# 48 Norrby Formulas for IOL Power Calculation

Sverker Norrby

## Prologue

My education and experience were in polymer science and technology. One of my first tasks at Pharmacia was to come up with a method to assign A-constants without the need for a clinical study. Although the SRK II formula was dominant at the time, I realized that the A-constant had something to do with the optics of the eye and the depth at which the IOL ended up. Having only high school knowledge in optics, I bought O'Shea's textbook on the subject [1]. It taught me that optical calculations are ideally treated in spreadsheets, which greatly helped me get a grip on the matter.

Next, I turned to the clinical department for studies in which the postoperative IOL position had been measured. My working hypothesis was that the position of the IOL was dependent on the plane where the haptics made contact with eye tissue. I termed it the lens haptic plane (LHP) and postulated that it was common to all IOL models implanted in the bag and that the offset from the plane was determined by the detailed mechanical and optical design of each IOL model. After a lot of calculations, an "average eye" emerged. For a new IOL model, it was "implanted" with the power that made that eye emmetropic. From there, we could back-calculate the A-constant. This procedure was eventually published [2].

In the process of developing the LHP concept, I became aware that biometry instruments could differ systematically from each other. This, rather than a surgical technique, required "personalization" of formula constants. To assess the differences, I asked several friends to measure my own eyes. The data collected resulted in a paper [3] that was accepted by the editor without peer review.

In a subsequent paper [4], differences between ultrasound and optical measurement of anterior chamber depth were studied. In another study [5], systematic differences between two ultrasound devices were investigated, followed by a suggestion [6] as to how to deal with them by transformation of data. With the introduction of the Zeiss IOLMaster in 1999, a new gold standard for axial length (AL) measurement was set. However, while it measures the optical AL to the retinal pigment epithelium and A-scan ultrasound measures to the inner limiting membrane, the output was re-calculated to agree with A-scan ultrasound [7], which in fact introduced systematic bias. This was commercially understandable but is unfortunate.

Systematic differences remain a problem in keratometry. The measured quantity is the corneal radius of curvature, which is transformed to

S. Norrby (✉)
Eindhoven, Netherlands



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corneal power by means of the keratometric index. As pointed out by Olsen [8], the index 1.3315 affords the power in the second principal plane (also known as the back principal plane, or the image principal plane), which should be used for thin lens calculations. The value 1.332 puts the power at the anterior surface of the cornea, while the index 1.3375, which is used in many keratometers, gives the power at the posterior vertex. The latter overestimates corneal power by about 0.80 D. In commonly used thin lens IOL power formulas, this is compensated by adjusting the formula constant(s) to result in a virtual IOL position that is posterior to the true one.

When I retired on July 1, 2010, I felt it was time to come up with an IOL power formula of my own. It became three formulas. They were presented at the IOL Power Club meeting on April 27–29, 2012, in Nashville/Memphis, USA. They have not been published until now, a decade later.

## Data

The data for this chapter was obtained in conjunction with a study [9] of IOL stability at Moorfields Eye Hospital (London, UK) involving the models Tecnis ZA9003 (3-piece) and Tecnis ZCB00 (1-piece) from AMO, Santa Ana, CA, USA. The company was later acquired by Johnson & Johnson Vision, Jacksonville, FL, USA.

Preoperatively measured AL, anterior chamber depth (ACD, anterior cornea to anterior lens), and corneal radius (CR) obtained with the IOLMaster software V.5 version (Carl Zeiss Meditec AG, Germany) are used. The implanted IOL powers had been calculated by the SRK/T formula. Refraction was determined 1 year postoperatively using a trial frame with the chart at 4 m. There are 44 complete datasets available for each IOL model. The data for ZA9003 were used for the development of the formulas and are summarized in Table 48.1.

**Table 48.1** Overview of parameters used for IOL model ZA9003: AL = axial length, ACD = anterior chamber depth (anterior cornea to anterior lens), CR = anterior corneal radius of curvature, and SE = spherical equivalent spectacle lens refraction. There were 44 complete datasets available

| Variable | Obtained with | Mean | SD | Range |
|---|---|---|---|---|
| Pre-op AL (mm) | IOLMaster | 23.51 | ± 0.64 | 22.02–25.37 |
| Pre-op ACD (mm) | IOLMaster | 2.98 | ± 0.33 | 2.32–3.83 |
| Pre-op CR (mm) | IOLMaster | 7.73 | ± 0.28 | 7.28–8.35 |
| Pre-op IOL power (D) | SRK/T | 21.75 | ± 1.71 | 17.5–26.0 |
| Post-op SE (D) | Trial frame @ 4 m | −0.82 | ± 0.38 | 0.00–1.75 |

## Norrby Thick Lens Formula

In 2004, I published a thick lens calculation scheme for IOL power calculation based on the LHP concept [10]. I no longer subscribe to several features in it, hence this new attempt.

The Tecnis lenses are designed to eliminate the average spherical aberration caused by the cornea. In that case, thick lens paraxial ray tracing should be appropriate for IOL power calculation. In a thick lens calculation model, every refracting surface is at its true position. There are no virtual principal planes involved. However, because spectacle lenses are labeled with their back vertex power, they can preferably be treated as thin lenses at the vertex distance from the cornea. In the model, the vertex distance is assumed to be 12 mm.

The anterior corneal surface is the reference for target distance, AL, and IOL position. In a previous paper [11], it was found that the position of the posterior IOL surface could be estimated by the formula.

$$\text{pLP} = 3.074 + 0.06524^{*}\,\text{AL} + 0.2957^{*}\,\text{ACD}$$

This formula was found to be valid for both ZA9003 and ZCB00. With the anterior capsule mechanically compromised by the capsulorrhexis, it could be argued that the intact posterior capsule becomes a support for the IOL optic for any model. It is open to others to prove or disprove this postulate. It is at least valid for the two models used here.

For the cornea, only the anterior radius is known by measurement. The le Grand eye model [12] is adopted to obtain the posterior radius by multiplication with the ratio 6.5/7.8 = 0.833. The corneal thickness is 0.55 mm. For the refractive indices of the ocular media, the Gullstrand [13] values of 1.376 for the cornea and 1.336 for aqueous and vitreous are chosen. Curvatures, thickness, and refractive index of the IOL must be obtained from the manufacturer. As a former employee, they are available to me, but I am not at liberty to divulge them in detail. A spreadsheet to generate a dummy equi-biconvex IOL for use here is given in Table 48.2.

Finally, for the purpose of optimization a thin refracting surface is introduced in the same plane as the posterior IOL surface. It is initially given zero power.

The ray tracing scheme is given in Table 48.3. The output, t6 in the table, we could call the optical back focal length (OBFL). The vitreous depth (VD) is the distance from the IOL to the inner limiting membrane and can be calculated as AL—pLP. The retinal thickness (RT) is the distance from the inner limiting membrane to the pigment epithelium. Assuming it is the same as the correction applied by the Zeiss IOLMaster to obtain AL from the measured optical path length, it can be calculated [7] as RT = −0.0429*AL + 1.3033 mm. For all cases pooled, RT was found to be (mean 0.29; SD ± 0.03; range 0.21 to 0.36; in mm). For simplicity, the mean value is used. The geometrical back focal length thus becomes GBFL = VD + 0.29 mm. The eye is focused if OBFL and GBFL are equal.

For the 44 cases with ZA9003, OBFL = 18.34 mm and GBFL = 18.31 mm were found without optimization ($N = 0$ D). To assess the agreement on the case level, the refractions that produced identical OBFL and GBFL values were calculated per case. The results are summarized in Table 48.4.

To use the formula, input the desired Rx to aim for and find the le IOL power that results in OBFL being just short of GBFL. Then, calculate the expected resulting Rx. This trial-and-error approach may be somewhat awkward for practical use, but a macro could be written to automate the procedure.

**Table 48.2** Spreadsheet formulas to generate input for a dummy equi-biconvex design. The values in column B result in a 20 D IOL

| | A | B | C | D |
|---|---|---|---|---|
| 1 | IOL radii Ra = −Rp (mm) | 13.255 | Power of each surface (D) | =(B2-B3)/B1*1000 |
| 2 | RI of IOL | 1.469 | | |
| 3 | RI of aqueous/vitreous | 1.336 | Central thickness (mm) | =2*(B1-SQRT(B1^2-(B5/2)^2)) + B4 |
| 4 | IOL edge thickness (mm) | 0.3 | | |
| 5 | IOL optic diameter (mm) | 6 | IOL power | =2*D1−D3/B2*D1^2/1000 |

**Table 48.3** Norrby thick lens formula ray tracing scheme. The tracing calculations involve height and slope. The other rows provide input for the calculations. The trace is opened by setting the slope s0. The value 2.5 is arbitrary to produce convenient height values. Any value would produce the same end result. The trace is closed by the calculation of t6, the distance from the IOL to the focal point, at which the ray has zero height at the image surface. The equation for pLP, the distance from anterior cornea to posterior IOL, is given in the text. The refractive error (Rx) can be given as input or calculated as output. Surface 6 is a corrector for use in optimization by adjusting N, initially set to zero. The system is in focus if the optical back focal length (OBFL; t6 in the scheme) is equal to the geometric back focal length (GBFL; defined in the text). If the scheme is set up as an Excel spreadsheet, its Goal Seek utility can be conveniently used to find the Rx by the condition that the difference between OBFL and GBFL be zero

| Surface | 0<br>Target | 1<br>Spectacle | 2<br>Anterior cornea | 3<br>Posterior cornea | 4<br>Anterior IOL | 5<br>Posterior IOL | 6<br>Corrector | 7<br>Image |
|---|---|---|---|---|---|---|---|---|
| Thickness (mm) | t0 = 3988 | t1 = 12 | t2 = 0.55 | t3 = pLP-t4-t2 | t4 = IOL thickness | t5 = 0 | t6 = -h6/s6 | |
| Refractive index | n0 = 1 | n1 = 1 | n2 = 1.376 | n3 = 1.336 | n4 = IOL Refractive index | n5 = 1.336 | n6 = 1.336 | |
| Curvature(mm) | | | r2 = corneal anterior radius | r3 = r2*6.8/7.7 | r4 = IOL anterior radius | r5 = IOL posterior radius | | |
| Power (D) | | p1 = Rx | p2 = 1000*(n2-n1)/r2 | p3 = 1000*(n3-n2)/r3 | p4 = 1000*(n4-n3)/r4 | p5 = 1000*(n5-n4)/r5 | p6 = N | |
| Height (mm) | h0 = 0 | h1 = h0 + s0*t0 | h2 = h1 + s1*t1 | h3 = h2 + s2*t2 | h4 = h3 + s3*t3 | h5 = h4 + s4*t4 | h6 = h5 + s5*t5 | h7 = 0 |
| Slope | s0 = 2.5/t0 | s1 = (n0*s0-h1*p1/1000)/n1 | s2 = (n1*s1-h2*p2/1000)/n2 | s3 = (n2*s2-h3*p3/1000)/n3 | s4 = (n3*s3-h4*p4/1000)/n4 | s5 = (n4*s4-h5*p5/1000)/n5 | s6 = (n5*s5-h6*p6/1000)/n6 | |

**Table 48.4** Results for the Norrby thick lens formula using the 44 cases with the ZA9003 IOL. *SE* spherical equivalent (D); *OBFD* optical back focal length (mm); *GBFD* geometric back focal length (mm). Differences were obtained as calculated minus measured refractions. Unoptimized results

| Parameter | OBFD | GBFD | SE measured | SE calculated | SE difference |
|---|---|---|---|---|---|
| Unit | mm | mm | D | D | D |
| Mean | 18.34 | 18.31 | −0.82 | −0.73 | 0.09 |
| SD | ± 0.62 | ± 0.58 | ± 0.38 | ± 0.23 | ± 0.32 |
| Range | 17.03 to 19.93 | 17.06 to 19.86 | −1.75 to 0.00 | −1.16 to −0.18 | −0.53 to 0.78 |

## Norrby Thin Lens Formula

Common IOL power formulas are based on thin lens theory, which describes a lens as a plane with an associated power. The power calculation is then reduced to a system of three refracting surfaces: spectacle, cornea, and IOL. This system also lends itself to be set up in a spreadsheet but can be given in closed form. I will first describe the spreadsheet approach.

The spectacle is at a vertex distance of 12 mm from the anterior cornea and is given its labeled power. The cornea is placed at its second principal plane, which is 0.06 mm anterior to the cornea for the le Grand model cornea. The power is calculated as 331.5/CR, where CR is the measured anterior corneal radius of curvature. The posterior IOL surface position, pLP, is computed with the formula given in the previous section. The equivalent plane of the thin lens is at the intersection between an incoming converging ray from the cornea and the outgoing ray. The distance from the posterior plane, IO, was found (mean − 0.35; SD ± 0.05; range − 0.45 to −0.21; unit mm). The negative sign means it is anterior to the posterior IOL surface. The mean is used in the calculations.

Finally, for the purpose of optimization, a thin refracting surface is introduced at the equivalent plane of the IOL. It is initially given zero power. The resulting spreadsheet is given in Table 48.5. The distance from the IOL plane to focus, t4 in the table, is termed optical back focal distance, OBFD, to distinguish it from OBFL used for the thick lens case. The geometrical back focal distance, GBFD, is calculated as.

$$\mathrm{GBFD} = \mathrm{AL} - \mathrm{pLP} + \mathrm{IO} + \mathrm{RT}$$

using the absolute value of IO. AL is the measured axial length, pLP is the position of the posterior IOL surface, and RT is the retinal thickness given the value of 0.29 mm.

For the 44 cases with ZA9003, OBFD = 18.63 mm and GBFD = 18.66 mm were found without optimization ($N = 0$ D). To assess the agreement on the case level, the refractions that produced identical OBFD and GBFD values were calculated per case. The results are summarized in Table 48.6.

To use the formula, input Rx to aim for and find the le IOL power that makes OBFD equal to GBFD. Choose the next higher available power. Then, calculate the expected resulting Rx.

In closed form, the thin lens formula can be written as

$$P = 1336 \times \left( \frac{1}{\dfrac{1.336}{\dfrac{1}{\dfrac{1}{\dfrac{1}{TD-VD} - \dfrac{Rx}{1000}} + (VD - CO)} - \dfrac{0.3315}{CR}} + \left(CO + (pLP - IO)\right)} + \frac{1}{AL - (pLP - IO) + RT} \right)$$

**Table 48.5** Norrby thin lens formula ray tracing scheme. The tracing calculations involve height and slope. The other rows provide input for the calculations. The trace is opened by setting the slope s0. The value 2.5 is arbitrary to produce convenient height values. Any value would produce the same end result. The trace is closed by the calculation of t4, the distance from the equivalent plane of the IOL to the focal point, at which the ray has zero height at the image surface. The equation for pLP, the distance from anterior cornea to posterior IOL, is given in the text. CO is the corneal offset, and IO is the IOL offset. They are both negative vectors, but to avoid confusion, their absolute values are used here. CR is the anterior corneal radius of curvature. Rx can be given as input or calculated as output. Surface 4 is a corrector for use in optimization by adjusting N, initially set to zero. The system is in focus if the optical back focal distance (OBFD; t4 in the scheme) is equal to the geometric back focal distance (GBFD; defined in the text). If the scheme is set up as an Excel spreadsheet, its Goal Seek utility can be conveniently used to find Rx by the condition that the difference between OBFD and GBFD be zero

| Surface | 0<br>Target | 1<br>Spectacle | 2<br>Corneal plane | 3<br>IOL plane | 4<br>Corrector | 5<br>Image |
|---|---|---|---|---|---|---|
| Thickness (mm) | t0 = 3988 | t1 = 12-CO | t2 = CO + pLP-IO | t3 = 0 | t4 = -h4/s4 | |
| Refractive index | n0 = 1 | n1 = 1 | n2 = 1.336 | n3 = 1.336 | n4 = 1.336 | |
| Curvature(mm) | | | r2 = CR | | | |
| Power(D) | | p1 = Rx | p2 = 331.5/r2 | p3 = IOL power | p4 = N | |
| Height(mm) | h0 = 0 | h1 = h0 + s0*t0 | h2 = h1 + s1*t1 | h3 = h2 + s2*t2 | h4 = h3 + s3*t3 | h5 = 0 |
| Slope | s0 = 2.5/t0 | s1 = (n0*s0-h1*p1/1000)/n1 | s2 = (n1*s1-h2*p2/1000)/n2 | s3 = (n2*s2-h3*p3/1000)/n3 | s4 = (n3*s3-h4*p4/1000)/n4 | |

**Table 48.6** Results for the Norrby thin lens formula using the 44 cases with the ZA9003 IOL. SE: spherical equivalent (D); OBFD: optical back focal distance (mm); GBFD: geometric back focal distance (mm). Differences were obtained as calculated minus measured refractions. Unoptimized results

| Parameter | OBFD | GBFD | SE measured | SE calculated | SE difference |
|---|---|---|---|---|---|
| Unit | Mm | Mm | D | D | D |
| Mean | 18.63 | 18.66 | −0.82 | −0.89 | −0.07 |
| SD | ± 0.60 | ± 0.58 | ± 0.38 | ± 0.27 | ± 0.33 |
| Range | 17.39 to 20.15 | 17.41 to 20.21 | −1.75 to 0.00 | −1.33 to −0.23 | −0.68 to 0.62 |

where P is IOL power (D). AL is axial length (mm), Rx is the desired refraction (D), TD is target distance (mm), VD is vertex distance (mm), CR is the corneal radius (mm), pLP is the position of the posterior IOL surface (mm), CO is the corneal offset (mm), IO is the IOL offset (mm), and RT is the retinal thickness (mm). Though CO and IO are negative vectors, their absolute value is used here to avoid confusion. In the present calculations, TD = 4000 mm, VD = 12 mm, CO = 0.06 mm, IO = 0.35 mm, and RT = 0.29 mm have been used as fixed values. pLP is calculated as before.

## Norrby Regression Formula

To a physicist, it is obvious that the original SRK formula ($P$ = A-2.5*AL-0.9*K) cannot be a correct description of the relation between its parameters, because they do not all have the same dimension. AL has the dimension length, while P and K have the dimension diopter, which is a reciprocal length.

Including also refraction, the following dimensionally correct representation can be set up:

$$0.7 \times P + Rx = C_1 + \frac{C_2}{AL} + \frac{C_3}{CR}$$

The factor 0.7 transforms P to the spectacle plane. The factor varies slightly from eye to eye, but 0.7 is a representative average. The Cs are coefficients found by linear regression to yield

$$0.7 \times P + Rx = -4.262 + \frac{1308}{AL} - \frac{286.0}{CR}$$

for which the statistical R-squared value of 0.93 was found. This means that the relationship accounts for virtually all variance in the data.

**Table 48.7** Results for the Norrby regression formula using the 44 cases with the ZA9003 IOL. SE: spherical equivalent (D). Differences were obtained as calculated minus measured refractions

| Parameter | SE measured | SE calculated | SE difference |
|---|---|---|---|
| Unit | D | D | D |
| Mean | −0.82 | −0.82 | 0.00 |
| SD | ± 0.38 | ± 0.16 | ± 0.33 |
| Range | −1.75 to 0.00 | −1.15 to −0.35 | −0.77 to 0.73 |

There is nothing more to be explained. The equation can be re-arranged to solve for either P or Rx. Using the P values implanted and calculating the expected Rx values per case gave the results summarized in Table 48.7 for the 44 cases with ZA9003.

## Calculations for Other IOL Models

The three formulas were developed on data from IOL model ZA9003. What about other models? Taking the regression formula as an example, one can proceed as follows for model ZCB00. The labeled A-constant for ZCB00 is 119.3 D and that of ZA9003 is 119.1 D. Powers for ZCB00 are therefore expected to be 0.2 D higher than for ZA9003 on average. This can be calculated by the formula

$$P = \frac{1}{0.7}\left(-Rx - 4.262 + \frac{1308}{AL} - \frac{286.0}{CR}\right) + N$$

where $N$ = 0.2 D for ZCB00. Taking the new P, compute the expected refraction with the original equation for ZA9003 (without N) re-arranged to solve for Rx:

$$Rx = -4.262 + \frac{1308}{AL} - \frac{286.0}{CR} - 0.7 \times P$$

Assume you have a patient with AL = 25.37 mm and CR = 8.125 mm. You aim for Rx = −0.25 D. With $N$ = 0.2 mm, you find $P$ = 17.8 D, which you round up to 18.0 D. With that power, you expect Rx = −0.50 and you find −0.625 as the spherical equivalent. You are probably not bothered by this difference.

Analyzing the 44 cases with ZCB00 in retrospect, $N$ = 0.2 D is subtracted from the IOL powers implanted to obtain the corresponding power for ZA9003. Computing the expected refractions yields Rx −0.80 D as the mean, which is −0.25 D more myopic than was found. By adding 0.25/0.7 = 0.36 D, N = 0.56 D is obtained. Rx (D) now becomes (mean − 0.54; SD ± 0.25; range − 0.91to 0.45; unit D), yielding the Rx difference (mean 0.00; SD ± 0.42; range − 1.39 to 1.20; unit D).

The N number approach is general and can be applied to any IOL power formula. If you want to start with a new IOL model, use the formula for your current IOL model, including the formula constant. Add N to the power calculated by your current formula. The starting assumption is that N is equal to the difference between the published A-constants (new A minus old A). Use it for 20 to 40 cases and determine the mean refraction. If you are not happy, you can increase or decrease the N number. Adding 0.36 D to your N number will drive your outcome by a quarter diopter in the myopic direction, subtracting in the hyperopic direction.

Applying the SRK/T formula to the ZA9003 data and optimizing the A-constant to achieve zero mean Rx difference yield the A-constant of 118.6 (D). The discrepancy with the labeled A-constant 119.1 (D) can be explained if the keratometric index of 1.3375 was used in the clinical data underlying the labeled constant. Be sure to use the A-constant of 118.6 (D) when translating results to other models than ZA9003.

Comparisons between the Norrby and SRK/T formulas are given in Table 48.8. First, the Norrby thick and thin formulas were optimized by adjusting N to achieve zero mean difference between calculated and measured refractions. The Norrby regression formula is already optimized by way of its derivation. The results are plotted in Fig. 48.1.

The correction procedure works also for IOL models that do not balance out the corneal spherical aberration. The effect of spherical aberration

**Table 48.8** Comparison between optimized results for the Norrby and SRK/T formulas for the 44 cases with the ZA9003 IOL. Results are for calculated minus measured refractions

| Parameter | Norrby thick lens formula | Norrby thin lens formula | Norrby regression formula | SRK/T formula |
|---|---|---|---|---|
| Unit | D | D | D | D |
| Optimization | $N = 0.14$ | $N = -0.09$ | $N = 0$ | $A = 118.6$ |
| Mean | 0.00 | 0.00 | 0.00 | 0.00 |
| SD | ± 0.32 | ± 0.33 | ± 0.33 | ± 0.37 |
| Range | −0.63 to 0.69 | −0.62 to 0.68 | −0.77 to 0.73 | −1.01 to 0.64 |
| MeanAE | 0.25 | 0.25 | 0.27 | 0.30 |
| MedianAE | 0.20 | 0.18 | 0.19 | 0.28 |

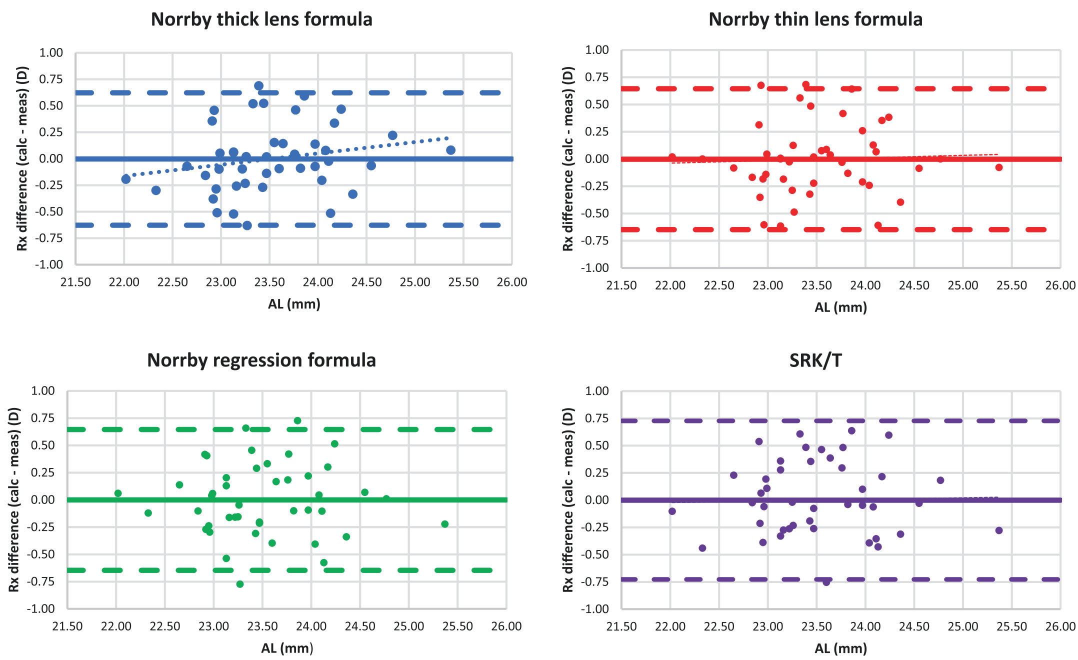


**Fig. 48.1** Refraction difference (calculated minus measured) vs. AL for four IOL power calculation formulas for the 44 cases of IOL model ZA9003. The results are optimized for all formulas (see Table 48.8). Dashed lines are 95% limits, and the full line is the mean. Trend lines are dotted and in some cases hidden by the line for the mean. Trend slopes are in all cases not statistically significant: Norrby thick lens formula $F = 0.16$; Norrby thin lens formula $F = 0.77$; Norrby regression formula $F = 0.98$; SRK/T formula $F = 0.87$

is that the best focus is anterior to paraxial focus. This effect is embedded in optimized formula constants. To illustrate the effect of spherical aberration, I used a calculation spreadsheet of mine that can handle aspheric surfaces. For an eye that is emmetropic with a 20 D ZA9003, a spectacle correction of −0.29 D is required if it is replaced by the same power of its spherical predecessor CeeOn 911A, assuming a 3-mm pupil. The effect of the spherical aberration thus gives an apparent increase in IOL power of 0.41 D. Note that the N number correction does not change the position of the IOL, as formulas like SRK/T do.

To challenge the Norrby formulas, prospective studies must be performed. It is then essential that measured AL, CR, and ACD (if used) are consistent with those obtained with the Zeiss IOLMaster software V.5 version that was employed in the data acquisition for their development. Otherwise, data must be corrected by suitable transformation [6] before applying the formulas. It is also important that postoperative refraction is determined with the chart at 4 m, or corrected by the addition of (1/6–1/4) = 0.08 D if measured at 6 m.

## Toric Calculation with Norrby Formulas

Fam and Lim have published [14] a method to calculate toric IOL sphere and cylinder powers to correct for measured corneal sphere and cylinder powers. It entails calculating the power in the steep and flat meridians separately and by rather elaborate calculations determine the nearest toric IOL power and cylinder combination available and then calculate the expected postoperative refractive outcome in terms of sphere, cylinder, and axis. They illustrate it with the Holladay 1 formula in their paper. I tested the method with other common IOL power formulas, and it works equally well for them. It should work for the Norrby formulas as well.

Another option is to transform the measured corneal cylinder to the IOL plane by dividing it by 0.7. This is how the Alcon toric calculator works (it applies a slightly different value for the transformation). However, as pointed out by Fam and Lim, that is less accurate.

Correction for surgically induced astigmatism in the toric calculation is in my opinion not called for. At least in the data coming from the study used here, no clinically significant surgically induced change was found [15], even though the incision was 3.2 mm. The same observation was made by Hirnschall and colleagues [16].

## Future

The Norrby formulas reported here have approximately an MAE of 0.25 D and a MedAE of 0.20 D, which is at least as good as commonly used power calculation formulas. I do not think one can hope to achieve better, considering the uncertainties in the determination of the corneal power [15, 17, 18] required for the power calculation, and the refraction [19, 20] used to assess the outcome. Keratometry has good repeatability [21], but the reproducibility is poor, not due to the measurement as such, but to fluctuations over time in the curvature of the cornea. Keratometry is thus a larger contributor to outcome error than previously thought [22, 16]. It is plausible that the uncertainty in refraction is correlated with fluctuations in the cornea, but I have not seen any such study. In conclusion, in my opinion, the quest for the ultimate IOL power formula has reached road's end.

For improvement in the predictability of IOL surgery, it is better to concentrate on the consistency of biometry. We are far from a situation where biometry equipment yields the same result for a given measured eye. Take keratometry, where the index used to convert measured curvature to K varies among instruments. The appearance of the IOLMaster may have meant there is a gold standard for AL measurement, but that length is not appropriate for exact optical calculations. Results for ACD and crystalline LT also vary among instruments. Admittedly, they are more difficult and not infrequently impossible to measure. We should aim for a situation where biometry equipment provide a clearly defined output that can be used interchangeably.

Many ophthalmologists believe that inaccuracy in IOL power is a major contributor to outcome error, referring to the international standard for IOL power [23, 24]. For example, a 20 D IOL has a tolerance of ± 0.40 D. Tolerances in industry are ± 3 standard deviations. As responsible for the development of the standard, I have pitifully failed to convince ophthalmologists that the IOL is unlikely to be a main contributor to outcome error. To put it in perspective, fluctuations in keratometry are about ± 0.25 D [15], giving a "specification" of ± 0.75 D for corneal K, with an unknown nominal value. Also, I am not a believer in statistical analysis of large datasets from multiple sources, which are bound to contain measurements obtained by multiple instruments. Likely, the data are also not dimensionally consistent. The result inevitably will be a large blur. What is not significant with 20–40 cases with well-controlled data acquisition is not worth pursuing.

After having advocated IOL calculation by exact ray tracing throughout my career, it came as a sobering revelation that a simple regression formula performed just as well and that AL and corneal curvature are sufficient as input. There is no need to know the ACD, while the estimation of IOL position is crucial for all formulas based on optical calculation, be it based on thin or thick lens theory.

For power calculation in eyes that had corneal refractive surgery, it seems ray tracing is the way to go. However, even in this case I am not wholly convinced any longer. I have ideas to approach it more simply but will not pursue them.

## Epilogue

This chapter is the result of ideas, proposals, assumptions, postulates, and opinions that have evolved and matured over the years. It is up to others to pursue, improve, refute, or forget them.

This is my final publication in the field of IOL power calculation. It has been a wonderful journey that has given me many good friends and fond memories.

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