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REVIEW/UPDATE

Intraocular lens power calculation in eyes with keratoconus

Nuria Garzón, PhD, Pedro Arriola-Villalobos, MD, PhD, Gema Felipe, Msc, Francisco Poyales, MD, María García-Montero, PhD

The purpose was to review and document the methods used to calculate the power of the intraocular lens (IOL) to be implanted in cataract surgery in the specific scenario of eyes with keratoconus (KC). This review was conducted of all scientific articles published in English that focused on the parameters and formulas used to calculate the power of the IOL to be implanted in eyes with KC undergoing cataract surgery. There are few publications that show in detail how IOL power is calculated in those particular cases. If the keratometric value is used based on the standard refractive index (1.3375), this results in a postoperative refractive error with a tendency to hyperopia. The SRK/T formula is the formula yielding the best outcomes. The greater the severity of KC, the greater the deviation of the postoperative refractive status deviation from the target outcome.

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Keratoconus (KC) is a disease affecting the cornea, in which there is collagen breakdown (leading to a drop in corneal rigidity) resulting in the cornea losing its normal spherical shape. KC is defined as a noninflammatory disorder, characterized by an increasingly steeper cornea of the central and paracentral cornea. The etiology of these changes is not known. From an optical perspective, it causes myopia and irregular astigmatism, which significantly impacts visual acuity (AV).[1,2] KC incidence and prevalence rates vary mainly because there is no standardized methodology agreed on for its diagnosis. It is estimated that 1 of every 2000 people will develop KC.[1,2] Its onset generally occurs during puberty, and it progresses until the patient is in their 30s or 40s, when it usually stops.[1,2] In the mild stages of KC, spectacles and contact lenses can manage to successfully solve AV problems, whereas in the more advanced stages, surgical techniques such as corneal crosslinking, intracorneal (stromal) ring implantation, or corneal transplant are the preferred treatment options.[3]

Because of the alterations and irregularities occurring at a corneal level, the cornea's anterior surface vs posterior surface ratio is outside the normality range defined by Fam.[4] Moreover, in eyes with KC, axial length is typically longer than usual, and keratometry (K) readings are difficult to interpret because of the corneal distortion caused by ectasia. All this makes it difficult to calculate the power of intraocular lenses (IOLs) to be implanted in the context of cataract surgery. In addition, in eyes with KC, the visual axis may not go through the cornea's steepest location, and therefore, the lens' effective position will have a greater impact on the refractive outcome.[5,6]

In this challenging context, the purpose of this review was to investigate and assess the different approaches to IOL power calculation for cataract surgery in the presence of KC.

METHODS

A bibliographic search in the PubMed database was conducted, looking for scientific articles written in English and published in peer-reviewed journals before March 15, 2019. Boolean operators and truncated terms were used to perform the search. As for the descriptors, they were MeSH ones or medical subject headings, except for a few that were free terms (KERATOCONUS and ECTASIA). The database query was (Keratoconus OR corneal ectasia) AND (IOL OR intraocular lens OR cataract surgery).

The bibliographic search yielded 851 articles that were subsequently reviewed and filtered; a large number of them were excluded because they did not meet the inclusion criteria (Table 1). We also went through the selected articles' reference list in case they included additional studies that had not been identified by the initial electronic search. As a result of this 2-step process, 19 articles were finally selected and analyzed for the purpose of the present review. Data referring to AV changes were not included in this article because they are not the subject of this review.

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From the IOA Madrid Innova Ocular (Garzón, Poyales), Optometry and Vision Department (Garzón, García-Montero), Faculty of Optics and Optometry, Complutense University of Madrid, Unidad de Superficie e Inflamación Ocular (Arriola-Villalobos), Servicio de Oftalmología, Hospital Clinico San Carlos, and Servicio de Oftalmología (Felipe), Hospital Clinico San Carlos, Madrid, Spain.

Corresponding author: Nuria Garzón, PhD, IOA Madrid Innova Ocular, C/Galileo 104, 28003 Madrid, Spain. Email: ngarzon@ioamadrid.com.

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Table 1. Inclusion criteria used during the bibliographic search in PubMed.

Population: people with keratoconus undergoing cataract surgery
Cataract surgery in eyes with keratoconus for patients with no history of ocular surgery (transplant, intrastromal rings, or crosslinking)
Explicit mention of how intraocular lens power calculation was performed

RESULTS

Most of the articles found refer to KC, although some of them focus on posterior KC and KC frustre. Kamiya et al. are the authors who have presented the largest case series of cataract surgeries in patients with KC.[7] It was a multicenter study comprising 102 eyes with KC whose severity ranged from 1 to 4 (according to the Amsler–Krumeich classification).[8] Kamiya estimated the corneal refractive power by taking keratometric readings with the IOLMaster 500 (Carl Zeiss Meditec AG)—within a ring located approximately 2.4 mm from the center and relying on the standardized anterior/posterior corneal ratio (1.3375). Their results showed a high tendency toward hyperopia in the most advanced KC cases. When the keratometric value of choice was total corneal power—as measured with the Pentacam topographer (OCULUS Optikgeräte GmbH)—within the 15 degrees central ring (equivalent to the 3.0 mm ring), the postoperative refractive error showed a myopic trend. Kamiya concluded that in the presence of KC, using a keratometric index of 1.3375 results in an overestimation of the corneal power, which causes errors when calculating the power of the IOL to be implanted.

Watson et al. retrospectively examined 92 KC eyes that had undergone cataract surgery and divided them into 3 groups according to the Krumeich classification: mild (K < 48 diopters [D]), moderate (48 > K < 55 D), and severe (K > 55 D) KC.[9,10] In the mild and moderate groups, the real K values were used—which relied on optical biometry data—whereas for the eyes with severe KC a standard K value of 43.25 D was used for more than half of the eyes. In all cases, the formula of choice for IOL power calculation was the SRK/T.[11] They found that biometric measurements in KC eyes generally overestimate corneal power and underestimate the power of the IOL to be implanted, with the resulting tendency toward hyperopic postoperative errors. However, in mild and moderate KC, these discrepancies were small and led to low postoperative refractive errors. In fact, in the mild KC group, 60% of the eyes had a postoperative refractive error below 1 D (relative to the target refraction). In the moderate KC group, this rate dropped to 41.9%, whereas in the severe KC, the results were significantly worse.

On the other hand, the study by Savini comprised 41 eyes. Besides being the most recent study of all (published in 2018), it is the one that describes in greatest detail how IOL power calculation was performed.[12] Keratometric values always obtained by measuring the corneal radius and converting it to corneal power using a refractive index of 1.3375, regardless of whether that measurement had been made by means of a biometer or a corneal topographer. As for power calculation formulas, they tested Universal Barrett II, Haigis, Hoffer Q, Holladay 1, and SRK/T and concluded that all 5 of them led to hyperopic postoperative errors and had considerably less accuracy in these eyes than in KC-free eyes.[13–16] This held true even for stage I KC eyes (according to the Amsler–Krumeich classification). For stages I and II, it was the SRK/T formula that yielded the best results, whereas for stage III eyes, the postoperative refractive error always exceeded 2.5 D.

Leccisotti performed a prospective study comprising 34 eyes with stage I (minimum corneal curvature of 7.5 to 6.5 mm) or stage II (minimum corneal curvature of 6.9 to 5.3 mm) KC.[17] Keratometry readings were obtained by axial topographic maps. The dioptric power of the steepest meridian over the central 3.0 mm of the cornea was considered K1, and the dioptric power of the flattest meridian over the central 3.0 mm of the cornea was considered K2. Each meridian power was calculated by averaging its 2 semimeridian values, always considering the central 3.0 mm. Biometry measurements were ultrasound based, and for IOL power calculation, the formula of choice was Holladay 2.[18] Mean postoperative refractive error was −1.31 D, but a significant number of IOLs had to be replaced: 26% of IOL replacements occurred during surgery, following intrasurgical measurements with an autorefractometer; in 6% of the cases—mostly stage II eyes—the IOL was replaced 2 weeks postoperatively because of large postoperative refractive errors (between −5.0 D and −6.0 D). Leccisotti suggests that this high rate of explantation could be partly due to using an ultrasound-type biometer, which has been found to be inaccurate in 1 of every 3 eyes. Thus, they recommend performing intraoperative autorefractometry for cataract surgery involving eyes with KC.

The study by Hashemi included 23 eyes from 17 patients; the eyes were split into 3 groups based on the maximum keratometry within the central 3.0 mm area (as seen in the axial map recorded with the Pentacam): mild (K < 48 D), moderate (48 D > K < 52 D), and severe (K > 52D).[19] Keratometry values were measured using various methods: (1) manual keratometry, (2) keratometry derived from the 3.0 mm central zone in the axial map of the Pentacam, (3) keratometry derived from the refractive map of the Pentacam and (4) keratometry derived from the equivalent K reading (EKR) of the Pentacam (3.0 mm zone). The IOL power calculation formula of choice was different in each case, depending on the eye's axial length: Hoffer Q (<22.0 mm), SRK II (22.0 to 24.5 mm), Holladay 1 (24.5 to 26.0 mm), and SRK/T (>26.0 mm).[20] In eyes with mild or moderate KC, the postoperative refractive outcome was about 0.50 D away from the target one, whereas in severe astigmatism, this error exceeded 2.5 D. Regarding keratometric measurement methods, for mild KC, the best results were obtained when calculations relied on keratometry derived from topography and manual keratometry, whereas for moderate KC, the best outcomes were achieved with keratometry derived from topography and for severe

KC keratometry derived from topography and manual keratometry. Hashemi concluded that because in KC eyes, the corneal apex is off-center, keratometry measurements should be made in the central corneal, which is the location that most closely corresponds to the visual axis.

The study by Jaimes et al. focused on retrospectively evaluating the surgical outcomes after in-the-bag IOL implantation in 7 eyes with KC, 10 eyes with frustrating KC, and 2 eyes with pellucid marginal degeneration, (where the severity of the KC ranged from stage I to stage IV, based on the Amsler–Krumeich classification).[8,21] For IOL power calculation, they relied on the SRKII formula, and the keratometric values were obtained either with a Pentacam or an Orbscan II topographer, although they did not indicate the exact approach they used to measure corneal power. Their results showed a 98.16% correlation between the target spherical equivalent and the actual one they obtained.

Alio et al. evaluated the implantation of toric lenses in 17 eyes with KC affecting the central 3.0 mm area.[22] Their IOL power calculations relied on either the Hoffer Q or the SRK/T formula, the latter yielding better outcomes, although the article does not specify how keratometric values (which need to be fed into these formulas) were measured.

Refractive outcomes were worst for the 2 eyes having the highest-stage KC. Regarding postoperative refractive outcomes, for patients with myopia, with the use of the SRK/T formula, there was a tendency toward undercorrection, whereas in hyperopes, with the use of the Hoffer Q formula, the tendency was toward overcorrection and in greater magnitude.

Thebpatiphat et al. performed a retrospective analysis in 12 eyes, where KC was classified as mild (K < 48.0 D), moderate (48.0 > K < 52.0 D), or severe (K > 52.0 D).[23] Keratometric readings were obtained by means of keratometry and corneal topography–based keratometry; the formulas that were evaluated were SRK I, SRK II, and SRK/T.[24] In most cases, multiple calculations were performed using the keratometry value and the keratometric value obtained from the topography with the 3 formulas, choosing the mean value of the power of the IOL obtained in those calculations. Their results showed that for mild KC, there was no difference between the 2 methods for corneal power estimation and that the most accurate formula was SRK II. On the contrary, those eyes having moderate or severe KC could not be assessed because spectacle plane refraction could not be successfully performed.

An article was found where posterior KC outcomes were evaluated. Tamaoki et al. included 4 eyes from 4 patients, which were extracted from a database comprising 4621 eyes.[25] Keratometric values obtained with 2 different instruments—namely, autokeratometer Tonoref II (Nidek Co., Ltd) and IOLMaster—estimated the entire corneal refractive power only from the anterior corneal radius using a modified refractive index by empirical estimations of the corneal thickness and posterior surface curvature. The cornea's total refractive power was also measured by means of optical coherence tomography using an anterior segment optical coherence tomography device (SS-1000 Casia, Tomey Corp.). This value (total corneal refractive power) was calculated by adding the corneal thickness correction to the sum of the anterior and posterior refractive powers, in addition to the anterior to posterior corneal curvature ratio. The IOL power calculation formula they used was SRK/T. For all 4 cases included in the study, total corneal power was lower than the values determined by means of the IOLMaster and the autokeratometer. In addition, the anterior to posterior surface ratio was higher than that found in normal eyes. They concluded that the best surgical outcomes would be obtained when using the value of total corneal power for IOL power calculations. We found several articles that discussed IOL power calculations in the presence of KC, but only included 1 or 2 clinical cases.

Visser et al. published 2 cases with toric IOL implantation in patients with KC.[26] In both cases, IOL power calculation relied on K values yielded by the Pentacam topographer, and the axis was determined with a manual keratometer. The formula chosen was SRK/T. Visser hypothesized that in eyes with KC, the astigmatism induced during surgery may be greater than normal because of the cornea's altered biomechanical properties. It is worth pointing out that the implantation of a toric IOL led to a drop in total astigmatism by 70% to 75% in both cases.

Celikkol et al. published a case report of a man with central KC in the right eye and oval inferotemporal KC in the left eye.[27] In the right eye, standard keratometry was used—measured with a keratometer and the SRK formula—whereas in the left eye, the Ks obtained with an anterior surface topographer (Topographic Modeling System-1, Tomey Corp,) and the SRK/T formula were used. The Ks used was the average value of those obtained with the topographer in the 3.0 mm ring. In addition, once the patient had undergone surgery, the authors performed an outcome simulation based on the K values obtained in various ways: (1) simulated K value: average of maximum meridional powers from rings 7, 8, and 9; axis at which the average value occurs, average power of the corneal surface for the same rings at the meridian 90 degrees away; (2) power at vertex normal; (3) mean ring power in each of the 25 rings; and (4) average of consecutive mean ring powers of all 25 rings. This simulation showed that the best outcomes would have been obtained with the K values corresponding to the power at vertex normal and the average power for the first 2 rings. The simulation also showed that better results would have been obtained with Holladay's formula instead.

Park et al. reported the case of an eye with posterior KC and elevated hyperopia (axial length: 20.79 mm).[28] Once the surgery had been performed, they simulated the surgical outcomes using the Hoffer Q, Haigis, or SRK/T formula and relying on different corneal values yielded by either the Pentacam or the Orbscan II devices. The best outcomes were obtained when choosing the exact central value in the true net power map and equivalent K reading at the 2.0 to 3.0 mm zone derived from the Pentacam.

Table 2 summarizes the clinical studies described in this T2 section that show, in detail, how IOL power was calculated in patients with KC. Aside from the studies mentioned

Table 2. Summary of studies on intraocular lens implantation for keratoconus.

Author	Study	Eyes	Pathology (Stage)	Keratometry (K)	Formula	Conclusions
Kamiya et al.[7]	Retrospective	102	Keratoconus (I to III)	K measured with IOLMaster 500 Total corneal refractive power measured by the Pentacam on the central 15-degree ring (equal to the 3.0 mm ring) for IOL power calculations	Haigis, Holladay 1, Holladay 2, Hoffer Q, and SRK II	Accuracy was good in mild keratoconus, but not in moderate to severe keratoconus. Large amount of hyperopic shift in advanced keratoconus when K measured with the IOLMaster was used. Myopic shift occurred, when total corneal refractive power was used.
Watson et al.[9]	Retrospective	92	Keratoconus (I to III)	K measured with the IOLMaster 500 or keratometer Eyes with advanced keratoconus, a standard K value of 43.25 D was used.	SRK-T	K values with a target Of low myopia is a suitable option for spherical IOL selection for eyes with a mean K of ≤55 D In severe keratoconus, the use of actual K values can result in a large hyperopic error and the use of the standard K value in these eyes should be considered.
Savini et al.[12]	Retrospective	41	Keratoconus (I to III)	Corneal curvature (radius) data were converted to corneal power by means of the standard keratometric index (1.3375). Corneal curvatures were measured with biometers	Barrett Universal, Haigis, Hoffer Q, Holladay 1, and SRK/T	All formulas led to a hyperopic refractive outcome. The SRK/T was the most accurate formula. In severe keratoconus, the residual error was higher than in the other stages.
Leccisoti[17]	Prospective	34	Keratoconus (I to II)	Keratometry readings were obtained by axial topographic maps. The dioptric power of the steepest meridian over the central 3.0 mm of the cornea was considered K1, and the dioptric power of the flattest meridian over the central 3.0 mm of the cornea was considered K2. Each meridian power was calculated by averaging its 2 semimeridian values, always considering the central 3.0 mm.	Holladay 2	Refractive lens exchange in keratoconic eyes predictably corrected myopia. IOL exchange due to inaccurate power occurred in 11 eyes (32%; 9 eyes intraoperative, 2 eyes postoperatively)
Hashemi et al.[19]	Retrospective	23	Keratoconus (I to III)	Manual keratometry Keratometry derived from the 3.0 mm central zone in the axial map of the corneal topography Keratometry derived from the refractive map of the Pentacam Keratometry derived from the EKR of the Pentacam (3.0 mm zone)	SRK II, SRK/T, Holladay I, and Hoffer Q	The lowest MAE was obtained with corneal topography–derived keratometry, manual keratometry, and the SRK/T formula in patients with mild KCN, corneal topography–derived keratometry and the SRK/T formula in patients with moderate KCN, and corneal topography–derived keratometry, manual keratometry, and SRK/T and SRK II formulas in patients with severe KCN.

(continued on next page)

Table 2. Continued

Author	Study	Eyes	Pathology (Stage)	Keratometry (K)	Formula	Conclusions
Jaimes et al.[21]	Retrospective	19	Keratoconus (7) Keratoconus Fruste (10) Pellucid marginal degeneration (2)	Keratometry measured with the Pentacam or Orbscan II topographer	SRK II	98.16% correlation between the attempted vs achieved spherical equivalent refraction
Alió et al.[22]	Retrospective	17	Keratoconus (I to II)	No described	Hoffer Q (with lower axial lengths) or SRK/T	The refractive accuracy was better in patients with higher axial lengths and when the SRK/T formula was used.
Thebpatiphat et al.[23]	Retrospective	12	Keratoconus (I to III)	Standard and corneal topography–derived keratometry	SRK, SRK II, and SRK/T An average IOL power was chosen from these calculations.	Patients with mild keratoconus, the SRK II formula was determined to give the most accurate IOL power There was no difference between standard keratometry and corneal topography–derived keratometry in this mild group.
Tamaoki et al.[25]	Retrospective case series	4	Posterior keratoconus	Keratometric values derived from the IOLMaster and autokeratometer estimated the entire corneal refractive power only from the anterior corneal radius using a modified refractive index by empirical estimations of the corneal thickness and posterior surface curvature.	SRK/T	The real corneal power values that take both the anterior and posterior corneal curvatures into consideration should be applied for IOL power calculations in cases with posterior keratoconus.
Visser et al.[26]	Case report	2	Keratoconus	K values obtained with the Pentacam	SRK/T	Patients showed a marked improvement in UCVA and a 70% to 75% reduction in refractive astigmatism with toric IOLs
Celikkol et al.[27]	Case report	2 (1 patient)	Keratoconus	Right eye: Standard K values Left eye: videokeratography-derived K values represented the mean power in ring 3	SRK/T	Determining IOL powers with videokeratography-derived K values might be more accurate than standard keratometry in patients with keratoconus.
Park et al.[28]	Case report	1	Posterior keratoconus	Conventional keratometry Pentacam and Orbscan	Hoffer Q, Haigis, and SRK/T	IOL power calculation from conventional keratometry may be inaccurate, causing hyperopia Pentacam may be one possible alternative to the conventional keratometry to predict the real corneal power of posterior KC.

EKR = equivalent K reading; IOL = intraocular lens; KC = keratoconus

A review of methods used to calculate the power of the IOL to be implanted in cataract surgery in the specific scenario of eyes with KC. The SRK/T formula is the formula yielding the best outcomes. The greater the severity of keratoconus, the greater the deviation of the postoperative refractive status deviation from the target outcome.

above, an additional article has been found in the literature describing the preliminary validation of an algorithm that has been optimized for IOL power calculation, focusing on the theoretical calculation of the keratometry to be used in the IOL calculation, evaluating 13 eyes with KC.

Camps et al. shown that the use of a unique standardized refraction index value (1.3375) for IOL power calculation in KC eyes can lead to inaccuracies—namely, to an overestimation of corneal power—, which could explain the refractive surprises emerging after cataract surgery.[29] However, these inaccuracies could be minimized theoretically using a variable refraction index, which would be dependent on the anterior corneal surface's radius of curvature and would lead to

a maximum error of approximately 0.6 D and over 1 D in his series.

DISCUSSION

There are few publications comprising a sufficient number of series of eyes with KC and showing precisely how to calculate the power of the IOLs, especially with regard to the keratometry value to be inserted in lens power calculation formulas. In this sense, keratometric power is the most complicated parameter to be assessed, although it can be concluded that using a refractive index of 1.3375 overestimates the corneal power of eyes with KC, which can lead to a hyperopic postoperative refractive status.[7,12,29,30] Using the total corneal power seems to lead to better outcomes, although there is no agreement on the specific corneal location where this measurement should be made: some authors propose a central location, whereas others opt for more peripheral ones.[19,27,28] As for the formula to be used, the SRK/T is the one that yields the best outcomes, outdoing the remaining third-generation formulas and even a fourth-generation one such as the Universal Barrett II.[12]

A finding that is common to all studies is that the higher the KC severity score, the less predictable the postoperative refractive outcome.[9,12,17,22,23] Therefore, the use of an intraoperative autorefractometer may help to determine the optimum power of the lens to be implanted in the most severe cases.[17]

During cataract surgery, in patients with KC, the incision position should be considered. Aiello et al. stated that cataract main incision sites should be planned during preoperative examination according to the peripheral corneal thickness rather than the astigmatism axis.[31] In the case of inferotemporal cone, the main incision should be placed superiorly or superotemporal. Other suggestion to reduce the risk of potential wound complications in this kind of surgery should be to suture the clear corneal incisions to ensure wound apposition and possibly regularize the astigmatism.[32] Some surgeons opt for modified scleral tunnel incisions with sutures instead of clear corneal incisions.[7,19,22]

Finally, it has to be emphasized that more studies with larger study populations are needed so that their findings help to calculate corneal power based not only on the KC severity score but also on the position of the apex relative to the center of the cornea.

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000 Intraocular lens power calculation in eyes with keratoconus

Nuria Garzón, PhD, Pedro Arriola-Villalobos, MD, PhD, Gema Felipe, Msc, Francisco Poyales, MD, María García-Montero, PhD

A review of methods used to calculate the power of the intraocular lens (IOL) to be implanted in cataract surgery in the specific scenario of eyes with keratoconus. The SRK/T formula is the formula yielding the best outcomes. The greater the severity of keratoconus, the greater the deviation of the postoperative refractive status deviation from the target outcome.

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