas

Formula	K	AL	ACD	Lens thickness	Others
SRK/T	Yes	Yes	No	No	No
Hoffer Q	Yes	Yes	No	No	No
Holladay 1	Yes	Yes	No	No	No
Holladay 2	Yes	Yes	Yes	Yes	Rx; age HCD
Haigis	No	Yes	Yes	No	No
Olsen	Yes/No	Yes	Yes	Yes	No
Barrett UII	Yes	Yes	Yes	Yes	HCD
Okulix	No	Yes	Yes	Yes	No
Kane	Yes	Yes	Yes	Yes	Gender
EVO	Yes	Yes	Yes	No	

K Mean keratometry, *AL* Axial length, *ACD* Anterior chamber depth, *Rx* Preoperative refraction, *HCD* Horizontal corneal diameter distance

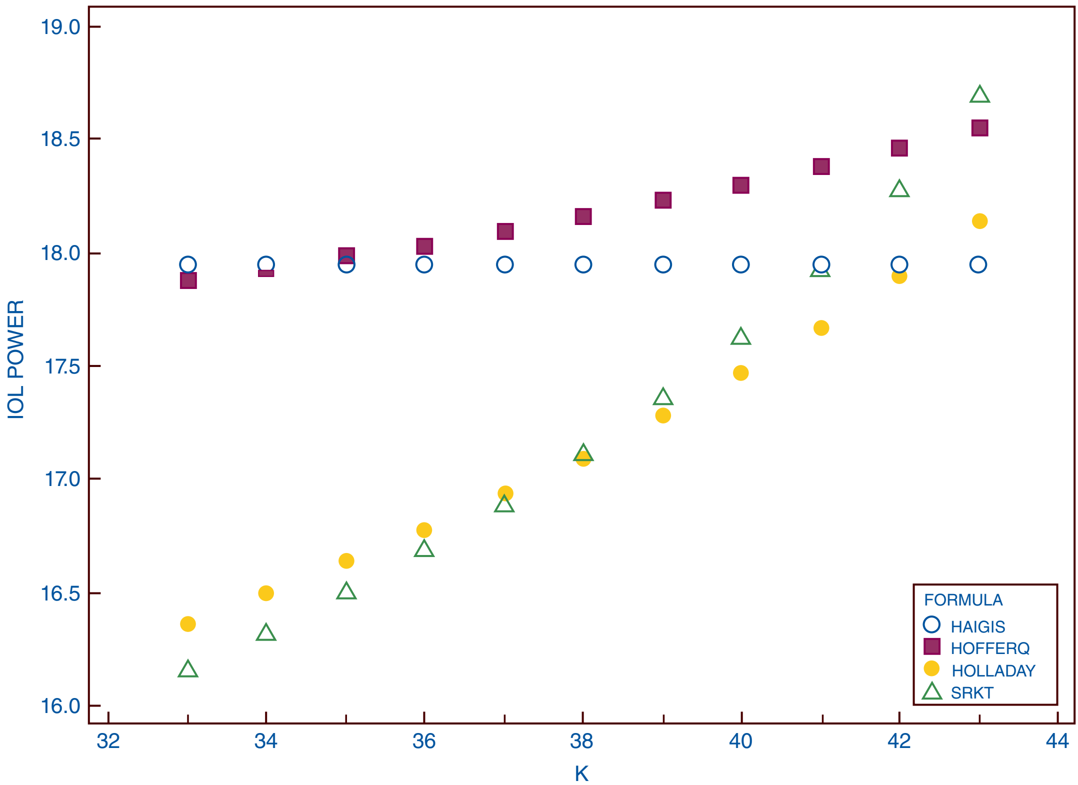


Fig. 65.3 IOL power prediction with different K pre values. SRK/T, Holladay 1, and Hoffer Q are programmed in Double K mode. In X axis different values of K pre, from 32 to 44 D. K post is always 38 D. AL is 27 mm. Haigis is not affected as K is not used to predict ELP

where $n2$ is 1.3375 (standard keratometric index of refraction, SKIR), $n1$ is 1 (index of refraction of air), and r is the corneal radius of curvature. The first is an arbitrary value to account for the unmeasured posterior corneal power effect. Each formula will internally recalculate this "total power" applying different corneal indices of refraction values: 1.3330 (SRK/T), 4/3 (Holladay 1), 1.3315 (Haigis), etc. [6]. The accuracy of SKIR depends on the normality of anterior/posterior surface proportion. The population mean value for anterior radius/posterior radius is around 1.21 ± 0.02. Many papers present the inverse ratio, posterior r/anterior r, with a mean value around 0.82 ± 0.02 [7].

After ablational laser CRS, either LASIK or PRK, there is a selective anterior flattening or steepening that doesn't change the posterior surface significantly [8]. This alters the anterior/posterior ratio and leads to a miscalculation of total corneal power by keratometers and topographers: overestimation of K after a myopic laser treatment and underestimation after a hyperopic laser treatment. E.g., measured K value is 37 D after myopic LASIK where the correct value should be 36 D. The ant/post ratio change is linearly proportional to the anterior curvature change, and therefore, to the CRS corrected diopters. This correlation allows calculating a predictive function and explains the, relative, success of so many published linear regression equations (Fig. 65.4).

Radial keratotomy, being a myopic surgery, curiously has a similar effect to hyperopic laser techniques: ant/post ratio decreases due to the simultaneous central flattening of both anterior and posterior surfaces. Camellin described a mean value of 1.12 ± 0.07 in a sample of 29 eyes measured with Pentacam [9]. Jaime Aramberri

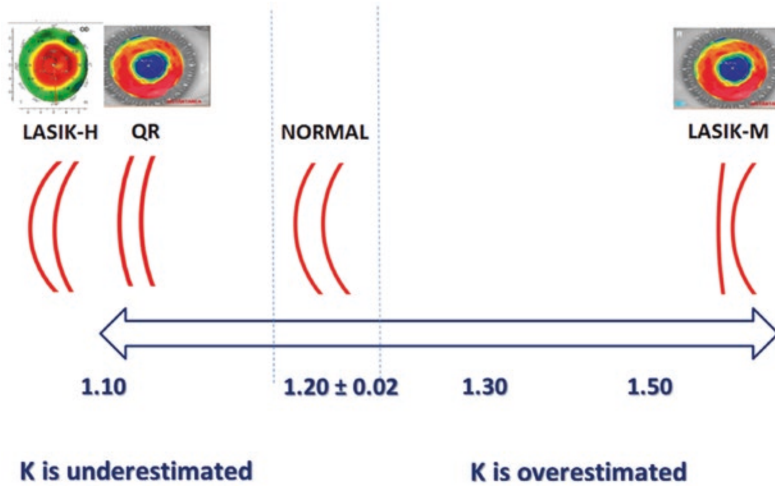


Fig. 65.4 Anterior curvature/posterior curvature ratio: Increases after LASIK/PRK-M and decreases after LASIK/PRK-H and RK

presented a series of 59 eyes in the annual meeting of the IPC in Haarlem 2013 where the average value was very similar: 1.15 ± 0.09. Measurements were performed with Pentacam and Sirius. The variance was high, even between both eyes of same subjects with identical number of cuts. This fact can be attributed to the manual nature of the technique and, opposed to laser surgeries, makes it difficult to calculate a predicting function based on anterior curvature.

– **Corneal radius of curvature measurement error:**

In normal corneas, K and Sim K values are calculated from radii of curvature measured in an annular paracentral zone of around 3 mm of diameter. But this value depends on the curvature and asphericity of the central cornea. Regarding curvature the bigger the measurement area gets, the flatter the cornea is and vice versa [10]. A high asphericity level means that the gradient of curvature, and power, is high. A combination of both factors will determine the sign and magnitude of radius of curvature measurement error. After myopic surgery, either laser or RK, the area of measurement is larger than normal and the curvature is measured in a more peripheral steeper zone. The flatter and more oblate the cornea is, the larger overestimation of K occurs (Fig. 65.5). This effect can be very relevant after high corrections, 6–12 D, which are very prevalent. After hyperopic laser, the effect is more variable, so in a very steep and prolate cornea there will be an overestimation of K if the measurement area is very small and central. However, it's more frequent to see a neutral or even K underestimation error if the central cornea is not very steep (e.g., 46 D) and the cornea is very prolate (topographic image of small optical zone), where the measurement is taken in a curvature changing area (Fig. 65.6).

Keratometric error after CRS will result from the combination of the previously exposed sources of error and will depend on the type of refractive surgery (Fig. 65.7):

– After myopic LASIK and PRK: Both the ant/post ratio change and the increase of measurement area produce an overestimation of K value.
– After hyperopic LASIK and PRK: The ant/post ratio change induces underestimation of K. The radius of curvature measurement sometimes shows underestimation but in very steep corneas there can be some overestimation. The net effect is normally underestimation of K value.
– After RK: The ant/post ratio change induces underestimation of K. But this is compensated by the peripheral measurement of steeper values whenever the cornea is very flat and

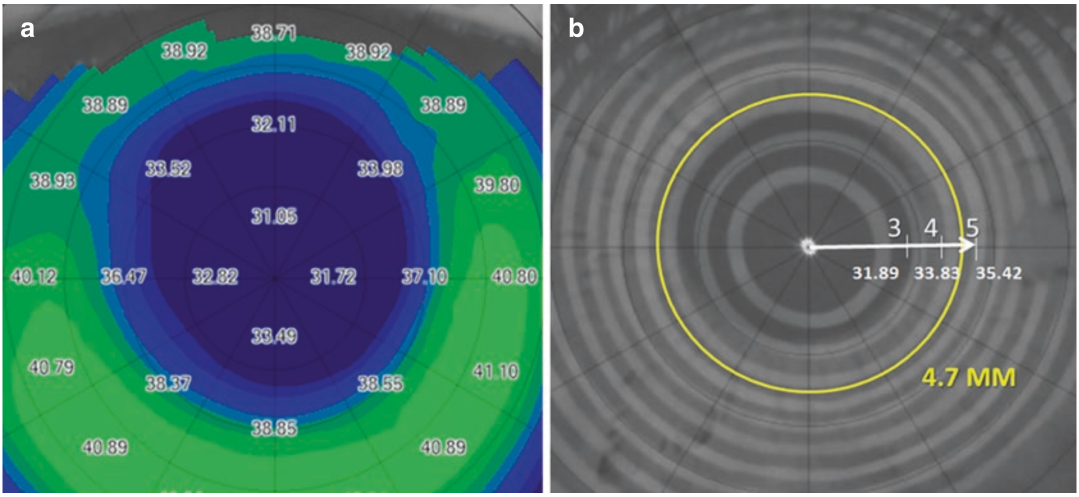


Fig. 65.5 Corneal reflection topography after LASIK-M. Sim K measurement area has become 4.7 mm due to corneal flattening. Corneal shape (oblate) determines a high power gradient as it can be seen by the values at 3, 4, and 5 mm of diameter

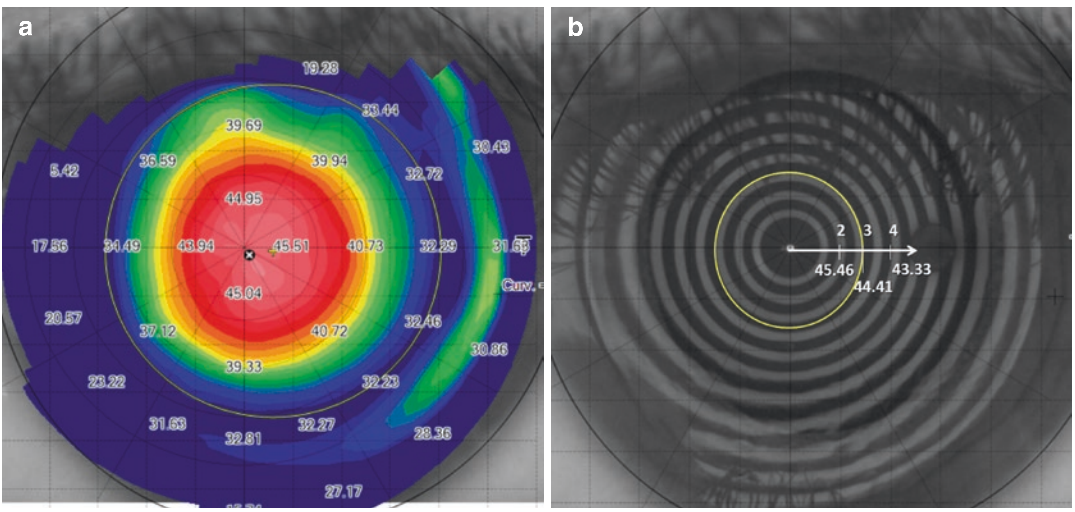


Fig. 65.6 Hyperopic LASIK cornea: Central curvature is not very steep and measurement area diameter is 2.98 mm. But asphericity is high (Q (4 mm): −1.15) and K value is underestimated (**a**) corneal map after hyperopic LASIK (**b**) Placido disc rings after hyperopic LASIK

prolate. The net effect depends on the curvature and asphericity of the cornea.

It is a frequent observation after myopic laser and RK that K value measured by autokeratometers is flatter than Sim K measured by corneal topographers due to the fact that in the former the measurement area is smaller. The opposite trend is seen after hyperopic laser surgery. However, this phenomenon will finally depend on the measurement method of each device.

The keratometric error has been estimated to account for 14–30% of the corrected refraction amount by the refractive surgery after myopic laser surgery [11, 12]. E.g., this means that if K value is 37 D and the refractive surgery has corrected 10 D, assuming a 15% correcting factor, the corrected K value will be 37 − 1.5 = 35.5 D.

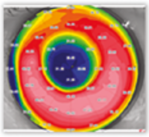
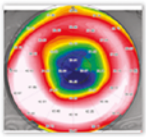
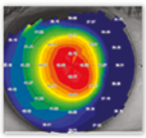
SURGERY	TOPOGRAPHY	CENTRAL CURVATURE	SHAPE	ANT/POST RATIO	KERATOMETRY ERROR
LASIK-M		FLAT	OBLATE	 INCREASE	OVERESTIMATION
RK		FLAT	OBLATE	 DECREASE	OVERESTIMATION UNDERESTIMATION
LASIK-H		STEEP	PROLATE	 DECREASE	UNDERESTIMATION

Fig. 65.7 Keratometric error after CRS. Topographic and keratometric changes vary depending on the type of surgery

The effect of higher order aberrations (HOA) in the optical performance of these eyes shouldn't be overlooked. It is a heterogeneous population of corneas with a high prevalence of HOA, spherical aberration and coma being the most frequent. There is an evident difference between old treatments, where small optical zones and decentrations are common, and modern treatments where optimized profiles and effective eye trackers render good optical quality. Very aberrated corneas are multifocal and can't be represented by a paraxial parameter as the K value. Even postoperative refraction in terms of sphere-cylinder diopters is inadequate as outcome metrics. This probably explains the variability in reported results among the published multiple studies.

Another issue is corneal power change after IOL surgery. This is particularly noticeable after RK, where there is some corneal flattening in the first postoperative months with a variable regression that can end in a different final K value. The reason is transitory incisional epithelial edema that increases the incisional flattening effect of radial cuts [13]. Moreover, there can be a hyperopic refractive shift through the years in some of these eyes.

Solutions

In order to get an accurate prediction, the IOL power calculation method must be adjusted providing solutions to the different problems:

Correct ELP Calculation

The easiest solution is to use a calculation formula that doesn't use K to predict the IOL position within the eye. Haigis formula uses ACD and AL to predict ELP and is quite accurate as long as the 3 IOL constants (a0,a1 and a2) are correctly optimized. Olsen formula should be used with the C-constant algorithm, which uses ACD and LT to estimate the ELP. Okulix software uses AL, ACD, and LT for this task and can be used with no specific correction. Shammas PL formula doesn't use K to predict ELP.

Any formula that uses corneal power to predict ELP can be used with a modification that allows a sequential use of two different K values: The pre CRS K value will be used in the ELP calculation algorithm and the post-CRS K value will be used in the final optical calculation of IOL power. This procedure has been called Double-K method [14]. At present time, most IOL calculators apply this method once the post-CRS calculation mode has been selected. The Holladay IOL Consultant software only applies it within the Holladay 2 formula. The online ASCRS IOL calculator (https://iolcalc.ascrs.org/) uses this method with the Holladay 1 and Barrett formulas. The Barrett true K formula is programmed in Double K manner. It can be accessed in the APACRS website (http://calc.apacrs.org/Barrett_True_K_Universal_2105/). Another option is to perform a regular calculation (single K) and then modify the result following some conversion tables as published by Koch [15].

If K pre-CRS is not available, and this is quite usual, an average number like 43.5 D can be used (Holladay 2 and ASCRS online calculator use 43.86 D). An alternative and probably more adequate recourse is to measure corneal posterior radius of curvature with a Scheimpflug or OCT tomographer, and applying the average post/ant ratio, 0.82 ± 0.02 [8], calculates the pre CRS radius of curvature: e.g., posterior radius 6.15 mm means a preCRS anterior radius of 7.5 mm (6.15/0.82 = 7.5). With the formula $\frac{n2-1}{r}$ being $n2 = 1.3375$, Kpre = 337.5/7.5 = 45 D.

It shouldn't be assumed that these third-generation double K formulas will keep the same accuracy as in the normal range of biometric variables. There are intrinsic biases that can express more, or differently, in this extreme K values combined with low or high AL values. E.g., In low K values, Haigis formula tends to overestimate IOL power while SRK/T tends to the opposite. In very high K values, SRK/T tends to overestimate ELP. Hoffer Q formula tends to overestimate ELP with K values lower than 42. Some of these trends are more notorious after myopic surgery because IOL power has increased while in non-operated eyes they were concealed by the low power of the implant.

Another K pre CRS choice is to select an arbitrary number that compensates the blindness of SRK/T, Hoffer Q, and Holladay 1 to the anterior segment size in cases where this is very long or short. This is frequent after myopic surgery where a deep anterior segment can lead to an underestimation of ELP that will have more effect than that before CRS as the IOL power is higher. One of the authors (JA) has recommended to neglect the actual Kpre (if known) and to choose 45 when the anterior segment depth parameter (ACD + 0.5*LT) is higher than 5.85 mm and 42 when it is lower than 4.9 mm.

The Double K formulas are quite tolerant to Kpre error: in an average eye 1 D of error in Kpre (the value used exclusively in ELP prediction) induces 0.50 D of error in IOL power, which means around 0.35 D in spectacle plane.

The Double K method, not using the measured K in IOL position prediction, should be used in any clinical situation where an abnormal K value can induce ELP calculation error: severe keratoconus, corneal scar, keratoplasty, etc.

Correct Keratometry Calculation

Each IOL power calculation formula is designed to admit corneal power in a certain way: most of them use K value calculated with the SKIR (1.3375). Any adjusted value must be referenced to the same optical plane.

- CRS correction-based calculation: The simplest way to calculate Kpost is to add the effect of the CRS to Kpre. This is the basis of the so-called Clinical History Method [16]. However, it seldom can be used for two usual issues: lack of preoperative information and difficulty to determine if any posterior refractive change was due to corneal or lens change.
- Modified K: a myriad of methods have been proposed to modify the measured K value, either keratometric or topographic, after

CRS. In the oldest papers, the keratometric error was not distinguished from the ELP estimation error and therefore in many cases overcorrecting the former compensated the latter as well. Among the most cited methods, these can be remarked: prepupillary area power (with or without Styles-Crawford effect) [10, 17]; K adjustment by 1 D subtraction [18]; linear regression formulas with a constant value for the posterior surface. Seitz first proposed a posterior corneal power of 5.9 D [1]. The Maloney method became popular later with a posterior value of 6.1 D [19]; empirical adjustment with a linear regression function by Shammas [20]; radius of curvature correction as a function of the CRS dioptric correction and AL [21]. Two methods that correct the anterior radius of curvature empirically still in use by many surgeons are the Haigis-L and the Barrett True K formulas [22, 23].

A method that consisted in averaging the K value calculated by different methods was called the consensus K method by Randleman. Included methods for this calculation were: refractive history, contact lens, manual K, Hamed, Shammas, and Maloney and corneal topography. Extreme values were eliminated (1.5 D off the mean) and the consensus K was averaged from a group located in the central 0.75 D range. The reported error with the Holladay 2 formula was 0.23 ± 0.61 D [24].

– K calculated from posterior surface measurement:

The development of technologies that can measure the corneal thickness and posterior curvature has allowed the calculation of total corneal power based in actual measurements getting rid of assumptions or any dependence on clinical history information. These technologies are scanning slit, Scheimpflug photography, OCT, and posterior surface reflection keratometry. However, it must be highlighted that central total corneal power calculated by numerical ray tracing or analytical vergence formulas with the Gullstrand refraction indices, 1.376 for cornea and 1.336 for aqueous, can't be used, at least with the same IOL constants, in the regular formulas because the reference plane will be more anterior than the one used by K. This parameter receives different names in the commercially available tomographers: TCRP in Pentacam, TCP in Galilei and Anterion, RP in Casia 2, MPP in Sirius and MS39, etc.

Holladay described a total corneal power value converted to the K (1.3375) reference plane that could be used in regular IOL power calculations: The equivalent K reading (EKR) [25]. In his paper, a conversion factor was calculated once the anterior radius of curvature was deduced from the normal anterior to posterior corneal ratio. In the Pentacam software, EKR can be calculated for different diameters. The 4.5 mm diameter value showed the best equivalency with the regular K. EKR can also be found in the Cassini topographer. However, the use of Pentacam EKR is in controversy as reported results have not satisfied expectations. Recently, Seo has proposed a new EKR value adding 0.7 to the Pentacam 4 mm TCRP (total corneal refractive power) getting better results than those with Holladay EKR [26]. One of the authors, JA, found good results in a series of 26 eyes after myopic LASIK/PRK with Cassini EKR and the Haigis formula with a predictive error of −0.16 ± 0.73 D.

Zeiss IOL Master 700 has included a similar parameter: Total Keratometry (TK). Both anterior and posterior surfaces are measured with SS-OCT which probably yields better image quality than Scheimpflug. Savini has reported excellent repeatability in normal and post-CRS eyes, with a Sw value of 0.07 D and 0.09 D, respectively [27]. This value can be used in any regular formula without further adjustments. On the contrary, formulas that already corrected K in eyes after CRS like Haigis-L and Barret True K shouldn't work with this value. Barrett true K allows introducing the posterior measured corneal power in order to perform calculation with actual values bypassing its K correcting empirical algorithm. This is called Barrett True K TK, and good results have been published [28].

There are several programs and formulas using thick lens pseudophakic eye models where the corneal radii of curvature are input avoiding any power- (K) related issues like incorrect anterior/posterior ratio or erroneous K equivalent value calculation. Some are based on ray tracing, like Olsen, Okulix, and Barret True K TK. The EVO formula performs the optical calculations with analytical vergence formulas. Corneal asphericity can be input in the Olsen formula taking account of the spherical aberration effect, sometimes high in these eyes. In certain topographers, exact ray tracing calculations can be done with these formulas: Olsen, Okulix, CSO proprietary software (MS39 and Sirius tomographers), and ExactIOL. The advantage is that the effect of HOA is computed and the IOL that produces the best visual quality can be selected going beyond the paraxial concept of spectacle refraction. This can be relevant in very irregular corneas.

Calculation Methods

Many methods have been published in the last 20 years since these eyes were identified as being problematic for IOL power calculation. Some have been abandoned and some are still in use. In this section, a list of still relevant methods will be presented. A practical classification is to distinguish between methods that require clinical history data and methods that don't.

Methods Requiring Clinical History Data (Original Keratometry and/or Refractive Change)

– PreLASIK/PRK calculation method

 It has been used by many surgeons since long time and published as AS technique [29] and corneal power bypass [30]. The IOL power is calculated with the original K value aiming for the refraction corrected by the CRS in the spectacle plane. Attractive for its simplicity, it usually faces the limitations of unavailability of the Clinical History and/or the error induced by any unknown K change in the time after CRS.

– Barrett True-K formula:

 This unpublished formula is a modification of the Barrett Universal II where the ELP estimation error is avoided using the Double K method and, on the other hand, the keratometric error is fixed using an internal regression formula that modifies the prediction in a different way for myopic laser, hyperopic laser, and radial keratotomy. The "history" version of the Barrett True-K formula requires the surgically induced refractive change (SIRC) and has been found to be an accurate option for IOL power calculation, as the prediction error (PE) is within ±0.50 D in 64–67% of eyes [23, 31, 32]. Its results are further improved by adding the posterior corneal curvature data measured by Scheimpflug or OCT. Savini reported that this was the best method with 70% of eyes within ±0.50 D of prediction error [31].

 This formula is available on the websites of the Asia-Pacific Association of Cataract & Refractive Surgeons (www.apacrs.org), the American Society of Cataract and Refractive Surgery (https://ascrs.org/tools/iol-calculator), and on several optical biometers and tomographers.

– Masket formula:

 In this commonly used formula, available at https://ascrs.org/tools/iol-calculator, the IOL power is calculated as if the eye had not undergone previous excimer laser surgery. The IOL power by Single-K SRK/T (in the case of myopia) or Single-K Hoffer Q (in the case of hyperopia) is then adjusted according to the following equation [33]:

$$\text{IOL power adjustment} = \text{SIRC} * (-0.326) + 0.101$$

In the ASCRS website, a modification of this formula by Warren Hill can also be found:

$$\text{IOL power adjustment} = \text{SIRC} * (-0.4385) + 0.0295.$$

This formula should be used using the Holladay 1 for AL > 23 mm and the Hoffer Q for AL < 23 mm [34].

Several studies have shown that this method is quite accurate (up to more than 70% of eyes with a PE within ±0.50 D), although it may give slightly hyperopic results [32, 35, 36].

– Savini's method:
– With this method, the keratometric index of 1.3375, which is no longer valid after LASIK or PRK, is decreased as the amount of myopic correction increases, according to the formula:

$$\text{Post CRS index of refraction} = \text{SIRC} * 0.0009856 + 1.338$$

Once the adjusted keratometric index has been calculated, the corneal power is calculated using the usual formula $P = (n-1)/R$ [37]. This method has been proven to give reliable results when combined with the Double-K SRK/T formula, as the percentage of eyes with a PE within ±0.50 D ranges between 64 and 73% [35, 38, 39]. The high accuracy of this method when the refractive change is known is offset by a high sensitivity to bad clinical data.

Similar methods have been developed by Camellin and Calossi and Jarade [40, 41].

– Seitz/Speicher's method:

This method, which has been described independently by Speicher and Seitz between 2000 and 2001 [42, 43], relies on preoperative keratometry and does not require the SIRC. It assumes that the total dioptric power of the cornea (P) can be calculated by adding the power of the anterior (P_a) and posterior (P_p) corneal surfaces:

$$P = P_a + P_p = (n_2 - n_1)/r_1 + (n_3 - n_2)/r_2$$

where n_1 is the refractive index of air (= 1), n_2 is the refractive index of the cornea (= 1.376), and n_3 is the refractive index of the aqueous humor (= 1.336). Both preoperatively and postoperatively, the power of the anterior corneal surface (P_a) can be obtained using the refractive index of the cornea (1.376) rather than the keratometric index (1.3375). This means that the keratometric power (K) provided by the corneal topographer or optical biometer has to be multiplied by 1.114 (corresponding to 376/337.5). Hence:

$$P_a = K \times 1.114$$

Before LASIK or PRK, knowing the power of the anterior corneal surface enables us to estimate the power of the posterior corneal surface (Pp) according to the formula:

$$P_p = P_a - P = (K \times 1.114) - K$$

After LASIK or PRK, the power of the anterior corneal surface can then be added to that of the posterior corneal surface (which is assumed to be unchanged), as expressed by the formula:

$$P = \text{postop}\,P_a + P_p = \text{postop}\,K \times 1.114 + (\text{preop}\,K \times 1.114 - \text{preop}\,K)$$

This method has been shown to provide excellent results when combined with the Double-K SRK/T formula [35, 39, 44]. The main advantage of this method is that it does not require perioperative refractive data, as the preoperative K readings are sufficient.

Methods Not Requiring Clinical History Data (Original Keratometry and/or Refractive Change)

Perioperative data, i.e., the pre-LASIK/PRK keratometry and the surgically induced refractive change, are often not available. Therefore, No-History methods represent the only solution in many cases. It is interesting to distinguish between methods that use the posterior corneal power measured by Scheimpflug or OCT and methods that don't. It could be thought a priori that IOL power calculation based on measurements should be more accurate than one based on empirical estimations.

Methods that Don't Use Posterior Corneal Measurement

– Barrett True-K No History formula:

This formula can work without historical data correcting the calculation as a function of the measured K and AL with an empirical algorithm. It can be accessed in the previously reported websites. The results are good (56–63% of eyes with a PE within ±0.50 D) [23, 31, 32] and can be improved by adding the posterior corneal curvature (up to 70% of eyes with a PE within ±0.50 D) [31, 45]. Compared to other No-History formulas, it appears to be the most accurate choice in eyes with axial length (AL) <28 mm [46].

– Haigis-L formula:

This is a modification of the Haigis formula where the anterior radius of curvature measured by the IOL Master is corrected with a formula empirically calculated from a series of cases. This is done separately for eyes with previous myopic and hyperopic corrections. In the case of myopia, the formula is

$$rcorr = \frac{331.5}{-5.1625 * \text{rmeas} + 82.2603 - 0.35}$$

where rmeas is the measured radius of curvature and rcorr is the corrected radius of curvature that will be input in the Haigis formula. With this formula, there is no need for ELP calculation correction (e.g., Double K method) as K is not used for this task [22].

The results reported have been good but not outstanding (34–61% of eyes with a PE within ±0.50 D), with a trend towards myopic outcomes [22, 23, 32, 45].

– Shammas-PL and PHL (for previously myopic and hyperopic eyes)

These formulas calculate the corneal power by means of the following equation:

$$\text{Corneal power} = 1.14\,K\text{post} - 6.8$$

where Kpost is the post-refractive surgery keratometry [20].

The calculated corneal power value has to be entered into the original Shammas formula, which does not need the Double-K adjustment as it does not depend on corneal curvature to estimate the ELP (so called Shammas-PL formula) [47]. Several studies reported good results not only in eyes without historical data, but also in those with perioperative data available, as the PE was within ±0.50 D in 46–60% of eyes [32, 35, 36, 39]. Compared to other No-History methods, Shammas PL-formula provided the highest accuracy in eyes longer than 30 mm, but was inferior to Barrett True-K and Triple-S in eyes with shorter AL [46]. A specific version (Shammas-PHL formula) can be used for eyes with previous hyperopic LASIK [48]:

$$\text{Corneal power} = 1.0457\,K\text{post} - 1.9538$$

– Triple-S method (Seitz/Speicher/Savini):

This method is a modification of Seitz/Speicher method that does not require pre-LASIK/PRK keratometry. The K measured by the keratometer is converted into the sum of the anterior power and a mean value of −4.98 diopters (D) for the posterior corneal surface empirically calculated from a series of cases [44]:

$$K = \text{measured}\,K \times 1.114 - 4.98\text{D}$$

Here, the preoperative unknown K must still be entered into the Double-K formula and several options are available to estimate it: an average value may be used (e.g., 43.50 D), the preoperative K may be obtained by adding the refractive change at the corneal plane to the modified postoperative K value, or it may be calculated from the posterior corneal surface parameters [49]. The results have been among the best for No-History formulas, as the PE was within ±0.50 D in 53–70% of eyes [35, 38, 46]. It has also been reported to be the best No-History formula in eyes with AL between 28 and 30 mm (compared to Barrett True-K, Haigis-L and Shammas PL) [46].

– Maloney and Wang-Koch-Maloney methods:

A very similar option is Maloney's method. The main difference lies in the choice of the topographic value, which in Maloney's method is not the SimK but rather the single power at the center of the axial map (Atlas topographer) and a posterior corneal power of −4.90 D rather than −4.98D.

Hence, corneal power according to Maloney's method reads as:

$$K = \text{measured}\,K\,1.114 - 4.90$$

Wang proposed a change for the posterior corneal value to −6.1 D and later further changed it to −5.59 D [19]. This modified K can be used in a Double K formula or in one that doesn't use K as ELP predictor (e.g., ASCRS online calculator uses Shammas-PL).

– Intraoperative aberrometry:

This method calculates the IOL power from the intraoperative aphakic refraction. The first reference was based in automatic refractometry [50], but it later evolved to using a Talbot-Moiré aberrometer (ORA System, Alcon, Fort Worth, TX) to get the measurement. The IOL power is calculated with a refractive vergence formula statistically optimized with a large database of thousands of cases. Ianchulev reported a PE of 67% of eyes within ±0.5 D in a sample of 246 eyes [51] and Fram a similar figure, 74%, in a simple of 39 eyes [52]. This method has a significant economic cost and time requirement during surgery to be considered when compared to other methods.

Methods that Use Posterior Corneal Measurement

– IOL Master Total Keratometry (TK):

This new parameter has been included recently in the IOL Master 700 biometer and follows the EKR concept introduced by Holladay in the Pentacam. TK is calculated from the OCT measured anterior and posterior corneal radii referenced to the same plane as K (1.3375). Therefore, it can be used in any standard formula. In normal eyes, TK should be very similar to K, with some difference explained by the anterior/posterior corneal ratio variability [27, 53]. After CRS, it can be used in any formula that doesn't use K to predict ELP, e.g., Haigis, or in any Double K formula as K post. In these cases, TK will be lower than K after myopic laser surgery, with a difference proportional to the surgery-induced anterior flattening, and it will be higher after hyperopic laser. After RK, it might be higher, similar, or lower. Wang reported a difference between TK and K of −0.39 ± 0.26 D, 0.06 ± 0.17 D, and 0.15 ± 0.32 D, in 53 eyes post-M-laser, 32 eyes post-H-laser, and 44 eyes post-RK [54]. PE after LASIK/PRK-M with 3ª generation formulas is around 60% of eyes within ±0.50 D. With Haigis formula, Wang reported 58.5%, Lawless 60%, and Yeo 64%. With Double K Holladay 1, Lawless reported 60% and Yeo 54.69%. With the Double K SRK/T, Yeo found 57.81% [28, 45, 54].

The Barrett True K formula has been modified to use the TK value taking the name Barrett True K TK. The algorithm that corrects the K value is disabled and measured anterior and posterior radii are used instead. Reported outcomes suggest an improved PE: Lawless reports 75% of eyes within ±0.5 D and Yeo 64% [28, 45].

The EVO 2.0 formula has been modified in a similar way, EVO TK, with a first paper by its author reporting 68.75% of cases within ±0.50 D of the target [45]. This is a thick lens vergence formula where the posterior corneal radii measured with IOL Master 700 can be input. The normal corneal posterior/anterior ratio (0.883) is used to calculate the pre-CRS K value in order to apply the Double-K method in the ELP algorithm.

– OCT-based calculation:

Tang published a method based in the corneal measurements of the SD-OCT RTvue where the total corneal power was calculated using a Gaussian equivalent power formula and later used in a thin lens vergence formula. IOL position was estimated using ACD, LT, and AL as predicting variables. Results in 16 eyes after LASIK-M were similar to Haigis-L formula: MAE 0.50 and 0.76, respectively [55, 56].

– Ray tracing models:

Numerical ray tracing models perform optical calculations tracing rays surface by surface applying Snell's law. In the paraxial mode, the main advantage over thin lens analytical formulas is that cornea is defined by anterior and posterior radii of curvature, both of which can be measured skipping power calculation issues. In the exact mode, the effect of HOA is also considered, and this can be significant in many of these cases where corneas can be very irregular: small optical zones, decentration, etc.

Okulix and Phacooptics are two commercial programs where IOL calculations are based on thick lens ray tracing. If only corneal radii are input, the calculation will be paraxial. If asphericity is added, spherical aberration effect will also be calculated. If cornea is defined by a topographic data matrix, then exact ray tracing will take account of HOA.

Okulix software uses AL, ACD, and LT for IOL position estimation and published results with anterior and posterior corneal measurements are fairly good: 63.6% of cases within ±0.50 D of the target [57]. Results might be even better if measurements are obtained with a SS-OCT device: Gjerdrum has reported excellent results with Anterion and Okulix: PE within ±0.5 D in 88% of eyes [58].

Phacooptics software is programmed with the Olsen formula. In post-CRS cases, the C constant method should be used to calculate the ELP. Only ACD and LT will take part in the IOL position calculation [59].

The Italian Company CSO has included an IOL power calculation program based on exact ray tracing in the AS-tomographers Sirius (Scheimpflug) and MS 39 (SD-OCT). ELP is calculated with a proprietary algorithm that doesn't use corneal parameters. Savini reported 71% of eyes with a PE within ±0.50 D with the Sirius [60] and 75% of eyes in a non-published series with the MS 39 instrument using optical segmented AL.

– Total corneal power:

All AS-tomographers provide some central corneal power parameter calculated by ray tracing from the measured anterior and posterior radii of curvatures. The name will be different for each device (Table 65.2):

These values can be used in regular formulas only if the IOL constant is adjusted ad hoc because the reference plane is different from the K calculated with the SKIR (1.3375). Then results are correct in normal eyes [61, 62]. After CRS, the values should be used in a formula that doesn't use cornea to predict ELP, e.g., Haigis, or in a Double-K formula: Savini

Table 65.2 AS-tomographers and central total corneal power

Instrument	Technology	Total K parameter
Galilei	Placido + Scheimpflug	Total corneal power
Pentacam	Scheimpflug	Total corneal refractive power
Sirius	Placido + Scheimpflug	Mean pupil power
Anterion	Swept source OCT	Total corneal power
Casia 2	Swept source OCT	Real power
MS 39	Placido + Spectral OCT	Mean pupil power
Revo NX	Spectral OCT	Real power

reported 70% of eyes within ±0.50 D of target with Total corneal power of Galilei and Double-K SRK/T formula [57].

– Fórmula Stop:

In this method, the calculation of Holladay 1 and SRK/T formulas is modified by the posterior/anterior corneal ratio. It was originally developed from a series of 61 eyes that had myopic and hyperopic laser surgery, measured with Pentacam and IOL Master [63]. These are the adjustment formulas

$$\text{Holladay1} = \left(5.73 - 8.69^{*} r\text{post} / r\text{ant} - 0.69^{*} r\text{ant} + 0.29^{*} AL\right) \times 1.5$$

$$\text{SRK} / T = \left(9.11 - 10.81^{*} r\text{post} / r\text{ant}\right) * 1.5$$

The obtained number must be added to the IOL power calculated by each formula. Savini reported fair results, comparable to other no-history methods: 60% and 62% of eyes within ±0.5 D of the target [38].

Calculation After Radial Keratotomy

After RK corneal topography has a similar shape after myopic laser surgery, LASIK or PRK, cornea. But there is a relevant geometrical and optical difference due to the fact that posterior cornea has flattened as well, decreasing the anterior/posterior corneal ratio in a similar way to a post-hyperopic LASIK cornea. This leads to an underestimation of K. This effect is very variable and doesn't correlate well with the number of cuts, probably due to the manual character of this surgical technique. However, the magnitude of anterior/posterior ratio change is not as intense as in laser surgery (for a similar refractive correction) and therefore the induced error is lower. Moreover, there is some compensation from the measured area enlargement produced by the corneal curvature and shape change. Hence, the net keratometric error is variable, under or overestimation, depending on the surgery effect. The flatter the cornea, the higher the trend toward K overestimation and vice versa. All this variability makes inaccurate any correcting regression function based on the anterior keratometry, differently to post-laser situation.

Another issue is the frequent temporal fluctuation of keratometry, and thus refraction, sometimes following a circadian cycle. Target refraction in these eyes is many times a moving target.

The first proposed calculation methods, based on Placido topography, substituted Sim K by central measurements like ACCP(3 mm) of the TMS device or Effective Refractive Power (EffRP) of EyeSys topographer [64, 65]. These values should be used in the adequate formulas to avoid the ELP error. Potvin didn't find a significant difference using several corneal parameters of Pentacam, with and without posterior curvature, in the Double K Holladay 1 formula, with a similar result to Placido topography: around 40% of eyes within ±0.50 D and 75% of eyes within ±1.00 D of target refraction [66]. Ma et al. reported similar results with Double K Holladay 1 with IOL Master K, OCT corneal power, and Barrett true K. They found a hyperopic early postoperative refraction that decreased in 4 months. Results were very variable and 27% of eyes had a final predictive error >1 D [67]. Curado compared different methods: ORA system, IOL Master K and Haigis, Holladay 2, and Barrett true K, with a predictive error ≤0.50 D in 48.1%, 53.8%, 57.7%, and 63.5% of eyes, respectively [68].

Recently, Turnbull has found better results with Barrett true K with historical data, 76.6%, than Barrett true K without data, 69.2%, Haigis, 69.2%, and Double K Holladay 1, 50%. Predictive error >1 D incidence in this series is lower than others [69].

Our experience with calculations based on ray tracing and posterior corneal measurement by OCT is positive with more than 60% of cases with ±0.50 D of target and few errors over 1 D.

Availability of These Methods

– Software of biometers and topo/tomographers:

All biometers in the marker have specific formulas for these calculations. 3° generation formulas are programmed applying the Double-K method, Shammas-PL and Barrett true K. Ray tracing software like Okulix and Phacooptics are optional in some devices and can be linked to the measuring software.

– Online calculators (free access):
  (a) ASCRS: Different methods are used depending on the inputs. Average calculation is also calculated (https://iolcalc.ascrs.org/wbfrmCalculator.aspx).
  (b) APACRS: Barrett True K formula is used (http://calc.apacrs.org/Barrett_True_K_Universal_2105/).
  (c) EVO formula: (https://www.evoiolcalculator.com/calculator.aspx).
  (d) IOL Power Club: An excel file programmed by Giacomo Savini and Ken Hoffer with different methods can be downloaded (https://www.iolpowerclub.org/post-surgical-iol-calc).

– Commercial software:

Phacooptics and Okulix ray tracing software can be acquired in their respective websites.

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