ARTICLES

Estimation of true corneal power after keratorefractive surgery in eyes requiring cataract surgery: BESSt formula

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PURPOSE: To describe a new formula, BESSt, to estimate true corneal power after keratorefractive surgery in eyes requiring cataract surgery.

SETTING: Moorfields Eye Hospital, London, United Kingdom.

METHODS: The BESSt formula, based on the Gaussian optics formula, was developed using data from 143 eyes that had keratorefractive surgery. The formula takes into account anterior and posterior corneal radii and pachymetry (Pentacam, Oculus) and does not require pre-keratorefractive surgery information. A software program was developed (BESSt Corneal Power Calculator), and corneal power was calculated in 13 eyes that had keratorefractive surgery and required cataract surgery.

RESULTS: In the eyes having phacoemulsification, target refractions calculated with the BESSt formula were statistically significantly closer to the postoperative manifest refraction (mean deviation 0.08 diopters [D] ± 0.62 [SD]) than those calculated with other methods as follows: history technique (−0.07 ± 1.92 D; P = .05); history technique with double-K adjustment (0.13 ± 2.39 D; P = .05); Holladay 2 with K-values estimated with the contact lens method (−0.76 ± 1.36 D; P = .03); Holladay 2 with K-values from Atlas topographer (Humphrey) (−0.55 ± 0.61 D; P<.01). Using the BESSt formula, 46% of eyes were within ±0.50 D of the intended refraction and 100% were within ±1.00 D.

CONCLUSIONS: The BESSt formula was statistically significantly more accurate than the other techniques tested. Thus, it could significantly improve intraocular lens power calculation accuracy after keratorefractive surgery, especially when pre-refractive surgery data are unavailable.

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After corneal refractive surgery, the direct use of the measured topographic or keratometric values, without any correction, results in less accurate calculation of intraocular lens (IOL) power required for cataract surgery[1–6] than calculation in virgin eyes. After laser refractive surgery for myopia, this could result in overestimation of keratometric readings, underestimation of the IOL power required, and hyperopic outcomes after phacoemulsification. Conversely, after laser refractive surgery for hyperopia, this could result in underestimation of keratometric readings, overestimation of the IOL power required, and myopic outcomes after phacoemulsification. There may also be a large deviation in spherical equivalent (SE) from the intended refractive outcome.

The main problem lies in the accurate assessment of the "true" refractive power of the cornea after keratorefractive surgery using corneal first-surface measurement by clinical keratometry or videokeratography (corneal topography). There are several reasons these instruments provide less accurate readings after keratorefractive surgery. Keratometers measure only 4 points on the cornea at a paracentral region, ignoring flatter (or steeper), more central regions resulting from myopic (or hyperopic) photoablation. Keratometers are generally calibrated on a standardized value for corneal refractive index (1.3375 in most devices), which may lead to inaccurate estimation of corneal power because the index of refraction of the cornea has been shown to change after keratorefractive surgery.[1,2,7–10]

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Keratometers and corneal topographers use the standardized index of refraction of the cornea to convert measurements of the anterior radius of curvature of the cornea to an estimate of the refractive power of the entire cornea. The formulas used for such conversion are based on 2 assumptions: The thickness of the cornea is constantly 500 μm, as in Gullstrand's exact schematic eye; and the relationship between the anterior curvature and posterior curvature of the cornea is always constant (approximately 82%, as in virgin corneas). Although this could still be valid after incisional procedures such as radial or astigmatic keratotomy, it does not apply after excimer laser procedures such as laser in situ keratomileusis (LASIK) or surface keratorefractive surgery (photorefractive keratectomy [PRK], laser-assisted subepithelial keratectomy [LASEK], or epi-LASIK).[11]

Several methods to estimate keratometric power after refractive surgery have been described.[2–5,12,13] These methods aim to improve IOL power calculation accuracy for cataract or refractive lens exchange (clear lens) surgery. They include the clinical history method,[14–16] contact lens overrefraction method,[11,16,17] double-K adjustment,[6] vertexed IOL power method,[17] effective refractive power calculated from corneal topography using the Holladay Diagnostic Summary (EyeSys Vision),[18] intraoperative autorefraction,[13] and Gaussian optics formula for paraxial imagery.[3,19,20] The Holladay 2 formula (Holladay IOL Consultant Program, Holladay Consulting, Inc.) seems to provide unprecedented levels of accuracy in eyes after keratorefractive surgery. However, it requires knowledge of the following data: preoperative refraction, horizontal white-to-white distance (WTW), phakic anterior chamber depth (ACD), and phakic lens thickness.

Detailed review of the different methods is outside the scope of this paper. However, we will briefly review the 2 most commonly adopted: the clinical history method and the hard contact lens overrefraction technique.

With the clinical history method,[11,17] corneal power after refractive surgery is estimated by subtracting the change in SE refraction after refractive surgery from the corneal keratometry before refractive surgery. This method has been shown to significantly reduce the incidence of a refractive "surprise" following phacoemulsification[21–23] performed after keratorefractive surgery. However, it is limited by a requirement for pre-refractive surgery data (corneal power and refraction) and post-refractive surgery refractive data. The refractive information before and after refractive surgery but before cataract formation may not be available. In that case, the cataract surgeon can only rely on the refractive data obtained before cataract surgery, which is affected by the refractive changes induced by the presence of the cataract.

The contact lens overrefraction method provides an estimate of corneal power after refractive surgery and does not require pre-refractive surgery information. This technique has significant limitations. First, as with the clinical history method, refraction performed immediately before phacoemulsification surgery is affected by the cataract and could potentially be inaccurate. Second, the meniscus between the back of the contact lens and the anterior corneal surface is increased in patients who have had myopic laser refractive surgery. The contact lens acts as a convex lens, potentially inducing a myopic shift in refraction. Third, the method is time consuming. Also, poor accuracy has been shown for this method in the literature.

We believe that the ideal method of calculating corneal power after refractive surgery should be based on direct measurement of the cornea independent of preoperative information. Until recently, clinical measurement of corneal power involved assumptions or empirical factors being introduced to compensate for the unknown corneal posterior radius of curvature and refractive index of the cornea after the ablation. The Oculus Pentacam is a rotating Scheimpflug camera anterior segment imaging system that can obtain a measure or estimation of both the anterior and posterior corneal curvatures. Theoretically, the measurement taken from the Pentacam could be used in the Gaussian optics formula to calculate corneal power in virgin eyes or in eyes with keratorefractive surgery because estimation of corneal power with this method depends purely on corneal radii.

PATIENTS AND METHODS

After Institutional Review Board approval, a retrospective review was performed of data of those who had primary wavefront-guided LASIK or surface ablation (LASEK) for the treatment of myopia, compound myopic astigmatism, hyperopia, compound hyperopic astigmatism, or mixed astigmatism. In all cases, surgery was performed using a Star S4-IR excimer laser (AMO-Visx). Data included were manifest refraction and results from Pentacam corneal scans preoperatively and 3 months after surgery. Excluded were all eyes with previous corneal or intraocular surgery and

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Giovanni Racciu, Xystum s.r.l., developed the software version of the BESSt formula, the BESSt Corneal Power Calculator, used in all calculations.

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cases in which severe dry eye affected the quality of the Pentacam scans or manifest refraction.

The following data were reviewed at baseline and 3 months after surgery: manifest refraction; simulated (automated) keratometry and autorefraction (using a Topcon KR-8100PA); anterior and posterior mean corneal curvature (cornea front and cornea back Rm values, as in the refractive maps of the Pentacam), and central corneal thickness (mean corneal thickness in the pupil center as presented in the Pentacam clinical software).

Considering the cornea as a 2-surface system and using the Gaussian optics formula, one can then calculate the effective power of the cornea as the sum of the refractive power of each surface (equation 1).

$$F_{tot} = F_{ant} + F_{post} - (d/n) \times \left(F_{ant} \times F_{post}\right) \quad (3)$$

Equation 1 can also be written as

$$F_{tot} = [1/r_{ant} \times (n_1 - n_0)] + \left[1/r_{post} \times (n_2 - n_1)\right] - (d/n_1) \times [1/r_{ant} \times (n_1 - n_0)] \times \left[1/r_{post} \times (n_2 - n_1)\right]$$

where F_{tot}, F_{ant}, and F_{post} are the power of the total, anterior, and posterior corneal surfaces, respectively, in diopters (D); d is the corneal thickness (m); n is the corneal refractive index; r_{ant} and r_{post} are the anterior and posterior radii of curvature of the cornea (m); n_0 is refractive index of air (1.000); n_1 is the refractive index of the anterior corneal surface (1.376); and n_2 is the refractive index of aqueous humor (1.336).

Mathematical analysis of the results comprised the following steps:

1. The accuracy of the Gaussian optics formula in estimating the corneal power in virgin corneas before refractive surgery was assessed, and the results were compared to the actual values measured with corneal topography (regression analysis and t test). The Gaussian optics formula was then modified on the basis of the results of regression analysis to take these differences into account. The modified version of the Gaussian optics formula was termed BESSt_vc (vc = virgin corneas) formula.
2. In eyes after keratorefractive surgery, the corneal power estimated with the BESSt_vc formula was compared by regression analysis to the values obtained with the clinical history technique (history), which in this study served as the reference method. (Note: The circumstances of this study overcame the 2 main limitations of the history method because all the required pre-refractive surgery information, such as refraction and keratometry, was available and one can assume no lens changes occurred between surgery and the time of observation 3 months later.)
3. The BESSt_vc formula was then refined on the basis of the results of the regression analysis until the closest possible fit with the K-values calculated with the history method was obtained. A correcting factor was introduced to compensate for steep and flat corneas after laser refractive surgery. This final version of the formula was named the BESSt formula (Appendix) and, together with the history technique and the SRK/T and Hoffer Q formulas (with or without the double-K adjustment), was implemented in a Microsoft Windows software program, the BESSt Corneal Power Calculator, which was used for all the calculations in the study (Figure 1).
4. The accuracy of the BESSt formula was tested in 13 eyes that had previous keratorefractive surgery and were referred for phacoemulsification cataract surgery.

It is standard practice at Moorfields Eye Hospital to obtain pre-refractive and post-refractive surgery refractive and keratometric data before performing cataract surgery in eyes that have had previous keratorefractive surgery. A hard contact lens

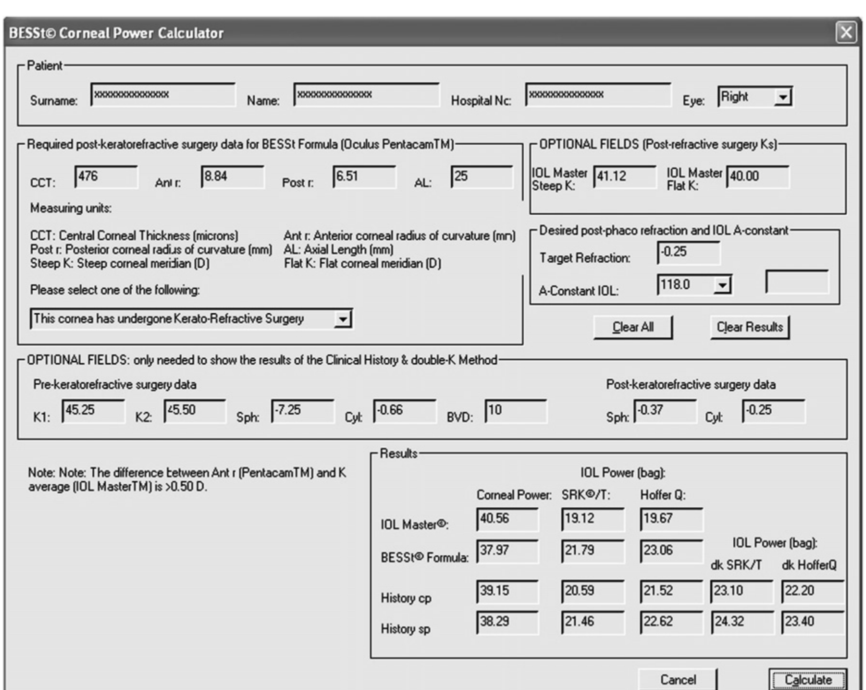

Figure 1. Snapshot of the BESSt Corneal Power Calculator, the program used for all calculations in the study.

refractive assessment estimation of corneal power, topographic analysis (Atlas corneal topography, Carl Zeiss Meditec, Inc.), and Pentacam assessment are also performed. The IOLMaster (Carl Zeiss Meditec, Inc.) was used for partial coherence interferometry assessment of the axial length (AL) of the eye. The power of the cornea after refractive surgery was estimated with the following techniques: (1) the BESSt formula; (2) the most commonly used technique (which requires pre-refractive surgery information): the clinical history technique, with or without the double-K adjustment; (3) the Holladay 2 formula with K-values estimated with the hard contact lens method (which does not require pre-refractive surgery information); (4) the Holladay 2 formula with K-values taken from Atlas corneal topography (which does not require pre-refractive surgery information but requires the knowledge of preoperative refraction, WTW distance, phakic ACD, and phakic lens thickness). When the double-K adjustment was applied to the clinical history method, the SRK/T formula was modified so that the K-values before keratorefractive surgery were used in the effective lens position equation and the history-derived K-values were used in the IOL power equation.

Except for when the Holladay 2 was used, the power of the IOL to be implanted during cataract surgery was calculated with the SRK/T[24] or Hoffer Q[25] formula, depending on AL (Hoffer Q if AL $\leq$22.0 mm). Finally, the IOL power was chosen by the surgeon taking into account the above-described techniques. Akreos Adapt IOLs (Bausch & Lomb) were implanted in all eyes. An optimized A-constant was used in all cases. The optimized A-constant value used, taken from previous series, was 118.43. For each patient, the surgeon considered the relatively large standard deviation in refractive outcome. The planned target incorporated the most favorable range of outcomes, and if the refractive target was not achieved, a further refractive procedure would be performed.

Six weeks after surgery, patients' postoperative manifest refraction and the mean and absolute differences between the achieved postoperative refraction and the target refraction were calculated (or back-calculated) using each method. These were compared using a paired *t* test (significance level $P<.05$). For each technique, the mean and mean absolute deviation from the target refraction, standard deviations, and confidence intervals were recorded. Refractive assessments were performed by an experienced optometrist familiar with the visual assessment of eyes after refractive surgery.

RESULTS

Preoperative and postoperative data from 210 consecutive eyes having laser refractive surgery were assessed. Forty-three eyes were excluded because of therapeutic or secondary laser eye treatments and 20 because of incomplete data sets (lack of Pentacam scanning preoperatively); 4 eyes were excluded because of artifacts on Pentacam scans caused by postoperative dry eye or poor Pentacam images from movement and partial ptosis with incomplete imaging. One hundred forty-three eyes (82 patients) were included in the analysis, meeting study criteria. Of these, 123 eyes had myopic wavefront-guided LASIK or LASEK (97 and 26, respectively) and 20 had hyperopic wavefront-guided LASIK based on the preoperative SE.

In the 143 virgin corneas (ie, before refractive surgery), there was a statistically significant correlation between corneal power measured by videokeratoscopy (Topcon KR-8100PA) and the power calculated with the Gaussian optics formula ($r = 0.97$; $r^2 = 0.95$; $P<.05$), although the Gaussian optics formula consistently underestimated topographic values by a mean of -1.30 D $\pm$ 0.29 (SD) (Figure 2). This was addressed after the index of refraction of the cornea used in the Gaussian optics formula was adjusted based on the results of a regression analysis (K-values BESSt_vc = 0.2431 + 0.9942 $\times$ K-values Gaussian optics formula). The improved version of the Gaussian optics formula, the BESSt_vc formula, marginally improved the correlation ($r = 0.984$; $r^2 = 0.97$; $P<.05$) but significantly reduced the difference from the topographical values (mean difference = -0.01 ± 0.24 D).

In the 123 eyes having myopic keratorefractive surgery, the mean preoperative refraction was -4.53 ± 2.12 D (mean preoperative K-value 43.38 $\pm$ 1.34 D). In the 20 eyes in the hyperopic group, the mean was $+1.61 \pm 0.80$ D (mean preoperative K-value 43.32 $\pm$ 1.68 D).

In the group that had myopic keratorefractive surgery, the mean corneal power calculated with the history method (the reference technique) was 39.18 $\pm$ 2.00 D compared to

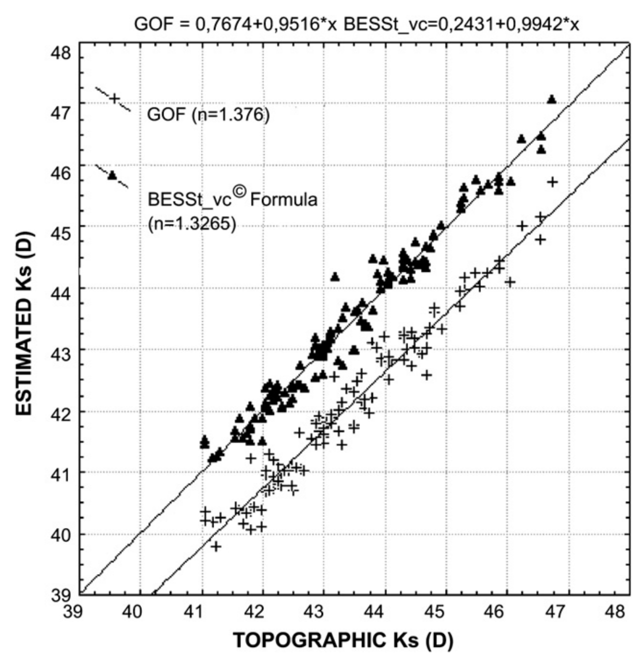

Figure 2. Graph of the correlation in untreated eyes between corneal power values calculated with videokeratoscopy (Topcon KR-8100PA) and the ones estimated with the Gaussian optics formula and the improved version of this formula, the BESSt_vc. The raw application of the Gaussian optics formula resulted in a gross and consistent underestimation of topographic corneal power in flat corneas and in steep corneas. Corneal power estimated with the BESSt_vc formula provided a much closer fit with topography (GOF = Gaussian optics formula; Ks = corneal power [D]; n = stromal refractive index of the cornea used in the formula).

Table 1A. Corneal power after myopic refractive surgery (n = 123; 97 LASIK, 26 LASEK).

Parameter	History (cp)	BESSt	GOF	BESSt (Abs)	GOF (Abs)
Corneal power (D)					
Mean ± SD	39.18 ± 2.00	39.17 ± 2.06	37.73 ± 1.92	—	—
Range	34.53 to 45.08	34.61 to 45.78	33.52 to 44.09	—	—
Corneal power Δ (D)					
Mean ± SD	—	−0.01 ± 0.55	−1.45 ± 0.56	0.41 ± 0.37	1.45 ± 0.56
Range	—	−2.21 to 1.52	−3.58 to 0.13	0.00 to 2.21	0.13 to 3.58

Δ = difference between corneal power values estimated with each technique and the reference values calculated with the clinical history method; Abs = absolute values; GOF = Gaussian optics formula; History (cp) = history technique with corneal power measured at the corneal plane

37.73 ± 1.92 D estimated with the Gaussian optics formula and 39.17 ± 2.06 D using the BESSt formula (regression analysis = K-values BESSt formula = 7.8385 + 0.7458 × K-values BESSt_vc formula (Table 1, *A*, and Figure 3). There was no statistically significant difference between corneal power estimated with the BESSt formula and the power calculated with the reference history technique (mean difference −0.01 ± 0.55 D) ($P>.05$).

In the group having hyperopic keratorefractive surgery, the mean corneal power calculated with the history technique was 44.79 ± 2.21 D compared with 43.10 ± 1.85 D estimated with the Gaussian optics formula and 44.34 ± 1.83 D estimated with the BESSt formula (Table 1, *B*). There was no statistically significant difference between the corneal power estimated with the BESSt formula and the power calculated with the history technique at the corneal plane (mean difference −0.45 ± 0.78 D ($P>.05$). Because the BESSt formula was calibrated and refined on eyes having myopic refractive surgery, it was not surprising that the correlation with the history-derived K-values was excellent for eyes after myopic ablations and slightly less accurate for eyes after hyperopic ablation.

In the 13 eyes having phacoemulsification with IOL implantation after previous keratorefractive surgery for myopia or hyperopia (Table 2), the mean difference from the actual postoperative refraction was 0.08 ± 0.62 D for the BESSt formula, −0.91 ± 0.80 D for the Gaussian optics formula, −0.07 ± 1.92 D for the history technique, 0.13 ± 2.39 D for the history technique with double-K adjustment, −0.76 ± 1.36 D for the Holladay 2 formula using K-values from the hard contact lens overrefraction technique, and −0.55 ± 0.61 D for the Holladay 2 formula using K-values from the Atlas topographer (Table 3). The standard deviation of the mean prediction error of the BESSt formula was 2 to 4 times smaller ($P<.05$) than the standard deviations of all the other techniques and similar to the one of the Holladay 2 formula with K-values from Atlas topographer. However, postoperative refraction prediction was statistically significantly more accurate with the BESSt formula than with the Holladay 2 formula (mean prediction error 0.08 D and −0.55 D, respectively ($P<.01$) (Figure 4, *A*). The standard deviation of the mean absolute error of the BESSt formula was half that of the Holladay 2 formula with K-values from the Atlas topographer (±0.26 D and ±0.49 D, respectively) (Figure 4, *B*).

The proportion of eyes within ±0.50 D of the intended postoperative refraction was 46% with the BESSt formula, 23% with the history technique, 39% with the hard contact lens technique with the Holladay 2 formula, 31% with the double-K SRK/T technique, and 54% with the Holladay 2 formula with K-values from the Atlas topographer. This proportion increased to 100% of eyes within ±1.00 D using the BESSt formula compared to 31%, 62%, 31%, and 69% with the other formulas, respectively (Table 4).

Table 1B. Corneal power after hyperopic refractive surgery (n = 20 LASIK).

Parameter	History (cp)	BESSt	GOF	BESSt (Abs)	GOF (Abs)
Corneal power (D)					
Mean ± SD	44.79 ± 2.21	44.34 ± 1.83	43.10 ± 7.85	—	—
Range	41.51–48.52	41.77–47.97	40.83–46.68	—	—
Corneal power Δ (D)					
Mean ± SD	—	−0.45 ± 0.78	−1.69 ± 0.78	0.62 ± 0.65	1.69 ± 0.78
Range	—	−2.85–0.76	−3.89–0.55	0.03–2.85	0.55–3.89

Δ = difference between corneal power values estimated with each technique and the reference values calculated with the clinical history method; Abs = absolute values; GOF = Gaussian optics formula; History (cp) = history technique with corneal power measured at the corneal plane

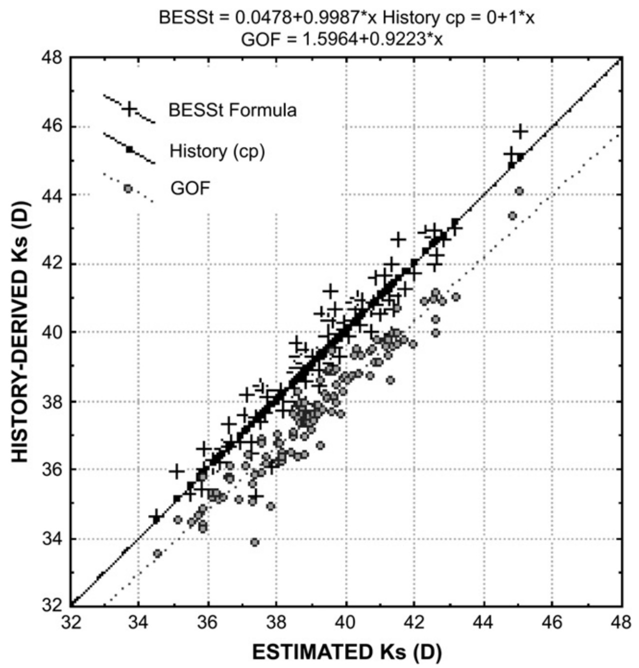

Figure 3. Corneal power after myopic wavefront-guided LASIK and LASEK calculated with the BESSt formula closely matches the power estimated with the history technique and is significantly more accurate than the power estimated with the Gaussian optics formula. GOF = Gaussian optics formula; Ks = corneal power (D); History cp = corneal power estimated with clinical history method with refraction vertexed at the corneal plane (D).

With the BESSt formula, no eye was beyond ±1.50 D of the intended refraction compared to 8% with the Holladay 2 formula/Atlas topographer.

DISCUSSION

The prediction accuracy and standard deviation of the postoperative refraction after IOL implantation that we obtained using the history method was comparable to those in published peer-reviewed literature (Table 5), which varied between a minimum of ±0.87 D to a maximum of ±2.81 D. The standard deviations were ±1.59 D (21 eyes),[26] between ±0.87 D and ±1.35 D (7 cases),[27] between ±0.90 D and ±1.00 D (6 eyes),[13] ±2.42 (19 eyes),[28] and ±2.81 (10 eyes).[2] The use of the historical method with double-K adjustment in our data set did not result in greater accuracy or a smaller standard deviation. Our results with this method are similar to those in a study by Rosa et al.[28] (SD ±3.64 D), in which 19 eyes were analyzed, but significantly worse than those published by Aramberri[6] (SD ±0.62 D), in which 9 eyes were analyzed. We could not find published data on the accuracy of the Holladay 2 formula with K-values taken from modern topographers. In our study population, the BESSt formula had half the absolute standard deviation and nearly 0.50 D greater accuracy than the Holladay 2 formula using K-values from the Atlas topographer. The R factor technique published by Rosa et al.[29] seems to perform similarly to the BESSt formula for ±0.50 D accuracy but had a smaller percentage of eyes (66%) within ±1.00 D of the intended refraction than with our formula (100%). The results using the BESSt formula compared favorably with those obtained with ray-tracing technology combined with corneal topography (mean error 0.31 ± 0.84 D versus 0.08 ± 0.62 D).[30] However, ray-tracing may be associated with unpredictability if applied to corneas with radii of curvature >10.0 mm. Other nomogram-based techniques[3,31,32] seem to perform better than the BESSt

Table 2. Original refractive error prior to refractive surgery and information on the power of the IOL implanted during phacoemulsification. All values are expressed in diopters.

Eye	Procedure	Sph	Cyl	SE cp	IOL
1	M LASIK	−6.25	−0.50	−6.03	21.5
2	M LASIK	−9.50	−1.00	−8.62	17.0
3	M LASIK	−5.00	0	−4.89	21.0
4	M LASIK	−4.75	−1.50	−5.15	20.0
5	M PRK	−2.25	−1.50	−2.89	20.0
6	M PRK	−7.00	−2.00	−7.40	17.0
7	M epi-LASIK	−2.75	−1.25	−3.24	18.0
8	H LASIK	1.75	−0.25	1.66	21.5
9	H LASIK	1.25	−0.25	1.15	21.5
10	H LASIK	8.00	−0.50	8.55	30.0
11	H PRK	7.00	0	7.64	30.0
12	H PRK	6.75	0	7.34	29.0
13	H CK	2.50	0.25	2.71	20.0

CK = conductive keratoplasty; Cyl = cylinder; H = hyperopic; IOL = intraocular lens power; LASIK = laser in situ keratomileusis; M = myopic; SE cp = spherical equivalent at the corneal plane; Sph = sphere

Table 3. Mean difference between actual postoperative refractions and target refractions calculated (or back-calculated) with the different formulae. *P* values refer to the results of *t* test comparison with those of the BESSt formula. All values are expressed in diopters.

Method	Mean ± SD	*P* Value	Abs Mean ± SD	*P* Value
BESSt	0.08 ± 0.62	—	0.54 ±0.26	—
GOF	−0.91 ± 0.80	<.01	0.95 ±0.74	.04
History	−0.07 ± 1.92	.75	1.54 ±1.06	<.01
d-K SRK/T	0.13 ± 2.39	.93	1.70 ±1.62	.03
CL Holladay 2	−0.76 ± 1.36	.03	1.10 ±1.8	.08
Atlas Holladay 2	−0.55 ± 0.61	<.01	0.65 ± 0.49	.40

Abs Mean = absolute mean; Atlas Holladay 2 = Holladay 2 formula using central K-values provided by Atlas corneal topography; CL Holladay 2 = contact lens overrefraction technique using Holladay 2 formula; d-K SRK/T = double-K SRK/T technique; GOF = Gaussian optics formula

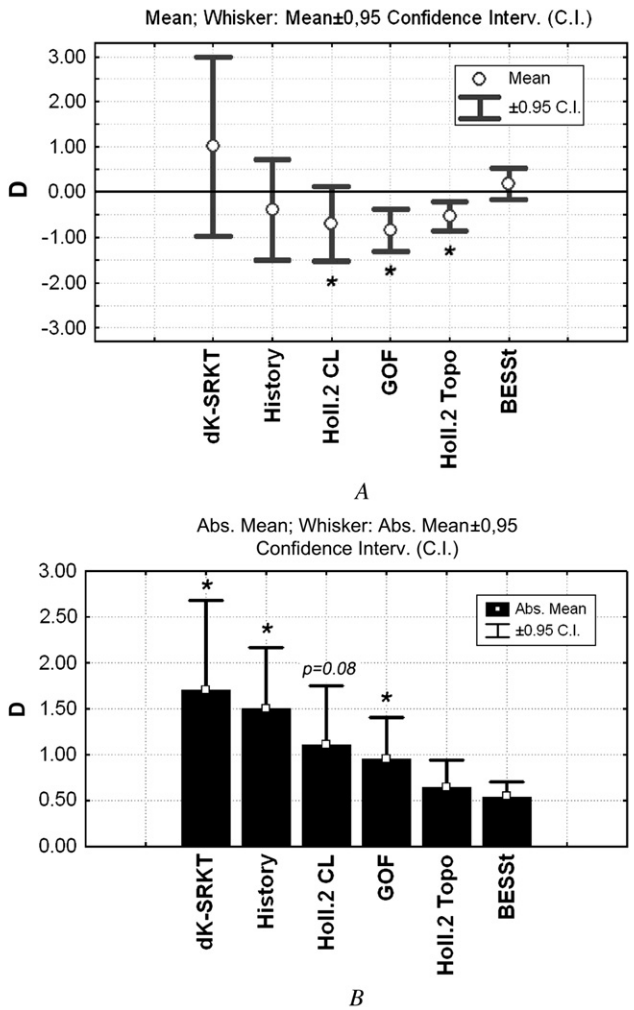

Figure 4. Mean deviation (*A*) and mean absolute deviation (*B*) from the target refractions calculated with the various techniques and the actual postoperative refractions after phacoemulsification in the 13 eyes that previously had refractive surgery. (Refer to Table 2 for the pre-refractive surgery refractions.) The zero line represents a perfect match between the target and the achieved post-phacoemulsification refraction. The BESSt formula provided the greatest accuracy and the smallest absolute standard deviation of the other formulas analyzed. *Statistically significant difference ($P<.05$) between current technique and BESSt formula; C.I. = confidence interval; Abs. Mean = absolute mean; d-K SRKT = history technique with double-K SRK/T adjustment; History = history technique; Holl.2 CL = contact lens overrefraction technique using Holladay 2 formula; GOF = Gaussian optics formula; Holl.2 Topo = Holladay 2 formula using central K-values provided by Atlas corneal topography.

formula in terms of the proportion of eyes within ±0.50 D of the intended refraction but are similar for the proportion of eyes within ±1.00 D. However, all these techniques, like the clinical history method, require knowledge of the refraction before refractive surgery.

We generally assume that topographic K-values are fairly accurate in virgin eyes. If this assumption stands,

Table 4. Proportion of the 13 operated eyes that were within ±0.50 D, ±1.00 D, and ±1.50 D of the intended postoperative refraction after phacoemulsification.

Deviation from Intended (D)	BESSt (%)	History (%)	d-K SRK/T	CL Holladay 2	Atlas Holladay 2
≤0.50	46.2	23.1	30.8	38.5	53.8
≤0.75	76.9	23.1	38.4	38.5	61.5
≤1.00	100	30.8	38.4	61.5	69.2
≤1.50	100	61.5	46.2	61.5	92.3
>1.50	0	38.5	53.8	38.5	7.7

Atlas Holladay 2 = Holladay 2 formula using central K-values provided by Atlas corneal topography; CL Holladay 2 = contact lens overrefraction technique using Holladay 2 formula; d-K SRK/T = double-K SRK/T technique

the corneal power calculated with the Gaussian optics formula based on the anterior and posterior corneal curvatures measured with the Pentacam should theoretically be close to the topographic K-values. However, the Gaussian optics formula consistently underestimated corneal values by 1.30 D on average (Figure 1), indicating that either K-values measured with corneal topography in virgin eyes overestimate corneal power by more than 1.00 D or anterior or posterior corneal curvatures measured with the Pentacam are not correct. This difference in measurement may be explained by the fact that whereas the Gaussian optics formula should theoretically measure total corneal power, standard keratometry measurement may not take into full account the (negative) posterior corneal power. It may be that historical assumptions about posterior corneal curvature on which standard keratometers are based are not completely correct even in virgin eyes. However, because there is no current gold standard against which to test the Pentacam and standard keratometers, neither of the 2 hypotheses can be excluded. The corneal refractive index we obtained after regression analysis in virgin corneas (1.3265) seems low for a virgin cornea, and it may be possible that unknown factors other than the sole index of refraction of the stroma were taken into account in the regression analysis.

In the 123 eyes that had myopic keratorefractive surgery, we observed a linear decrease in central corneal thickness (CCT) after surgery, which was proportional to the amount of myopia treated (unpublished data). The history method was the reference used to calculate corneal power after refractive surgery in virgin eyes in our study (see note, number 2 in list, Patients and Methods). To measure corneal power after refractive surgery, we back-calculated the index of refraction of the cornea in the Gaussian optics formula that would have been required to achieve a match between the refraction so calculated and the one calculated with the history method (Figure 5). We termed this the

Table 5. Refractive outcomes of phacoemulsification after previous keratorefractive surgery in the published literature.

	Percentage					
Deviation from Intended (D)	History	d-K SRK/T	R Factor	History + Nomogram (Laser Ablation)	Nomogram (Laser Ablation)	Ray Tracing + Topography
≤0.50	30[2] 26.1[28]	66.6[6]	45.4[26]	71[3,30]	63.2[29]	40[27]
≤1.00	55.7[28] 50 to 66[13]	88.9[6]	65.9[26]	94[3,30]	84.2[29]	70[27]
≤1.50	—	—	—	—	100[29]	100[27]
>1.50	40[2]	—	—	—	—	—
≤2.00	63.2[28]	52.6[28]	—	—	—	—

d-K SRK/T = double-K SRK/T technique; R Factor = R factor technique[26]

adjusted index of refraction of the cornea. On the *x*-axis of the graph in Figure 5, we plotted the amount of myopia treated (in diopters) and on the *y*-axis, the adjusted corneal refractive index in the Gaussian optics formula. We found that this (theoretical) adjusted index of refraction of the cornea increased proportionally to the amount of myopia treated ($r = -0.57$; $r^2 = 0.32$; $P < .0001$; regression analysis: adjusted n = 1.3187 − 0.0045 × SE myopia treated). These findings suggest that the corneal refractive index may theoretically increase after myopic refractive surgery as measured with the Oculus Pentacam. A change in the apparent corneal refractive index was found by Patel et al.,[7] who measured the corneal refractive index using a handheld Abbe refractometer. They found that the initial refractive index of the anterior stromal surface of the human cornea after removing the epithelium ranged from 1.372 to 1.381 within 1 hour of enucleation. The refractive index then increased exponentially after exposure to air as a result of progressive stromal dehydration. They also measured the refractive index of the stroma before and after LASIK in vivo in 44 previously untreated eyes and found a statistically significant increase in the stromal refractive index (from 1.372 to 1.384) immediately after photoablation. It has been shown that the refractive index is not uniform throughout the cornea: 1.401 for the epithelium; 1.380 for the anterior stroma; 1.373 for the posterior stroma.[9] After surface laser treatment, a wound is created between the stroma and the corneal epithelium; whereas after a LASIK procedure, an interface is generated within the anterior stroma, with possible effects on the overall stromal refractive index.

From the change in corneal pachymetry resulting from refractive surgery, there can be some prediction of the adjusted corneal refractive index in the Gaussian optics formula, and this can also be derived from post-refractive surgery CCT alone. We found a statistically significant correlation between post-refractive surgery pachymetry and the adjusted refractive index ($r = -0.25$; $r^2 = 0.06$; $P = .006$) (Figure 6). However, post-refractive surgery CCT is

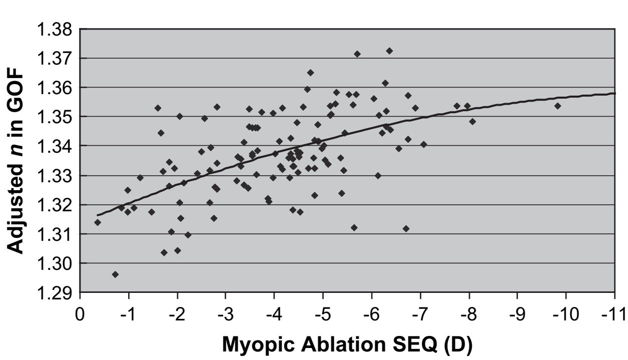

Figure 5. Correlation between SE refraction of the myopic treatment applied to the cornea and the adjusted index of refraction of the cornea (n) in the Gaussian optics formula (N = 123; $r = -0.57$; $r^2 = 0.32$; Regression: AblationSEQ = −1838.07 + 1371.49 × x; $P < .0001$). Refer to text for full explanation (SEQ = spherical equivalent refraction at the corneal plane; GOF = Gaussian optics formula).

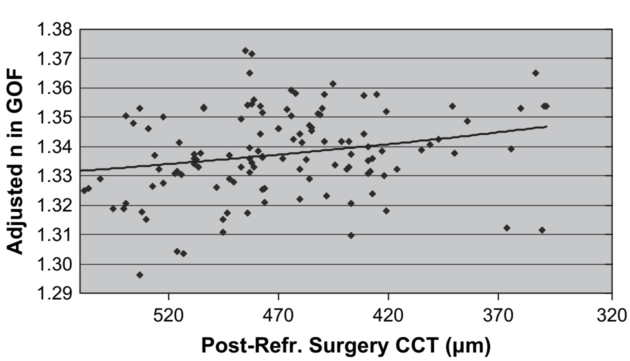

Figure 6. Correlation between post-refractive surgery CCT and the adjusted index of refraction of the cornea (n) in the Gaussian optics formula (N = 123; $r = -0.25$; $r^2 = 0.06$; Regression: PostCCT = 9604.26 − 12855.050 × x + 4504.36 × x^2; $P = .006$). Refer to text for full explanation (CCT = central corneal thickness; GOF = Gaussian optics formula).

mainly dependent on pre-refractive surgery pachymetry and the type of refractive procedure performed. With time and age, there may also be long-term changes in corneal thickness and the refractive index.

Since the BESSt formula was the result of fine-tuning of the Gaussian optics formula using the basis data set of eyes having myopic refractive surgery, there was a possibility there would be a wider standard deviation in outcome after phacoemulsification in the eyes with previous hyperopic refractive surgery. However, the formula had no difference in predictability for hyperopic refractive surgery in the eyes assessed in this study (Figure 7).

We used the SRK/T formula to calculate IOL power in "normal" eyes and the Hoffer Q formula in eyes with AL of 22.0 mm or less. The published SRK/T formula is known to be affected by 2 phenomena that could result in inaccurate IOL power calculation in eyes with particular combinations of AL and keratometric values. These phenomena are known as the zero argument problem and the cusp phenomenon, and they occur most frequently in eyes with very steep corneas[33] (Appendix). The first phenomenon occurs when the argument of the square root of the ACDest equation in the SRK/T formula becomes negative. This results in an error in the formula as it was published in 1990,[24] therefore not allowing IOL power calculation. This problem was later addressed in the version of the formula implemented in the IOLMaster by assigning the value 0 to the argument of the square root of the ACDest equation whenever such value is negative. The SRK/T cusp is another unexpected side effect of the combination of the previous problem and the specific form of the ACD prediction in the SRK/T formula (J.A. Retzlaff, MD, et al., "SRK/T Formula "Cusp," Ocular Surgery News, August 15, 1992, page 3).

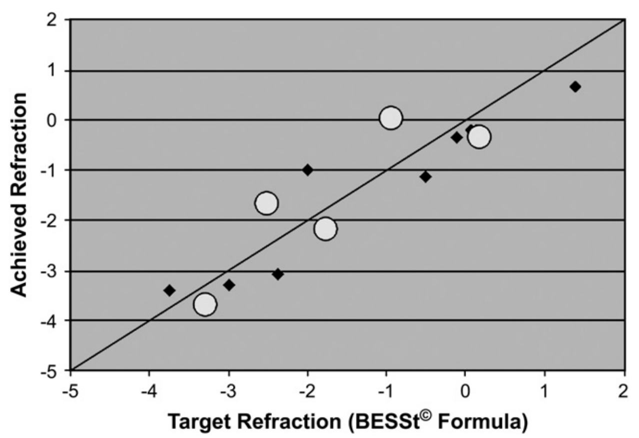

Figure 7. Achieved versus target refraction after phacoemulsification following refractive surgery. The diamonds and the circles represent eyes that had myopic keratorefractive surgery and eyes that had hyperopic keratorefractive surgery, respectively, before phacoemulsification. All values are in diopters. The graph shows that the BESSt formula was equally accurate after myopic and hyperopic treatments.

When they occur, these phenomena may give rise to markedly inaccurate IOL power calculations. In this situation, alternative formulas such as the Hoffer Q can be used. In our software, we implemented an algorithm to automatically detect when either phenomenon occurred and opted for alternative formulas in those situations. No eye was affected by these phenomena.

One limitation of the data set on which the basis data of this formula was created is that it is based on modern wide-optical-zone laser refractive correction. The Staar S4-IR laser uses a minimum optical zone of 6.0 mm and a blend zone between 8.0 mm and 9.5 mm. The treated zones have a smooth change in curvature, whereas early excimer laser procedures used a relatively small treatment zone diameter. Early excimer lasers and software created effective optical zones that were much smaller than those of modern systems. Such treatments over the pupil entrance may have multifocal optical properties, and biometric determination is then a weighted average of the optical powers measured. Nonlaser procedures such as radial keratotomy and conductive keratoplasty may also involve very small optical zones, multifocality, and optical irregularity within the pupil entrance. The BESSt formula was developed using corneal curvature measurements taken from an Oculus Pentacam instrument. Currently, no published data exist on the reproducibility of measurements of posterior corneal curvature with this instrument. A randomized prospective clinical trial is underway to compare the outcomes of the BESSt and those of the Holladay 2 formula and Pentacam Holladay Report in eyes having phacoemulsification after keratorefractive surgery. A software version of the BESSt formula is available online (www.besstformula.com).

CONCLUSION

We present 2 formulas that calculate an estimation of corneal power in virgin eyes (BESSt_vc) or in eyes after refractive surgery (BESSt). The calculations are based on information from the anterior and posterior corneal curvatures rather than keratometry.

The BESSt formula, which uses a variable rather than a static index of refraction for each cornea, showed significantly smaller (better) standard deviations and proved to be statistically significantly more accurate than published methods such as the history technique (with or without double-K adjustment) and the Holladay 2 formula with K-values taken from modern topography. Our formula has significant advantages over the other techniques in that it does not requiring any pre-refractive surgery data to estimate corneal power and can be used successfully in eyes after either myopic or hyperopic laser keratorefractive surgery. It is not yet determined how predictable the formula is in eyes with other keratorefractive refractive procedures, such as astigmatic or radial keratotomy. A separate data set with new basis data may be required. We believe the BESSt formula represents a significant leap forward in IOL power calculation accuracy after keratorefractive surgery, and we think it should reduce the risk for refractive surprises in these eyes.

APPENDIX

BESSt and BESSt_vc Formulas

Input Variables

rF (front corneal radius [mm])
rB (back corneal radius [mm])
CCT (central corneal thickness [μm])

Formula

$$n\ air = 1$$

$$n\_vc = 1.3265$$

$$n\_CCT = n\_vc + (CCT \times 0.000022)$$

$$k\_conv = 337.5/rF$$

$$n\_adj$$

IF $k\_conv < 37.5$, n_adj EQUALS $n\_CCT + 0.017$

IF $k\_conv < 41.44$, n_adj EQUALS n_CCT

IF $k\_conv < 45$, n_adj EQUALS $n\_CCT - 0.015$

ELSE, n_adj EQUALS n_CCT

$$n\_acq = 1.336$$

$$d = d\_cct/n\_vc$$

$$d\_cct = CCT/1\,000\,000$$

$$Fant = 1/rF \times (n\_vc - n\_air)$$

$$Fpost = 1/rB\,(n\_acq - n\_vc)$$

Outputs

$$\begin{aligned} \text{BESSt\_vc K (corneal power in virgin corneas [D])} = \{&[1/rF \times (n\_vc - n\_air)] \\ &+ [1/rB \times (n\_acq - n\_vc)] \\ &- [d \times 1/rF \times (n\_vc - n\_air) \\ &\times 1/rB \times (n\_acq - n\_vc)]\} \times 1000 \end{aligned}$$

$$\begin{aligned} \text{BESSt K (corneal power after keratorefractive surgery [D])} = \{&[1/rF \times (n\_adj - n\_air)] \\ &+ [1/rB \times (n\_acq - n\_adj)] \\ &- [d \times 1/r \times (n\_adj - n\_air) \\ &\times 1/rB \times (n\_acq - n\_adj)]\} \times 1000 \end{aligned}$$

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