

Sources of error in intraocular lens power calculation

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PURPOSE: To identify and quantify sources of error in the refractive outcome of cataract surgery.

SETTING: AMO Groningen BV, Groningen, The Netherlands.

METHODS: Means and standard deviations (SDs) of parameters that influence refractive outcomes were taken or derived from the published literature to the extent available. To evaluate their influence on refraction, thick-lens ray tracing that allowed for asphericity was used. The numerical partial derivative of each parameter with respect to spectacle refraction was calculated. The product of the partial derivative and the SD for a parameter equates to its SD, expressed as spectacle diopters, which squared is the variance. The error contribution of a parameter is its variance relative to the sum of the variances of all parameters.

RESULTS: Preoperative estimation of postoperative intraocular lens (IOL) position, postoperative refraction determination, and preoperative axial length (AL) measurement were the largest contributors of error (35%, 27%, and 17%, respectively), with a mean absolute error (MAE) of 0.6 diopter (D) for an eye of average dimensions. Pupil size variation in the population accounted for 8% of the error, and variability in IOL power, 1%.

CONCLUSIONS: Improvement in refractive outcome requires better methods for predicting the postoperative IOL position. Measuring AL by partial coherence interferometry may be of benefit. Autorefractometry increases precision in outcome measurement. Reducing these 3 major error sources with means available today reduces the MAE to 0.4 D. Using IOLs that compensate for the spherical aberration of the cornea would eliminate the influence of pupil size. Further improvement would require measuring the asphericity of the anterior surface and radius of the posterior surface of the cornea.

J Cataract Refract Surg 2008; 34:368–376 © 2008 ASCRS and ESCRS

In 1992, Olsen¹ performed a Gaussian error-propagation analysis of the influence of axial length (AL), corneal power, and estimation of postoperative intraocular lens (IOL) position on the refractive outcome of cataract surgery with IOL implantation. In clinical practice, power calculation is accomplished

by obtaining corneal power by keratometry and AL by biometry, using ultrasound A-scan or partial coherence interferometry (PCI), and then applying a power calculation formula. It is not the purpose of this paper to evaluate the accuracy of these formulas, but those in common use are all based on the thin-lens approximation of the optics of the eye. However, in addition to AL and corneal power, numerous other parameters influence the refractive outcome. Some are measurable, and others are not. The measurable parameters could be taken into account, but not by the application of thin-lens theory.

The purpose of this paper is to analyze how the variability of all influential parameters affects refractive outcome. Such an analysis can only be done by exact ray tracing that takes asphericity into account. Furthermore, an error analysis is incomplete unless it also considers variability in the measurement of the outcome, in this case postoperative refraction. The error analysis

Accepted for publication October 16, 2007.

From AMO Groningen BV, Groningen, The Netherlands.

The author has no financial or proprietary interest in any material or method mentioned.

Presented in part at the ASCRS Symposium on Cataract, IOL and Refractive Surgery, San Francisco, California, USA, March 2006.

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is done for random variability only. In addition, there may be systematic variability, in which case the total error in refractive outcome is even greater.

The study is limited to normal cataract surgery and does not consider eyes that have had previous corneal refractive surgery.

PATIENTS AND METHODS

Calculations

Gaussian error-propagation analysis assumes that the parameters are independent of each other. The influence of each parameter is given by its partial derivative with respect to spectacle refraction. For each parameter, the partial derivative was obtained numerically by calculating the change in refraction for a small change in the parameter around its nominal value, while keeping all other parameters constant. The magnitude by which a parameter influences refraction is given by its variability times the partial derivative. The most common measure of variability is the standard deviation (SD), but other measures such as the 95% confidence interval can also be used. For this study, the SD was chosen because it is the one most commonly reported in the literature. Multiplying the SD with the partial derivative for a parameter yields the SD in terms of spectacle diopters (D). (Directly calculating the change in spectacle D caused by 1 SD in the parameter gives essentially the same result, but is procedurally less correct.)

The SDs (expressed as spectacle D) for all parameters were squared to obtain the variances, which were then summed, including the variance in determination of postoperative refraction. The relative contribution of a given parameter is its percentage of the total variance. The SD for the whole procedure is the square root of the sum of variances. The mean absolute error (MAE) is $\sqrt{2/\pi} = 0.80 \times \text{SD}$ assuming a perfectly Gaussian distribution.

The ray tracing was performed using a Microsoft Excel spreadsheet with a technique that has been described in detail.² The focus of a ray traced at $1/\sqrt{2}$ of the pupil radius was used as the best-focus criterion. This "focusing ray" lies on a circle that divides the pupil into an inner circle and an outer annulus of equal areas. Such a ray can therefore be considered to represent the average of all rays.

Input Parameters

Table 1 shows the parameters of the basic eye model with the nominal values and SDs. The mean values in the table represent an "average eye." The choices are somewhat arbitrary, although the precise values are not critical. The choices of sources for SDs represent the author's selection and to his knowledge are representative of what is found in the literature and in clinical practice. It is beyond the scope of this paper to review all sources for each parameter. The important message is that there is variability in all parameters, and this influences the refractive outcomes of cataract surgery with IOL implantation.

Axial length is the distance from the anterior corneal apex to the inner limiting membrane. The mean AL was taken from Haigis et al.³ and was measured by PCI. The SD was obtained from Norrby⁴ and applies to A-scan ultrasound. However, because the perceived image is formed on the retinal receptors, the retinal thickness and SD of retinal thickness were also taken into account.⁵

The anterior corneal radius refers to the corneal apex. The mean comes from Dubbelman et al.,⁶ who used corrected Scheimpflug imaging. The SD was taken from Norrby⁴ and applies to keratometry. Keratometry measures the local curvature at an aperture of approximately 3.0 mm. If the Q value is known, the radius at the apex can be calculated from the curvature at 3.0 mm and the SD should be virtually the same for the apical radius. The assumed corneal anterior Q value is calculated for an individual 70 years of age using a relationship from Dubbelman et al.⁶ and indicates an almost spherical cornea ($Q = 0$ defines a sphere), while the SD comes from an earlier study by Dubbelman et al.⁷ The corneal posterior Q value for a 70-year-old person was calculated using a formula given in the text of Dubbelman et al.,⁶ where the corresponding SD is also stated.

Gullstrand's⁸ indices of refraction for the ocular media are assumed because they are so widely used and they do not differ appreciably from the references cited for the SDs.^{9,10} Patel et al.⁹ measured the refractive index of the human cornea, and the SD was taken from their measurement. Duke-Elder¹⁰ gives a range for the refractive index of aqueous. The SD was inferred by assuming this range to span 6 SDs. This assumption can be criticized because the range may represent differences in measurement rather than a Gaussian distribution, in which case it is an overestimation of the true SD. However, as will be seen, even the assumed SD has little influence on the refractive outcome. The same SD was assumed for vitreous because both vitreous and aqueous are dilute aqueous solutions with the same refractive index. The refractive index of air is 1.0003 over a wide range of wavelengths at normal temperatures and pressures, and the SD was estimated as one quarter the difference between dry and moisture-saturated air.¹¹

The refractive index of the IOL applies to in situ conditions for the material in the CeeOn 911A IOL and Tecnis Z9000 IOL models (both Advanced Medical Optics). These 2 models differ only in the shapes of the anterior surfaces, which are spherical and modified prolate, respectively. In the International Organization for Standardization (ISO) standards for IOLs,¹² the tolerance for power is ± 0.40 D in the range between 15.00 D and 25.00 D. This tolerance was set based on extensive interlaboratory testing.¹³ In accordance with the principles of modern quality assurance, tolerances should comprise 6 SDs; thus, $\text{SD} = 0.13$ D. The overall tolerance comprises the manufacturing tolerances on surface curvatures and thickness of IOLs, the refractive index of the material, and the limited repeatability of measuring IOL power (approximately 0.5% of the labeled value¹³). Rather than varying all the parameters, their combined effect on IOL power was simulated by an SD in the refractive index. Therefore, the SD in Table 1 was calculated for the most challenging case in the range, a 25.0 D lens at ± 0.4 D. (A 15.0 D lens at ± 0.3 D and a 30.0 D lens at ± 0.5 D, in accordance with the ISO standard, can be simulated by almost the same SD in refractive index.)

The pupil size (3.59 mm) and SD (0.76 mm) in Table 1 apply under photopic light conditions,¹⁴ which is representative for the situation in which refraction is usually measured. It is the pupil size seen through the magnification of the cornea, which is also the entrance pupil used in optical ray tracing.

In a study that assessed the reproducibility of determining refraction, Bullimore et al.¹⁵ found that the 95% limits of agreement for manual refraction by 2 experienced optometrists using a phoropter ranged from -0.90 to $+0.65$ D. The 95% limits comprise 4 SDs; hence, $\text{SD} = 0.39$ D.

Table 1. Average eye model for error analysis.

Parameter	Nominal Value	Source* and Date	Standard Deviation	Source* and Year
Axial length (mm)	23.41	Haigis ³ 2000	0.11	Norrby ⁴ 2001
Retinal thickness (mm)	0.23	Lim ⁵ 2005	0.01	Lim ⁵ 2005
Corneal anterior apical radius (mm)	7.79	Dubbelman ⁶ 2006	0.02	Norrby ⁴ 2001
Corneal posterior/anterior radius ratio	0.84	Dubbelman ⁶ 2006	0.02	Dubbelman ⁷ 2002
Corneal anterior asphericity (Q value)	-0.03	Dubbelman ⁶ 2006	0.18	Dubbelman ⁷ 2002
Corneal posterior asphericity (Q value)	-0.43	Dubbelman ⁶ 2006	0.14	Dubbelman ⁶ 2006
Corneal thickness (mm)	0.574	Dubbelman ⁷ 2002	0.033	Dubbelman ⁷ 2002
Corneal refractive index	1.376	Gullstrand ⁸ 1909	0.0050	Patel ⁹ 1995
Aqueous refractive index	1.336	Gullstrand ⁸ 1909	0.00056	Duke-Elder ¹⁰ 1968
Vitreous refractive index	1.336	Gullstrand ⁸ 1909	0.00056	Duke-Elder ¹⁰ 1968
Air refractive index	1.0003	Weast ¹¹ 1967	0.00001	Weast ¹¹ 1967
IOL refractive index	1.458	Specification	0.00065	Calculated to simulate power tolerance (ISO ¹² 2000; Norrby ¹³ 1996)
Chart distance (mm)	6000	Assumed	250	Assumed
Pupil size (mm)	3.59	Cheng ¹⁴ 2006	0.76	Cheng ¹⁴ 2006
Postoperative anterior chamber depth (mm)	4.60	Norrby [†] 2006	0.31	Olsen ¹ 1992
Postoperative refraction (D)	—	—	0.39	Bullimore ¹⁵ 1998

IOL = intraocular lens; ISO = International Organization for Standardization

*First author or editor

†Norrby S, et al., "Pilot Biometry Study for Development of Power Calculation with Regard to Spherical Aberration; Postoperative ACD by Zeiss ACMaster Measured in 24 Cases Implanted with AMO CeeOn 911A or TECNIS Z9000 at Rostock University, Germany, 2006." Data on file.

To evaluate the influence of AL, a short eye (21.52 mm) and a long eye (26.91 mm) were also defined. The ALs were chosen so that they require a 30.0 D CeeOn 911A IOL and 10.0 D CeeOn 911A IOL, respectively. Table 2 shows the details of designs of the IOLs used in the cases analyzed. By convention, a radius convex toward the incidence of light is given a positive sign and a concave one, a negative sign. Because IOLs were chosen that render the eyes as close as possible to emmetropia, the variability in spectacle lens vertex distance was ignored in the error analysis.

The anterior surface of the Tecnis IOL is described as a prolate conicoid of revolution with 2 modifying terms

$$z = \frac{\left(\frac{1}{R}\right)r^2}{1 + \sqrt{1 - \left(Q + 1\right)\left(\frac{1}{R}\right)^2 r^2}} + a_4 r^4 + a_6 r^6 \quad (1)$$

where R is the radius of curvature at the apex, Q is the degree of asphericity, r is the radial distance from the optical axis, and z is the sag in the direction of light propagation. For a spherical surface, $Q = 0$, and the coefficients of the modifying terms (a_4 , a_6) are zero. For a prolate surface (increasingly flatter toward the periphery), Q is negative (-1 for a paraboloid). Deviation from the pure prolate shape is characterized by nonzero coefficients in the modifying terms. The corneal surfaces were treated as pure conicoids of revolution, with the Q values given in Table 1.

RESULTS

Table 3 shows the results of the error analysis of the eye with a 21.5 D spherical IOL (CeeOn 911A). Figure 1

shows the data as a bar chart in decreasing order of percentage error contribution. The largest source of error is the preoperative prediction of the postoperative position (anterior chamber depth [ACD]) of the IOL. This error and the errors made in determining postoperative refraction and measuring AL make up 80% of the total error. Attempts to improve the predictability of postoperative refraction should therefore be concentrated on these 3 parameters.

Figure 2 compares the error contribution in terms of variance for eyes with different ALs. The short eye has an AL of 21.52 mm but is otherwise the same as the eye in Table 3. With a 30.0 D CeeOn 911A IOL, the refraction in the short eye is 0.01 spectacle D. The AL in the long eye is 26.91 mm, which with a 10.0 D CeeOn 911A IOL gives a refraction of -0.01 spectacle D; the medium-length eye implanted with a 21.5 D CeeOn 911A IOL has a refraction of $+0.02$ spectacle D (Table 2). Postoperative ACD is a large contributor to the error, particularly in the short eye. It is known that short eyes are more sensitive to errors in input in general and to errors in axial distances in particular. The MAE in spectacle D of each case is also given.

Figure 3 shows the case of a 22.0 D Tecnis Z9000 IOL in the average eye in Table 3 compared to the average case in Figure 2. With this IOL, the refraction is $+0.12$ D. The error arising from pupil size has vanished because

Table 2. Intraocular lens design details, refraction, and AL in the cases analyzed.

Axial Length (mm)	Model	Power (D)	Refraction (D)	Anterior Radius (mm)	Posterior Radius (mm)	Central Thickness (mm)	Q Value (-)	a_4 (mm ⁻⁴)	a_6 (mm ⁻⁶)
23.41; average	Tecnis Z9000	22.0	+0.12	11.043	-11.043	1.16	-1.04	-9.44×10^{-4}	-1.37×10^{-5}
23.41; average	CeeOn 911A	21.5	+0.02	11.301	-11.301	1.13	0	0	0
21.52; short	CeeOn 911A	30.0	0.01	8.075	-8.075	1.39	0	0	0
26.91; long	CeeOn 911A	10.0	-0.01	24.362	-24.362	0.91	0	0	0

the cornea and the IOL balance each other when the cornea has its average Q value. Note, however, that variability in corneal Q causes a small error that depends on pupil size.

DISCUSSION

Intraocular Lens Power Calculation: Systematic and Random Errors

The Holladay,¹⁶ SRK/T,¹⁷ and Hoffer Q¹⁸ formulas all use thin-lens theory, with different prediction algorithms for postoperative effective lens position (ELP)

and adjustment factors for short and long eyes. These algorithms and factors were derived from large sets of clinical data and reflect the surgical techniques and IOL models that were available at the time of their derivation. Effective lens position, although related to the true IOL position, is neither that nor the position of its principal plane; rather, it is a fictitious position that gives the desired result. The Holladay II formula, which has not been published but resides in the Holladay IOL Consultant software, uses additional preoperative parameters in the ELP prediction, but it is otherwise similar. The prediction of ELP involves

Table 3. Gaussian error propagation analysis results for the eye described in Table 1 with a 21.5 D spherical IOL (CeeOn 911A), which gives a refraction of +0.02 spectacle D (see Table 2).

Parameter	Nominal Value	SD	Partial Derivative (Spectacle D per Unit)	Expressed as Effect in Spectacle Power		Relative Error Contribution (%)
				SD (D)	Variance (D) ²	
Axial length (mm)	23.41	0.11	2.82	0.3098	0.0960	17.03
Retinal thickness (mm)	0.23	0.01	2.82	0.0282	0.0008	0.14
Corneal anterior apical radius (mm)	7.79	0.02	-5.72	0.1144	0.0131	2.32
Corneal posterior/anterior radius ratio	0.84	0.02	7.21	0.1442	0.0208	3.69
Corneal anterior asphericity (Q-value)	-0.03	0.18	0.662	0.1192	0.0142	2.52
Corneal posterior asphericity (Q-value)	-0.43	0.14	-0.108	0.0151	0.0002	0.04
Corneal thickness (mm)	0.574	0.033	0.366	0.0121	0.0001	0.03
Corneal refractive index	1.376	0.0050	-18.9	0.0947	0.0090	1.59
Aqueous refractive index	1.336	0.00056	80.4	0.0447	0.0020	0.36
Vitreous refractive index	1.336	0.00056	-99.1	0.0552	0.0030	0.54
Air refractive index	1.0003	0.00001	-132	0.0018	0.0000	0.00
IOL refractive index*	1.458	0.00065	126	0.0818	0.0067	1.19
Chart distance (mm)	6000	250	0.00003	0.0072	0.0001	0.01
Pupil size (mm)	3.59	0.76	0.281	0.2138	0.0457	8.11
Postoperative ACD (mm)	4.60	0.31	-1.44	0.4472	0.2000	35.47
Postoperative refraction	—	—	—	0.3900	0.1521	26.98

ACD = anterior chamber depth; SD = standard deviation; IOL = intraocular lens

*The 0.13 D SD in IOL power is simulated by the SD in refractive index.

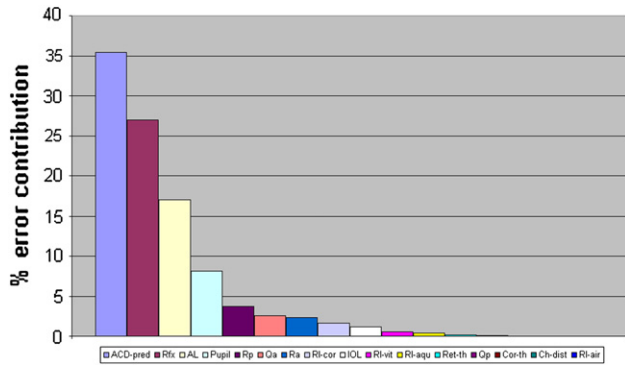


Figure 1. Relative (percentage) error contribution of all factors influencing the refractive outcome of cataract surgery, arranged in order of decreasing magnitude. Eye of average dimensions and properties (see Table 3) implanted with a 21.5 D IOL with spherical surfaces (see Table 2) (ACD-pred = prediction of postoperative IOL position; AL = axial length; Ch-dist = chart distance; Cor-th = corneal thickness; IOL = IOL power; Pupil = pupil size; Qa = corneal anterior asphericity; Qp = corneal posterior asphericity; Ra = corneal anterior radius; Ret-th = retinal thickness; Rfx = postoperative spectacle refraction; RI-air = air refractive index; RI-aqu = aqueous refractive index; RI-cor = corneal refractive index; RI-vit = vitreous refractive index; Rp = corneal posterior radius).

a constant (A constant, ACD constant, or SF constant) that is specific for an IOL model. Manufacturers label their IOL models with recommended constant values; however, these should be customized for the surgeon by feedback taken from his or her clinical cases. The need for customization stems from differences in biometry equipment⁴ rather than from the IOL model itself. Customization will, on average, nullify systematic

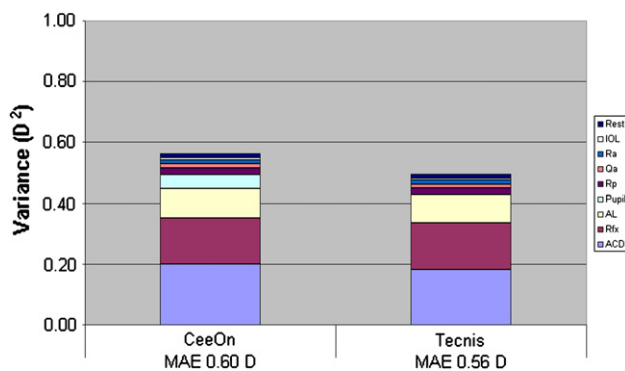


Figure 3. The eye defined in Table 3 with an aberration correcting IOL (TECNIS) compared to the same eye with a spherical IOL (CeeOn) in terms of absolute (variance) error contributions. See Table 2 for IOL parameters. The MAE, which is $\sqrt{2/\pi}$ times the square root of the sum of variances (height of the bars), is given under the bars in spectacle D (ACD = prediction of postoperative IOL position; AL = axial length; IOL = IOL power; MAE = mean absolute error; Pupil = pupil size; Qa = corneal anterior asphericity; Ra = corneal anterior radius; Rest = sum of remaining factors; Rfx = postoperative spectacle refraction; Rp = corneal posterior radius).

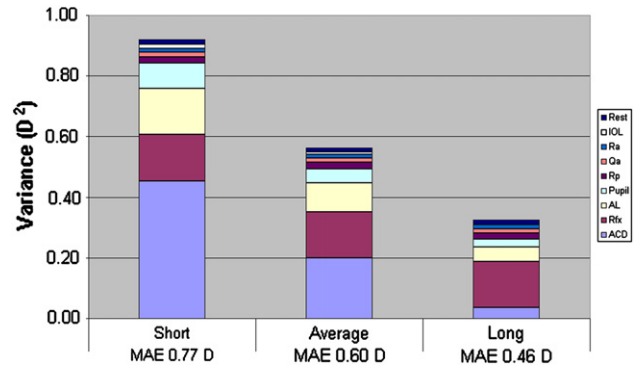


Figure 2. Influence of AL on the absolute (variance) error contribution of factors influencing the refractive outcome of cataract surgery for eyes implanted with spherical IOLs. See Table 2 for axial lengths and IOL parameters, and Table 3 for parameters other than axial length. The MAE, which is $\sqrt{2/\pi}$ times the square root of the sum of variances (height of the bars), is given under the bars in spectacle D (ACD = prediction of postoperative IOL position; AL = axial length; IOL = IOL power; MAE = mean absolute error; Pupil = pupil size; Qa = corneal anterior asphericity; Ra = corneal anterior radius; Rest = sum of remaining factors; Rfx = postoperative spectacle refraction; Rp = corneal posterior radius).

errors, although not eliminate them in short and long eyes.¹⁹ Customization not only nullifies systematic measurement error but also those due to neglect of including factors such as retinal thickness and the effect of aberrations.

The Haigis formula²⁰ differs in that the ELP prediction involves 3 constants that can better approximate the nonlinear relationship between AL and IOL position and it uses no other adjustment factors. Olsen²¹ developed a formula based on exact thick-lens theory. In its latest version, it uses 5 preoperative parameters to predict IOL position. It is still limited to paraxial calculation, but the advantage is that in the thick-lens model the ocular components are at their true positions. The challenge with exact calculation is that all input parameters must be correct. There are no “fudge” factors to tweak the result with, except the ACD prediction formula itself.

Norrby et al.²² also developed a thick-lens formula and deliberately limited the ACD prediction to the 2 parameters required for the optical calculation (AL and corneal radius). Corneal radius is reproducibly obtained by keratometry,⁴ but its conversion to corneal power (K value) varies due to use of different keratometric indices.²³ In general, ALs cannot be reproducibly obtained due to systematic differences between instruments^{4,24}; however, they can be transformed to a common scale with a simple procedure.¹⁹ The IOLMaster (Zeiss) is a suitable reference for such a scale. If additional parameters, such as preoperative ACD and lens thickness, are used in the ACD

prediction formula, the result may be worse if the formula was developed in a setting with instrumentation different from that in which it is being applied. This could also be the consequence if the additional parameters are obtained with poor precision.

Gaussian error-propagation analysis amounts to evaluating the influence of random errors around the assumed nominal values for all parameters. Ray tracing through thick lenses, taking spherical aberration into account, is suitable for error-propagation analysis of IOL power calculation. Such analyses cannot be properly performed using paraxial theory because this simplified theory omits many parameters that influence the outcomes just as much, or even more than, when they are ignored. Although the analysis could be extended to include systematic errors, these were deliberately not included for 2 reasons. First, there are no data in the literature for every parameter involved. Second, as stated above, they are nullified on average by personalization of formula constants, which the conscientious surgeon should apply. Otherwise, systematic errors in the input will manifest as potentially very large systematic errors, in addition to the random error, in the refractive outcome in every patient.

Postoperative Anterior Chamber Depth

Because postoperative ACD is predicted by formulas involving preoperative parameters, errors in the parameters will lead to errors in the predicted ACD. It is therefore not surprising that prediction of ACD is a dominant source of error in the total IOL power calculation. However, the assumed SD comes from an old study¹ and improvements have been made since. A pilot study found an algorithm based on preoperative measurements by the IOLMaster that can predict the postoperative position of the IOL, measured by the ACMaster (Zeiss) as ACD, with an SD of ± 0.22 mm for the 2 IOL models used in the examples presented in this paper (Norrby S, et al., "Pilot Biometry Study for Development of Power Calculation with Regard to Spherical Aberration; Postoperative ACD by Zeiss ACMaster Measured in 24 Cases Implanted with AMO CeeOn 911A or TECNIS Z9000 at Rostock University, Germany, 2006." Data on file).

There is also a hidden source of error from the IOL, namely variability in compressed vault height. Vault height is the distance from the plane through the outer diameter of the haptic to the front surface of the IOL optic. The tolerance for vault height of 3-piece IOLs is ± 0.35 mm,²⁵ which translates to an SD of 0.12 mm. The associated variance in IOL power prediction is $0.03 D^2$. In relative terms, the assumed variance in vault height amounts to 15% of the variance of ACD in all cases in Figure 2. In the eye, compression of the haptics further influences the vault height by an

amount that is not possible to quantify generally but is dependent on the design properties of the haptic. However, both errors are implicitly part of the overall variance in ACD prediction.

Postoperative Refraction

The SD of manual refraction was estimated to be one quarter of the 95% limits of agreement, or 0.39 D, as determined by Bullimore et al.¹⁵ This is of the same order of magnitude as in a recent study by Leinonen et al.,²⁶ who found 0.37 D, again estimated as one quarter of the 95% limits in a mixed group ($n = 99$) of healthy, pseudophakic, and cataractous patients. In patients with a visual acuity of 0.7 or better ($\approx 20/30$) they found 0.25 D, but the difference was not statistically significant. Bullimore et al. found autorefraction to be more reproducible (SD ± 0.19 D) than manual refraction, which was not reported by Zadnik et al.²⁷ However, as pointed out by Bullimore et al., autorefraction can be confounded by accommodation in presbyopic subjects. Even if patients in general receive manually measured spectacle prescriptions, autorefraction may be the better choice for studying predictability in refractive outcomes of cataract surgery.

To some it may seem strange to include the outcome parameter in the error analysis. It is, however, an integral contributor to the total error and it would be misleading not to include it.

Axial Length Measurement

The SD (± 0.11 mm) assumed for AL measurement is from a study conducted before the availability of the IOLMaster, for which an SD of ± 0.03 mm was reported under optimal conditions.²⁸ (Strictly speaking, AL measurement with the IOLMaster is dependent on the refractive indices of the ocular media, violating the assumption of parameter independence. However, the variance in the indices is so small that its influence on the measured AL is negligible.) Although AL measurement is the most influential parameter measured for IOL power calculation, this increased precision has not always been reflected in better refractive outcomes, as discussed by Olsen.²⁹ It is possible that the larger errors in postoperative ACD estimation and refraction overshadow the relatively smaller error in AL.

Optimal Cases

Using the smaller SDs indicated above for estimating ACD and measuring refraction and AL, optimal cases can be defined as shown in Figure 4. In comparison with the average case of Figure 2, the total variance has been more than halved, which is probably

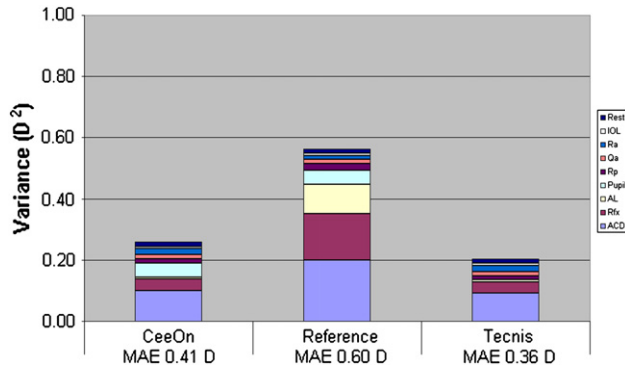


Figure 4. Comparison of optimal cases for an average eye, implanted with a spherical IOL (CeeOn) and an aberration correcting IOL (TECNIS), with the average case of Figure 2 as reference. In the optimal cases, SDs of 0.22 mm for estimation of postoperative IOL position (ACD), 0.19 D for determination of postoperative refraction, and 0.03 mm for measurement of AL were used. All other parameters are as in Table 3, and IOL dimensions those for the average length eye are in Table 2. Estimation of postoperative ACD remains the dominating source of error, although its variance is halved. With a spherical lens (ie, in the presence of spherical aberration), pupil size is the second largest source of error. The other sources of error contribute virtually the same for both types of IOL, and determination of postoperative refraction is the largest among them. The MAE, which is $\sqrt{2/\pi}$ times the square root of the sum of variances (height of the bars), is given under the bars in spectacle D (ACD = prediction of postoperative IOL position; AL = axial length; IOL = IOL power; MAE = mean absolute error; Pupil = pupil size; Qa = corneal anterior asphericity; Ra = corneal anterior radius; Rest = sum of remaining factors; Rfx = postoperative spectacle refraction; Rp = corneal posterior radius).

close to as good as can be achieved with currently available methods for IOL power calculation.

Pupil Size

The fourth largest source of error in Figure 1 is variation in pupil size. However, when there is no spherical aberration, pupil size has no effect on refraction. Figure 3 shows negligible error from pupil size in the case of the Tecnis IOL, which compensates for the spherical aberration of the cornea. Current power calculation formulas are incapable of taking spherical aberration into account; thus, unless the pseudophakic eye is free of spherical aberration, aspherical power calculation in combination with measurement of the pupil is needed to understand the true impact of this source of error. From a practical standpoint, if spherical aberration is present, refraction will depend on the pupil size induced by the light level of the environment; for example, night myopia can occur.

Keratometry

The next largest error sources stem from keratometry (Figure 1). Measurement of anterior curvature is

probably as precise as it can be using keratometers. Topographers could be used to measure the anterior corneal surface asphericity and take that into account in the power calculation.³⁰ Instruments such as the Pentacam (Oculus) or Orbscan (Bausch & Lomb) could be used to measure corneal posterior curvature and asphericity as well as thickness. By application of aspherical ray-tracing calculations, the errors resulting from these parameters could be reduced provided that the measurements are sufficiently accurate. As seen in Figure 3, the error due to anterior asphericity is equally large for the CeeOn IOL and Tecnis IOL. Although the Tecnis IOL compensates for the spherical aberration of the average cornea, eyes with corneas with more or less than the average amount of spherical aberration will be slightly aspherical; hence, there is some variance due to pupil size. Elimination would require customization of the IOL for the individual patient. The error due to the asphericity of the posterior surface is negligible (Table 3).

Intraocular Lens Power

The error from variability in IOL power is very small when manufacturers adhere to the ISO 11979-2¹² and apply ISO 13485,³¹ which is compulsory in the United States, Europe, and many other countries. Compliance in manufacturing and sales is supervised by the Food and Drug Administration in the U.S. and Notified Bodies under the Medical Device Directive in Europe. The error should be even smaller because a conscientious manufacturer should apply an internal tolerance of ± 0.25 D (SD 0.08 D), as pointed out in the standard with reference to the paper by Norrby et al.¹³ This is to guard against third-party control, taking into account the limited reproducibility (approximately 1% of the labeled value) between laboratories in measurement of IOL power.

Another matter is how near to the desired refractive outcome one could come. With IOLs coming in steps of 0.50 D, which translates to about 0.36 D in the spectacle, the deviation from the desired outcome would have a mean of 0.09 D and a maximum of 0.18 D. Customization to reduce this small deviation will not pay off, however, until the major sources of refractive error are substantially reduced.

Other Sources of Error

The remaining sources of error are so small that they can be neglected. Of them, the refractive indices of the ocular media cannot be measured in the living eye. Corneal thickness and posterior surface asphericity could be measured, and there is no harm in including them in the power calculation. The chart distance should be correct more for the purpose of determining

visual acuity than for refraction. Influence of fluctuations in the refractive index of air is totally negligible.

There are additional parameters that were not considered in the calculation model used in this paper. Astigmatism and higher-order aberrations exist in the cornea. Cornea, pupil, lens, and fovea are not perfectly aligned with each other. Finally, there is chromatic aberration. The influence of these factors could all be calculated with the help of existing optical design software packages, but it would be tedious and not likely to reveal large error contributors other than those discussed.

Surgically induced change in corneal power is another source of error not considered. A previous study²² found a mean increase of 0.04 D in corneal power with an SD of 0.25 D measured by keratometry (not published in the article). However, that study was conducted before the advent of foldable IOLs and small-incision surgery.

CONCLUSION

Improvement in predictability of IOL power calculation should focus on the 3 largest sources of error: (1) estimation of postoperative IOL position; (2) determination of postoperative refraction; (3) measurement of AL. Until these 3 sources of error are sufficiently reduced, refining power calculation by taking asphericity into account and including measurements of both corneal surfaces will have little impact on the outcome.

Part of the variability in IOL position is due to the design and mechanical properties of the haptics. Attention to haptic design could therefore improve the predictability of IOL position, hence of refractive outcomes. Accuracy in IOL power labeling is sufficient. Some improvement in obtaining exactly the desired outcome could be achieved by customization of IOL power and asphericity.

REFERENCES

- Olsen T. Sources of error in intraocular lens power calculation. *J Cataract Refract Surg* 1992; 18:125–129
- Norrby S. The Dubbelman eye model analysed by ray tracing through aspheric surfaces. *Ophthalmic Physiol Opt* 2005; 25:153–161
- Haigis W, Lege B, Miller N, Schneider B. Comparison of immersion ultrasound biometry and partial coherence interferometry for intraocular lens calculation according to Haigis. *Graefes Arch Clin Exp Ophthalmol* 2000; 238:765–773
- Norrby S. Multicenter biometry study of 1 pair of eyes. *J Cataract Refract Surg* 2001; 27:1656–1661
- Lim MCC, Hoh S-T, Foster PJ, et al. Use of optical coherence tomography to assess variations in macular retinal thickness in myopia. *Invest Ophthalmol Vis Sci* 2005; 46:974–978
- Dubbelman M, Sicam VADP, van der Heijde GL. The shape of the anterior and posterior surface of the aging human cornea. *Vision Res* 2006; 46:993–1001
- Dubbelman M, Weeber HA, van der Heijde RGL, Völker-Dieben HJ. Radius and asphericity of the posterior corneal surface determined by corrected Scheimpflug photography. *Acta Ophthalmol Scand* 2002; 80:379–383
- Gullstrand A. The optical system of the eye. In: Southall JPC, ed, *Helmholtz's Treatise on Physiological Optics*, translated from 3rd German edition. Rochester, NY, Optical Society of America, 1924; Vol. 1 Appendix II.3; 350–358. Available at: <http://www.psych.upenn.edu/backuslab/helmholtz>. Accessed November 19, 2002
- Patel S, Marshall J, Fitzke FW III. Refractive index of the human corneal epithelium and stroma. *J Refract Surg* 1995; 11:100–105
- Duke-Elder S, ed, *System of Ophthalmology*. Vol. 4: The Physiology of the Eye and Vision. St Louis, MO, Mosby, 1968; 108, 201
- Weast RC, ed, *CRC Handbook of Chemistry and Physics* 48th edition. Cleveland, OH, Chemical Rubber Co, 1967; E-160
- International Organization for Standardization. *Ophthalmic Implants – Intraocular Lenses—Part 2: Optical Properties and Test Methods*. Geneva, Switzerland, ISO 2000 (ISO 11979–2)
- Norrby NES, Grossman LW, Geraghty EP, et al. Accuracy in determining intraocular lens dioptric power assessed by interlaboratory tests. *J Cataract Refract Surg* 1996; 22:983–993
- Cheng ACK, Rao SK, Cheng LL, Lam DSC. Assessment of pupil size under different light intensities using the Procyon pupillometer. *J Cataract Refract Surg* 2006; 32:1015–1017
- Bullimore MA, Fusaro RE, Adams CW. The repeatability of automated and clinician refraction. *Optom Vis Sci* 1998; 75:617–622
- Holladay JT, Prager TC, Chandler TY, et al. A three-part system for refining intraocular lens power calculations. *J Cataract Refract Surg* 1988; 14:17–24
- Retzlaff JA, Sanders DR, Kraff MC. Development of the SRK/T intraocular lens implant power calculation formula. *J Cataract Refract Surg* 1990; 16:333–340; correction, 528
- Hoffer KJ. The Hoffer Q formula: a comparison of theoretic and regression formulas. *J Cataract Refract Surg* 1993; 19:700–712; errata 1994; 20:677
- Norrby S, Lydahl E, Koranyi G, Taube M. Reduction of trend errors in power calculation by linear transformation of measured axial lengths. *J Cataract Refract Surg* 2003; 29:100–105
- Haigis W. The Haigis formula. In: Shammas HJ, ed, *Intraocular Lens Power Calculations*. Thorofare, NJ, Slack, 2004; 41–57
- Olsen T. The Olsen formula. In: Shammas HJ, ed, *Intraocular Lens Power Calculations*. Thorofare, NJ, Slack, 2004; 27–40
- Norrby S, Lydahl E, Koranyi G, Taube M. Clinical application of the lens haptic plane concept with transformed axial lengths. *J Cataract Refract Surg* 2005; 31:1338–1344
- Haigis W. Biometrie. In: Straub W, Kroll P, Kühle HJ, eds, *Augenärztliche Untersuchungsmethoden*, 2nd ed. Stuttgart, Germany, Ferdinand Enke Verlag, 1995; 255–304
- Norrby S, Lydahl E, Koranyi G, Taube M. Comparison of 2 A-scans. *J Cataract Refract Surg* 2003; 29:95–99
- International Organization of Standardization. *Ophthalmic Implants—Intraocular Lenses—Part 3: Mechanical Properties and Test Methods*. Geneva, Switzerland, ISO 2006 (ISO 11979–3)
- Leinonen J, Laakkonen E, Laatikainen L. Repeatability (test-retest variability) of refractive error measurement in clinical settings. *Acta Ophthalmol Scand* 2006; 84:532–536

27. Zadnik K, Mutti DO, Adams AJ. The repeatability of measurement of the ocular components. *Invest Ophthalmol Vis Sci* 1992; 33:2325–2333
28. Sheng H, Bottjer CA, Bullimore MA. Ocular component measurement using the Zeiss IOLMaster. *Optom Vis Sci* 2004; 81:27–34
29. Olsen T. Improved accuracy of intraocular lens power calculation with the Zeiss IOLMaster. *Acta Ophthalmol Scand* 2007; 85:84–87
30. Preussner P-R, Wahl J, Weitzel D. Topography-based intraocular lens power selection. *J Cataract Refract Surg* 2005; 31:525–533
31. International Organization for Standardization. *Medical Devices – Quality Assurance Systems—Requirements for Regulatory Purposes*. Geneva, Switzerland (ISO 13485)



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