Development of the SRK/T intraocular lens implant power calculation formula

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ABSTRACT

A new implant power calculation formula (SRK/T) was developed using the nonlinear terms of the theoretical formulas as its foundation but empirical regression methodology for optimization. Postoperative anterior chamber depth prediction, retinal thickness axial length correction, and corneal refractive index were systematically and interactively optimized using an iterative process on five data sets consisting of 1,677 posterior chamber lens cases. The new SRK/T formula performed slightly better than the Holladay, SRK II, Binkhorst, and Hoffer formulas, which was the expected result as any formula performs superiorly with the data from which it was derived. Comparative accuracy of this formula upon independent data sets is addressed in a follow-up report. The formula derived provides a primarily theoretical approach under the SRK umbrella of formulas and has the added advantage of being calculable using either SRK A-constants that have been empirically derived over the last nine years or using anterior chamber depth estimates.

Key Words: A-constant, A-scan, anterior chamber depth, axial length, biometry, height formula, intraocular lens power calculation, regression formula, SRK, SRK II, SRK/T, theoretical formula

Regression-derived lens implant power formulas have an excellent accuracy record.[1-8] Still, theoretical formulas, because they are based on physiologic optics, may be more accurate than regression formulas when extended past a given database as in unusually long or short eyes.

In addition to proven accuracy, regression formulas are simpler to derive and manipulate than theoretical formulas.[9] Residual error, due to surgeon technique or intraocular lens (IOL) design, is combined into a single constant. In the SRK and SRK II formulas, there are existing A-constants that were empirically derived and individualized by manufacturers and surgeons over the last nine years.

Many surgeons have expressed a desire to compare regression formula results with theoretical formula results for a given case and, if possible, have some sort of definitive correlation between the regression A-constants and the theoretical anterior chamber depth (ACD) determinations. We decided, therefore, that it would be valuable to offer a theoretical approach to implant power calculation under the SRK umbrella of formulas. We sought to merge the theoretical and empirical approaches,

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using the best attributes of both, by combining the principles and methods of data analysis used for development of the SRK formulas with the principles and methods which have evolved in the development of the theoretical formulas. This paper presents the SRK/T (SRK/theoretical) formula and the methods used to derive it.

MATERIALS AND METHODS

Five formula derivation data sets, consisting of a total of 1,677 posterior chamber IOL cases, were used to optimize the constants in the formula empirically. These data sources are detailed in Table 1. Each data source consisted of one or more surgeon's series of cases using a single posterior chamber lens style. Cases with more than three diopters (D) of postoperative astigmatism or with postoperative visual acuity of worse than 20/40 were excluded. The database was meant to represent a heterogeneous, real-world sample. For the most part, applanation style A-scan units equipped with oscilloscopes were used. Different brands of keratometers were used and K-readings were recorded in diopters; radius of curvature was converted to diopters using 1.3375 refractive index.

Analysis was performed on an IBM PC AT with a 8087 math coprocessor using the SPSS PC statistical software.[10]

After developing the formula, the prediction accuracy was compared with that of the original and modified Binkhorst formulas,[11,12] the Holladay formula,[13] the Hoffer-Colenbrander formula,[14,15] and the SRK II[8] formula in the following way. The formulas were used as recommended by the authors; ACD-constant and A-constant values were optimized by iteration to obtain mean absolute errors of zero.

Expected postoperative refraction was calculated for each IOL case using each formula and compared to the actual measured postoperative refraction.

Standard errors of the estimates, mean absolute errors, standard errors of the mean deviations, and the distributions of the deviations were computed and evaluated.

FORMULA DEVELOPMENT

Development of the final SRK/T model consisted primarily of empirically optimizing (1) postoperative ACD prediction, (2) retina thickness correction factor, and (3) corneal refractive index.

Early refinements of the value assumptions of the various correction factors in the original theoretical formulas, for the most part, were developed concentrating on one factor at a time. We decided to explore each constant and procedural step systematically

Table 1. SRK/T development data sets.

Data Set	Company	Style	Source	Number of Cases
1	3M	PC 30	Multiple MDs	600
2	CooperVision	JFIRLU G70G	Jaffe and Clayman	359
3	IOLAB	707G 107G	Shearing	313
4	IOLAB	G706 707G	Kraff	305
5	Surgidev	B2020	Lindstrom	100

and interactively to create an empirical formula that uses the nonlinear terms of the theoretical formula as its foundation.[16] Thus, the three steps listed were performed interdependently; changing any one changed the other two so several repetitions of each optimization (iterations) were required to optimize all three interactively.

For example, if a corneal refractive index of 1.334 were chosen for trial, the calculated optical ACD for each case would be different than for any other refractive index so all ACDs would have to be recalculated. These new ACD values might require a different retina thickness correction factor which, in turn, could change the ACD values.

Predicting Postoperative ACD

To explore different ACD prediction methods, we algebraically rearranged the theoretical formula solving for postoperative ACD. (This required solution of a quadratic equation; we discovered, in retrospect, that Holladay[13] had used the same method earlier in his "reverse solution" of the theoretical formula.) We then calculated, retrospectively, the theoretical optical ACD for each case in the five formula development data sets.

Next, we devised and evaluated different methods of predicting this optical ACD; the relationship of the axial length and corneal curvature to this ACD value was exhaustively explored using many different regression models and the corneal height formula[17-21] in a variety of ways.

The simple linear regression equation proved to be as accurate a predictor of ACD as more complex regression models and was virtually as accurate as the corneal height formula. The corneal height formula, implemented as described, was chosen because it is more physiologic than the regression line and might be expected to perform better in extreme cases.

Axial Length Modifications for ACD Prediction in Very Long Eyes. Hoffer,[14] Shammas,[22] and Olsen[21] use no axial length correction for long eyes in their prediction of postoperative ACD. Binkhorst[12] uses an abrupt upper limit of 26 mm in his ACD prediction, stating, "Beyond 26 mm the increase in axial length is believed to be mostly in the posterior segment." Holladay[13] sets a cutoff at 25.3 mm for axial length modification and 48.31 D for corneal curvature.

We tested the idea that very myopic eyes have proportionally greater elongation of the posterior than the anterior segment by comparing different axial length corrections in long eyes. We reasoned that, if this phenomenon occurs at all, it might occur gradually with increasingly long eyes rather than abruptly, so we tested curvilinear corrections as well as abrupt cutoff limits. The number of long eyes among our 1,677 cases was insufficient to reach an absolute conclusion, but use of a correction for long eyes did appear warranted by the data. A parabolic curve beginning at 24.2 mm appeared to give the most accurate prediction. Thus

If $L \leq 24.2$, then $LCOR = L$

If $L > 24.2$, then $LCOR = 3.446 + 1.715 \times L - 0.237 \times L^2$,

where L = axial length, LCOR = corrected axial length

was adopted as part of the SRK/T ACD prediction method. Figure 1 compares the SRK/T curvilinear correction to abrupt corrections. We also tested axial length correction in short eyes and K-reading corrections in steep and flat eyes; these did not improve accuracy of corneal height predictions so they were not adopted.

Corneal Height Formula. The corneal height formula was presented by Fyodorov et al.[17,18] in 1967 and in 1975, examined by Bagan and Brubaker[20] in 1980, and used by both Olsen[21] and Holladay[13] in their versions of the theoretical formula.

As Olsen[21,23] described, "the height formula regards the cornea as a section of a sphere the base of which forms a plane at the level of the anterior iris, the calculated iris plane" (Figure 2). The height (H) of the corneal dome is computed from the corneal width (width) and the corneal curvature (r):

$$H = r - \sqrt{r^2 - (\text{width}/2)^2}$$

Corneal Width. No white-to-white or other direct clinical estimate of corneal width was available in our data, so it was necessary to devise a prediction of corneal width (C_w). We found the linear formula

$$C_w = -5.41 + 0.58412 \times LCOR + 0.098 \times K$$

to be optimum.

Indirect evidence suggests that for use in the corneal height formula, predicting corneal width in this way may be more effective than using the white-to-white measurement.

Intraocular Lens to Iris Plane Offset. The corneal height formula hypothesis says that the intraocular position of any given style IOL lies a constant distance from the calculated iris plane in any eye.[17,18,21] Thus, the calculated iris plane serves as a reference point for IOL position (Figure 3). The constant distance from this plane to the optical plane of the specific IOL has been termed an offset by Olsen[21] and the surgeon factor by Holladay.[13] Holladay's surgeon factor also includes a factor of 0.56 mm to account for corneal thickness.

In our model the average eye calculated iris plane was 3.336 mm from the corneal vertex.

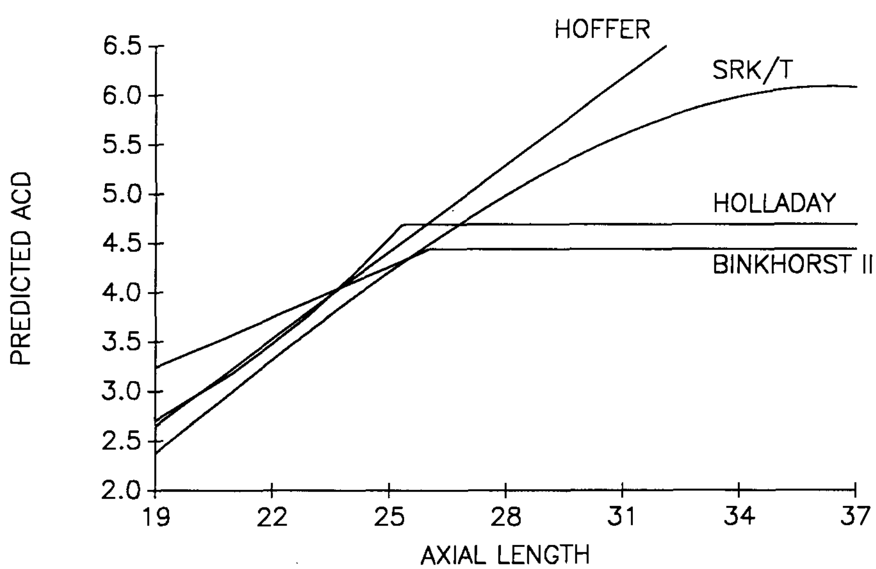

Fig. 1. (Retzlaff) Graph showing postoperative ACDs predicted by different formulas for different length eyes for an IOL with an ACD-constant of 4.0. The keratometry value of 43 D was used for SRK/T and Holladay calculations.

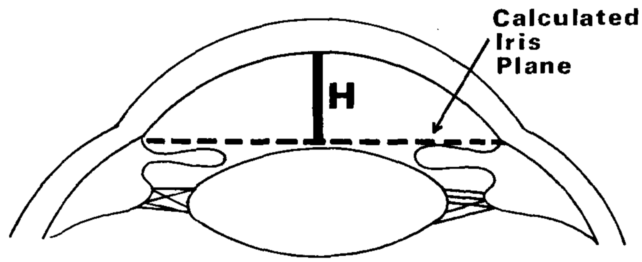

Fig. 2. (Retzlaff) Diagram of the anterior segment showing the height (H) of the corneal dome, computed by the height formula, and the location of the calculated iris plane.

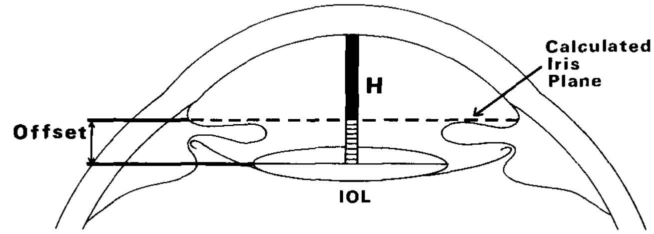

Fig. 3. (Retzlaff) Diagram of the anterior segment with an IOL in place showing the offset from the calculated iris plane to the optical plane of the IOL. The offset value, as calculated in this paper, also includes the corneal thickness.

Computation of Offset and the Patient's Predicted Postoperative ACD. The ACD-constant (ACD_{const}) for a specific style IOL is **the ACD of that IOL in an average eye.** The difference between the average eye calculated iris plane and the ACD-constant is the offset value for that IOL:

$$\text{offset} = ACD_{const} - 3.336$$

The offset computed in this manner includes the corneal thickness dimension.

In our data, the more complex linear form

$$\text{offset} = ACD_{const} - b \times 3.336$$

was analyzed and the value for the b-constant (the slope coefficient) was almost exactly 1, so the simpler form can be used with no sacrifice in accuracy.

The patient's postoperative ACD is predicted, then, by adding the computed corneal height for the patient's eye to the offset of the IOL to be implanted (see formulas (4), (5), and (6) in the formula appendix). Table 2 compares predicted postoperative ACD values for short, medium, and long eyes from different formulas.

Table 2. Predicted postoperative ACDs for different length eyes for an IOL with an ACD-constant of 4.0 mm.

Formula	Short 19 mm	Medium 23 mm	Long 27 mm	Very Long 31 mm	Very Long 35 mm
SRK/T	2.4	3.6	4.7	5.6	6.0
Holladay	2.7	3.8	4.7	4.7	4.7
Binkhorst II	3.2	3.9	4.4	4.4	4.4
Hoffer	2.6	3.8	5.0	6.2	7.4

Keratometry value of 43 D used for SRK/T and Holladay formulas

Axial Length Correction Factor for Retinal Thickness

Many workers have theorized that physiologic optical axial length is greater than ultrasonically measured axial length by the distance from the vitreoretinal interface to the center retinal elements[1] (i.e., retinal thickness) (Figure 4).

Values from 0 to 0.5 mm have been used for the retinal thickness correction factor by various authors.[1] The Binkhorst formula uses 0.25 mm, the Hoffer formula uses 0, and the Holladay formula uses 0.20 mm.

In our model, retinal thickness axial length corrections from 0 through 0.5 mm were tested and found to be very nearly equivalent in accuracy. However, we noted that in long eyes, smaller correction values gave best accuracy and in short eyes, larger values gave best accuracy. This led us to

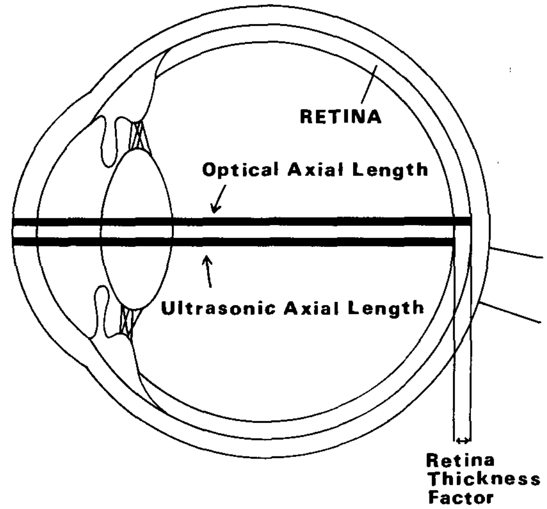

Fig. 4. (Retzlaff) Diagram of the eye showing retinal thickness, ultrasonic axial length, and optical axial length.

evaluate different models for this axial length correction factor. We found the linear formula

$$\text{axial length correction} = .65696 - 0.2029 \times L$$

gave a slightly more accurate prediction in every one of the five data sets used to develop the formula. We speculate that vagaries of the ultrasound measurement may account for this unexpected finding. Hoffer (personal communication) suggested that our finding may be partly because shorter eyes have faster average speed of sound than longer eyes because the ultrasound travel distance through the crystalline lens is a higher proportion of axial length in shorter eyes.

We felt the consistency of this empirical correction factor warranted our adopting it in the SRK/T formula. Table 3 shows this correction for various axial lengths.

Table 3. Axial length correction for different length eyes.

Axial Length (mm)	Retinal Thickness Correction (mm)
18	0.29
20	0.25
23	0.19
26	0.13
33	−0.01

Corneal Refractive Index

The early theoretical IOL power calculation formulas used a corneal refractive index (n_c) of 1.336.[18,24] Binkhorst chose the value of $1.\overline{3}$ (4/3), explaining, "The reduction in corneal power resulting from this would seem justified to compensate for a slight degree of postoperative flattening of the cornea."[19] Retzlaff[1] later pointed out that studies analyzing eyes in which multiple sutures were used have shown surgically induced steepening of the cornea.

Olsen[25] advocates a value of 1.3315, based on a rather elegant analysis of corneal optics, and emphatically points out, as have others before him, that all these corneal refractive indices are fictitious in that they "regard the cornea as a single refracting surface whose curvature equals the front curvature."

Holladay[13] used the value $1.\overline{3}$ (4/3) in his formula, choosing a lower value than 1.336 for reasons similar to Olsen's.

We approached this question heuristically, testing values from 1.330 through 1.338. Values from 1.331 to 1.334 yielded the most accurate predictions, about equal in accuracy across this range. The values from 1.331 to about 1.332 resulted in seemingly unphysiologically shallow ACD values which were considerably less than manufacturers' generally recommended ACD-constants for IOLs in this country. Thus, we chose the value of 1.333, which gives ACD-constant values in harmony with currently published ACD-constants, which is similar to the value used by Binkhorst and Holladay, and which empirically is as accurate as any other corneal refractive index value. The value 1.333, which is a terminated decimal number that can be precisely expressed in a computer, is used in SRK/T; $1.\overline{3}$ (4/3) is used in the Binkhorst and Holladay formulas. Theoretical formulas are so sensitive to changes in n_c that even this tiny difference results in expected refraction prediction differences of 0.05 D to 0.06 D.

Relationship of A-Constants and ACD-Constants

As noted, the ACD-constant (ACD_{const}) for a specific style IOL is **the ACD of that IOL in an average eye.** This value **is a constant** for a given IOL or IOL/surgeon and the term ACD-constant should be used when referring to this constant rather than loosely referring to it as the ACD. By contrast, the estimated postoperative ACD value (ACD_{est}) is **not** a constant; it **varies** considerably from eye to eye being tailored for each patient's eye by all the modern theoretical formulas.

The intraocular position of the five styles of posterior chamber IOLs varied from quite anterior (uniplanar plano-convex IOL) to quite posterior (ten-degree angulated biconvex IOL). The resultant wide range of optimal A-constants and ACD-constants in these datasets facilitated effective exploration of the relationships of these values. As is often the case, a simple linear regression equation (see formula 12) gave an excellent fit, providing a good means of predicting ACD-constants from A-constants. Holladay[13] reported similar findings. The relationship will be discussed further in a subsequent paper.

RESULTS

The formulas derived are shown in the formula appendix.

In the five formula derivation data sets, the new SRK/T formula performed slightly better than the Holladay and the SRK II formulas in all the data sets individually (Table 4) and in the 1,677 cases as a group (Table 5). This is the expected result because any formula performs superiorly with data from which it is derived.

DISCUSSION

The first theoretical implant power formula was presented by Fyodorov and Kolinko[17] in 1967. The

Table 4. Comparison of standard error of estimate of different formulas in five data sets.

Data Set	N	Standard Error of Estimate SRK/T	SRK II	Holladay	Hoffer/ Colenbrander	Binkhorst	Binkhorst II
1	600	.91	.94	.91	.95	1.02	.96
2	359	.77	.78	.77	.82	.88	.82
3	313	1.02	1.04	1.05	1.15	1.16	1.14
4	305	.63	.67	.65	.70	.77	.70
5	200	.94	.90	1.01	1.15	1.16	1.22

first English language publication was by Colenbrander in 1973.[24] Other early theoretical models were formulated by Thijssen,[26] Van Der Heijde,[27] and R.D. Binkhorst.[19] All these formulas except Fyodorov's used a constant value for estimated postoperative ACD. Early efforts to predict postoperative ACD, mostly by using preoperative ACD measurements, proved unsuccessful; thus, use of a fixed value remained standard practice until 1981 when Binkhorst recommended that estimated postoperative ACD be adjusted for different length eyes.[12] Shammas,[22] Hoffer,[14] Olsen,[21] and Holladay[13] followed with their own methods of adjusting estimated postoperative ACD.

We sought to enhance the accuracy of the theoretical approach to implant power calculation by empirically and interactively optimizing the constants in the formulas. The formula derived provides a theoretical formula under the SRK umbrella that uses existing A-constants and optimization methods. Software comparing the theoretical and regression approaches has been developed for IBM personal computers and compatibles and will be inbuilt in most new A-scan units.

Our goals were to (1) improve ease of use by creating a theoretical formula under the SRK umbrella that would use existing A-constant and optimization methods and provide easy comparison of the theoretical and regression approaches and (2), if possible, improve on the accuracy of existing formulas. This first point has been addressed in this paper; the second is addressed in a follow-up report.[28]

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Table 5. Comparison of errors in prediction of implant power in 1,677 formula derivation cases.

Formula	Mean Absolute Error	Error in Power Prediction (% of Cases) < 0.5 D	< 1 D	> 2 D	Standard Error of Estimate*
SRK/T	.64	50	80	3.3	.86
Holladay	.65	50	80	3.5	.88
SRK II	.67	48	77	3.6	.89
Hoffer	.70	42	78	4.9	.94
Binkhorst II	.70	47	78	4.8	.94
Binkhorst (old)	.74	47	75	5.5	.99

*Standard error of estimate (in diopters) $= \sqrt{\frac{\text{sum (actual refraction} - \text{predicted refraction)}^2}{N}}$

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FORMULA APPENDIX

Postoperative ACD Computation

(1) Corneal radius of curvature, mm (r): $r = 337.5/K$

(2) Corrected axial length, mm (LCOR):

If $L \leq 24.4$, then $LCOR = L$

If $L > 24.4$, then $LCOR = 3.446 + 1.716 \times L - 0.0237 \times L \times L$

(3) Computed corneal width, mm (C_w)

$C_w = -5.41 + 0.58412 \times LCOR + 0.098 \times K$

(4) Corneal height, mm (H)

$H = r - \sqrt{r \times r - ((C_w \times C_w)/4)}$

(5) Offset for specific IOL to be implanted:

$Offset = ACD_{const} - 3.336$

(6) Estimated postoperative ACD for patient:

$ACD_{est} = H + offset$

Intraocular Lens Power Computations

(7) Constants:

$V = 12;\ n_a = 1.336;\ n_c = 1.333;\ n_c ml = 0.333$

(8) Retinal thickness, mm (RETHICK) and optical axial length, mm (LOPT):

$RETHICK = 0.65696 - 0.02029 \times L$

$LOPT = L + RETHICK$

(9) Emmetropia IOL power, D (IOL_{emme}):

$$IOL_{emme} = \frac{1000 \times n_a \times (n_a \times r - n_c ml \times LOPT)}{(LOPT - ACD) \times (n_a \times r - n_c ml \times ACD)}$$

(10) Ametropia IOL power, D (IOL_{amet}):

$$IOL_{amet} = \frac{1000 \times n_a \times (n_a \times r - n_c ml \times LOPT - .001 \times REFTGT \times (V \times (n_a \times r - n_c ml \times LOPT) + LOPT \times r))}{(LOPT\text{-}ACD) \times (n_a \times r - n_c ml \times ACD - .001 \times REFTGT \times (V \times (n_a \times r - n_c ml \times ACD) + ACD \times r))}$$

(11) Expected refraction, D (REFX):

$$REFX = \frac{1000 \times n_a \times (n_a \times r - n_c ml \times LOPT) - IOL \times (LOPT\text{-}ACD) \times (n_a \times r - n_c ml \times ACD)}{n_a \times (V \times (n_a \times r - n_a ml \times LOPT) + LOPT \times r) - .001 \times IOL \times (LOPT\text{-}ACD) \times (V \times (n_a \times r - n_c ml \times ACD) + ACD \times r)}$$

Determining ACD-Constant from the A-Constant

(12) $ACD_{const} = 0.62467 \times \mathbf{A} - 68.747$

Tailoring, Optimizing, the A-Constant

(13) Refraction factor (RF):

If $IOL > 16$, then $RF = 1.25$ If $IOL \leq 16$, then $RF = 1$

see p 141 March '88

(14) Short and long eye correction:

If $L < 20$, then $C = 3$

If $20 \leq L < 21$, then $C = 2$

If $21 \leq L < 22$, then $C = 1$

If $22 \leq L < 24$, then $C = 0$

If $L \geq 24$, then $C = -0.5$

24.5
24.5

(15) Individual A-constant (A_{indiv}):

$A_{indiv} = IOL + (REF \times RF) + 2.5 \times L + 0.9 \times K - C$

(The mean value of A-indiv for a data set is the personalized A-constant for that data set's IOL/surgeon)

VARIABLES

ACD_{const} = constant used for anterior chamber depth in SRK/T formula for specific IOL/surgeon; can be computed from A-constant
ACD_{est} = estimated postoperative anterior chamber depth for a given eye (mm)
A = constant used for SRK/T and SRK II
A_{indiv} = A-constant from postoperative values of an individual eye
C = short and long eye correction factor for SRK II
C_w = corneal width computed from L and K (mm)
H = height of corneal dome (mm)
IOL = power of intended or implanted IOL (D)
IOL_{amet} = power of IOL for given amount of ametropia, for a given REFTGT (D)
IOL_{emme} = power of IOL for emmetropia (D)
K = averaged keratometry (D)
L = axial length measured ultrasonically (mm)
LOPT = "optical" axial length (mm) = L + RETHICK
LCOR = axial length with long eye correction; used in height formula
n_a = refractive index of aqueous and vitreous
n_c = refractive index of the cornea
$n_c ml$ = n_c minus 1, used in theoretical formula
offset = difference between corneal height of the average eye and the ACD-constant of a given IOL (see Figure 3)
r = averaged corneal radius of curvature (mm)
REF = actual postoperative refraction (D)
REFTGT = targeted or desired postoperative refraction (D)
REFX = expected postoperative refraction (D)
RETHICK = sensory retinal thickness (mm)
RF = refraction factor