Relationship of the Actual Thick Intraocular Lens Optic to the Thin Lens Equivalent

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• PURPOSE: To theoretically derive and empirically validate the relationship between the actual thick intraocular lens and the thin lens equivalent.
• METHODS: Included in the study were 12 consecutive adult patients ranging in age from 54 to 84 years (mean ± SD, 73.5 ± 9.4 years) with best-corrected visual acuity better than 20/40 in each eye. Each patient had bilateral intraocular lens implants of the same style, placed in the same location (bag or sulcus) by the same surgeon. Preoperatively, axial length, keratometry, refraction, and vertex distance were measured. Postoperatively, keratometry, refraction, vertex distance, and the distance from the vertex of the cornea to the anterior vertex of the intraocular lens (AV_{PC1}) were measured. Alternatively, the distance (AV_{PC1}) was then back-calculated from the vergence formula used for intraocular lens power calculations.
• RESULTS: The average (±SD) of the absolute difference in the two methods was 0.23 ± 0.18 mm, which would translate to approximately 0.46 diopters. There was no statistical difference between the measured and calculated values; the Pearson product-moment correlation coefficient from linear regression was 0.85 ($r^2 = .72$, $F = 56$). The average intereye difference was −0.030 mm (SD, 0.141 mm; SEM, 0.043 mm) using the measurement method and +0.124 mm (SD, 0.412 mm; SEM, 0.124 mm) using the calculation method.
• CONCLUSION: The relationship between the actual thick intraocular lens and the thin lens equivalent has been determined theoretically and demonstrated empirically. This validation provides the manufacturer and surgeon additional confidence and utility for lens constants used in intraocular lens power calculations. (Am J Ophthalmol 1998;126:339–347. © 1998 by Elsevier Science Inc. All rights reserved.)

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CURRENT INTRAOCULAR LENS POWER CALCULation formulas assume that the thickness of an intraocular lens is zero (thin lens equivalent). Formulas that assume the lens has no thickness are often referred to as "thin lens" formulas.[1–3] Although the thin lens formula works well for intraocular lens power calculations, it does not provide any direct information about the position of the actual thick intraocular lens within the eye.[4] The following discussion and formulas relate the position of the thin lens equivalent with respect to the actual thick lens. These relationships will allow the manufacturer and surgeon to validate the lens constant used for intraocular lens power calculations by two methods: (1) using the postoperative refraction, axial length, and keratometry to back-calculate from the thin lens formula, and (2) using the actual measurement of the anterior vertex of the actual thick lens. Knowing the relationship of the actual thick lens to the thin lens equivalent will also provide the tools necessary to refine the existing formulas for powers greater than +34 diopters, two intraocular lenses (IOLs) (piggyback IOLs), and negative power IOLs, that is, the actual position of the high-powered, piggyback, and negative IOLs must be known before the thin lens vergence formulas can be appropriately modified. Secondly,

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knowledge of the effective thin lens position (ELP_o) from direct measurement provides all of the variables necessary to back-calculate the value of an intraocular lens that may have been mislabeled, causing a refractive surprise. The term effective lens position (ELP_o) was recommended to the United States Food and Drug Administration in 1995 to describe the position of the lens in the eye, since the term anterior chamber depth (ACD) is not anatomically accurate for lenses in the posterior chamber and can lead to confusion for the clinician with the anatomic anterior chamber depth (AACD). The A-constant, familiar to many clinicians, does not directly give information about the position of the lens, but can be converted to an ELP_o by the following regression equation[4]:

$$ELP_o = [(A\ constant * 0.5663) - 62.005]/0.9704.$$

MATERIALS AND METHODS

INCLUDED IN THE STUDY WERE 12 CONSECUTIVE adult patients ranging in age from 54 to 84 years (mean ±SD, 73.5 ± 9.4 years) with best-corrected visual acuity better than 20/40 in each eye. Each patient had bilateral IOL implants of the same style, placed in the same location (bag or sulcus) by the same surgeon. At least 1 year had elapsed since the second eye surgery for all patients. Patients who satisfied the criteria above were selected as they presented for their routine annual visit. In addition to the normal measurements taken preoperatively (K-readings, axial length, and refraction) and postoperatively (K-readings and refraction), the distance from the vertex of the cornea to the anterior vertex of the intraocular lens (AV_{PC1}) was measured by means of the Haag-Streit anterior chamber depth gauge. Measurements of the distance to the lens vertex were performed by two observers. If the two measurements differed by more than 0.05 mm, they were repeated by the two observers until the difference satisfied this condition. The value for AV_{PC1} was then calculated from postoperative refraction, postoperative K-readings, and the axial length, using equations 2 through 8.

RESULTS

THE INPUT VALUES AND RESULTS FOR AV_{PC1} BY THE calculation and measurement are shown in Table 1. There was no statistical difference between the values obtained by the two methods, and the correlation coefficient was 0.85 (r^2 = .72, F = 56). The difference in the average values for the two methods was 0.23 mm (SD, 0.18 mm; SEM, 0.052 mm) which would be approximately 0.46 diopters. This tolerance is near the accuracy possible for intraocular lens calculations and would never be a significant factor in the refractive outcome of a specific patient. The mean K-reading was 44.58 diopters (SD, 1.23; SEM, 0.355) and the mean axial length was 22.89 mm (SD, 0.71; SEM, 0.205).

Because all patients had bilateral implants, the difference between the right and left eyes (intereye difference) was calculated for both methods.[5-7] The average intereye difference was −0.030 mm (SD, 0.141 mm; SEM, 0.043 mm) by the measurement method and +0.124 mm (SD, 0.412 mm; SEM, 0.124 mm) by the calculation method. Comparing the SD and SEM for each method, we see that the calculation method has approximately 2.9 times more variability than the measurement method (0.412/0.141 and 0.124/0.043). This greater variability with the calculation method is expected because the measurement method has only one parameter introducing measurement error variability, whereas the calculation method has three parameters, the axial length, keratometry, and refraction, each introducing variability.

DISCUSSION

THE THEORETICAL THIN LENS FORMULA FOR INtraocular lens power calculations has not changed since Gauss invented first-order optics almost 150 years ago.[8] Credit for initially applying and publishing gaussian optics to modern day IOLs was given to Fedorov and associates[9] in 1967. Although several investigators have presented the theoretical formula in different forms,[10] there are no significant differences except for slight variations in the choice of retinal thickness, corneal index of refraction, and corneal principal planes.[4] There are six variables in

TABLE 1. Input Variables for Calculated and Measured AVpc1*

Patient No.	Eye	APostRx SEQ (Diopters)	Vtx (mm)	Mean K_K (Diopter)	IOL Manufacturer	IOL Model	IOL_e (Diopters)	AL_u (mm)	Calculated AVpc1 (mm)	Measured AVpc1 (mm)	Algebraic Difference (mm)	Absolute Difference (mm)
1	OD	0.625	14	45.620	Storz	P047UV	23.00	22.03	4.70	5.04	0.34	0.34
	OS	0.625	14	45.745	Storz	P047UV	22.50	22.05	4.59	5.20	0.61	0.61
2	OD	−0.250	14	43.060	Storz	P506UV	20.50	23.60	4.23	4.40	0.17	0.17
	OS	−0.250	14	43.935	Storz	P506UV	21.00	23.39	4.70	4.56	−0.14	0.14
3	OD	1.125	14	46.185	Storz	P047UV	22.50	21.89	4.88	4.95	0.07	0.07
	OS	2.875	14	45.245	Storz	P047UV	24.50	21.60	5.64	5.11	−0.53	0.53
4	OD	−0.375	14	43.310	Storz	P506UV	24.00	22.65	4.16	3.98	−0.18	0.18
	OS	−0.500	14	43.250	Storz	P506UV	24.00	22.50	3.80	4.03	0.23	0.23
5	OD	1.125	14	44.685	Storz	P011UV	20.00	23.30	5.62	5.04	−0.58	0.58
	OS	0.750	14	43.810	Storz	P011UV	21.50	23.00	4.75	5.08	0.33	0.33
6	OD	−0.500	14	46.620	Storz	P506UV	21.50	22.52	4.87	4.91	0.04	0.04
	OS	−0.125	14	46.995	Storz	P506UV	21.00	22.35	4.81	4.88	0.07	0.07
7	OD	−1.625	14	44.245	Iolab	707G	18.00	24.36	4.61	4.54	−0.07	0.07
	OS	−1.500	14	44.250	Iolab	707G	18.00	24.15	4.27	4.20	−0.07	0.07
8	OD	0.000	14	43.870	Storz	P506UV	21.50	23.18	4.66	4.25	−0.41	0.41
	OS	−0.375	14	44.060	Storz	P506UV	21.50	23.03	4.23	4.37	0.14	0.14
9	OD	−0.375	14	44.745	Storz	P506UV	18.00	23.85	4.61	4.43	−0.18	0.18
	OS	−0.375	14	44.560	Storz	P506UV	18.50	23.74	4.50	4.45	−0.05	0.05
10	OD	−0.250	14	44.870	Storz	P506UV	22.50	22.78	4.85	4.83	−0.02	0.02
	OS	0.000	14	44.250	Storz	P506UV	23.00	22.80	4.84	5.01	0.17	0.17
11	OD	−0.750	14	45.435	Iolab	707G	21.00	22.29	3.59	3.26	−0.33	0.33
	OS	−2.250	14	46.310	Iolab	707G	21.50	22.12	3.14	3.19	0.05	0.05
12	OD	−0.500	14	42.560	Storz	P506UV	24.00	23.01	4.27	4.74	0.47	0.47
	OS	−0.750	14	42.375	Storz	P506UV	24.50	23.05	4.30	4.65	0.35	0.35
Average		−0.15	—	44.58	—	—	21.58	22.89	—	—	0.02	0.23
SD		1.00	—	1.23	—	—	1.98	0.71	—	—	0.29	0.18

APostRx SEQ = actual postoperative refraction sphero-equivalent; Vtx = vertex; Mean K_K = mean keratometric corneal power; IOL = intraocular lens; IOL_e = intraocular lens equivalent power; AL_u = ultrasonically measured axial length; AVpc1 = location of anterior vertex of intraocular lens with respect to the anterior vertex of the cornea.

*Location of anterior vertex of intraocular lens (AV) with respect to the anterior vertex of the cornea (pc1).

the formula: (1) optical net corneal power (K_o), (2) optical axial length (AL_o), (3) intraocular lens effective power (IOL_e), (4) effective thin lens position (ELP_o), (5) desired refraction (DPostRx), and (6) the vertex distance (V) of the desired refraction. An intraocular lens power is labeled by means of the effective power as opposed to vertex power since Food and Drug Administration standardization in 1984.[11] Normally, the intraocular lens power is chosen as the dependent variable and solved for using the other five variables, where distances are in millimeters, refractive powers are in diopters, and indices of refraction have been multiplied by 1,000:

$$IOL_e = \frac{1336}{AL_o - ELP_o} - \frac{1336}{\dfrac{1336}{\dfrac{1000}{\dfrac{1000}{DPostRx} - V} + K_o} - ELP_o} \quad [1]$$

The 1,336 is 1,000 times the refractive index of aqueous and vitreous and the 1,000 is 1,000 times the refractive index of air. The only variable that cannot be chosen or measured preoperatively is the effective thin lens position (ELP_o). Figure 1 illustrates the physical locations of these variables. The average values for the keratometric reading and axial length of the human eye from

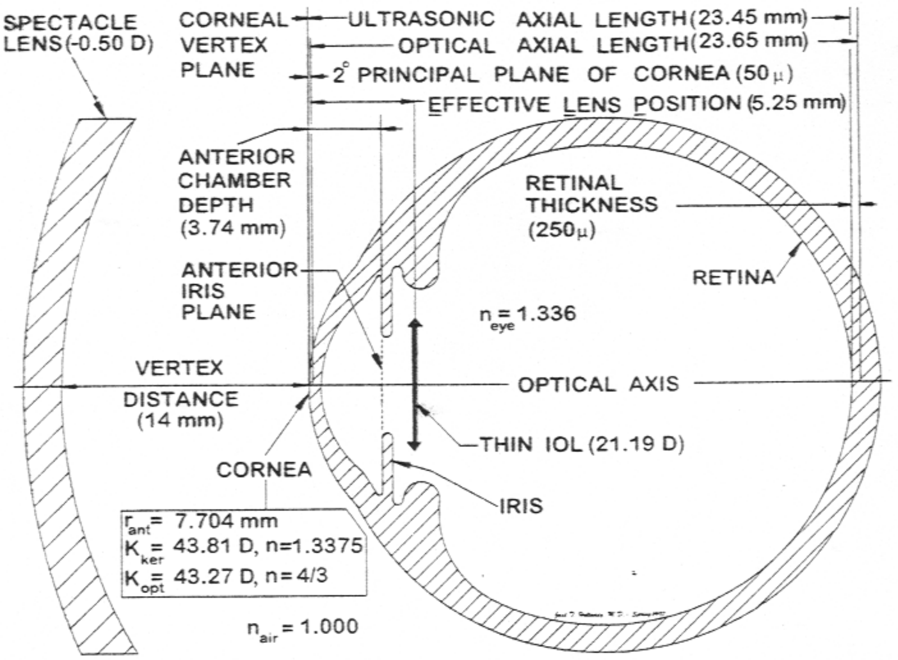

FIGURE 1. Standardized pseudophakic schematic eye (thin intraocular lens [IOL]). The values shown are the mean values for a pseudophakic eye: keratometric power of the cornea (K_{ker}), net optical power of the cornea (K_{opt}), and anterior radius of the cornea (r_{ant}). Using these values, the required thin IOL power is 21.19 diopters (D) at an effective lens position (ELP) of 5.25 mm.

large populations have been used for the model.[12,13]

The optical axial length (AL_o) of the human eye is defined as the axial distance from the secondary principal plane of the cornea to the photoreceptors in the fovea, as shown in Figure 1. The location of the secondary principal plane of the cornea (P_{C2}) is 0.05 mm posterior to the corneal vertex.[4,14,15]

The thickness of the retina (R_t), the distance between the vitreoretinal interface and the visual cell layer, is chosen to be 0.25 mm.[4,13] The ultrasonically measured axial length (AL_u) would be the distance from the corneal vertex to the vitreoretinal interface and would therefore have the following relationship to the optical axial length (AL_o):

$$AL_o = AL_u - P_{C2} + R_t \qquad [2a]$$

$$AL_o = AL_u - 0.05 \text{ mm} + 0.25 \text{ mm} \qquad [2b]$$

$$AL_o = AL_u + 0.20 \text{ mm}. \qquad [2c]$$

This is the recommended standardized conversion from the ultrasonically measured axial length (AL_u) to the optical axial length (AL_o).

All keratometers measure the front radius of curvature of the cornea, then convert to power by dividing into the difference of two indices of refraction. The formula for converting the radius of curvature of a refractive surface bounded by two optical media is referred to as the simple spherical refractive surface formula:

$$K_k = \frac{n_2 - n_1}{r}. \qquad [3a]$$

The variables n_1 and n_2 are the indices of refraction of the first and second media, respectively, and r is the radius of curvature of the interface. The value for n_1 is 1.000 (index of refraction for air) and the standardized keratometric index of refraction (1.3375) was chosen for n_2 many years ago, so that an anterior radius of curvature of the cornea of 7.5 mm would yield a power of 45.00 diopters.[16]

$$K_k = \frac{1.3375 - 1.000}{r_a} = \frac{0.3375}{r_a}. \quad [3b]$$

where r_a is the anterior radius of curvature of the cornea.

There is no other rationale for choosing the index of refraction of 1.3375 other than to make these two numbers (7.5 and 45) agree exactly. The origin of the standardized keratometric index of refraction remains obscure, dating back to the 19th century. If a more physiologic choice of 1.336 (tear film) were used as the index of refraction, the resulting power would be 44.80 diopters. This was the original value proposed by Javal,[17] the inventor of the keratometer more than 100 years ago. For this value to be correct, the anterior and posterior radii of the cornea must be equal. Several studies have shown that the posterior radius of the cornea is at least 1.2 mm steeper than the anterior radius, which reduces the net optical power of the cornea even more than 0.2 diopters.[18–22] Using the index of refraction of the corneal stroma of 1.376, a posterior corneal radius that is 1.2 mm steeper, and a corneal thickness of 0.55 mm results in the calculated net optical power of a cornea to be 44.44 diopters. The calculated net optical power of the cornea with these conditions is approximately 0.56 diopter less than the keratometric power.

With an anterior radius of 7.5 mm and a net optical power of 44.44 diopters, a net corneal index of refraction can be calculated that would yield 1.3333. Recent studies have suggested that using an even lower value of 1.3315 is appropriate for intraocular lens calculations, suggesting that the posterior radius of the cornea is more than 1.2 mm steeper than the anterior radius.[23] Binkhorst chose 4/3 (1.3333 . . .) as the optical net index of refraction for the cornea because it yielded the best results for his calculations, the same reason Olsen[23] chose 1.3315. Although Binkhorst's value yielded more accurate results with his formula, his explanation in 1975 was incorrect.[24] He thought that the reduced power was caused by a 0.56-diopter flattening of the cornea after cataract surgery, which was documented and published by Floyd.[25] With today's modern small-incision surgery, however, there is no significant change in the spheroequivalent power of the cornea. In any case, Binkhorst's use of an index of 1.333 (4/3) was more accurate than using the standardized keratometric index of refraction. The value of 4/3 for the net corneal index of refraction is an appropriate value and would have the minimum impact on current formulas.

Using the value of 4/3 as the net corneal index of refraction, the net optical corneal power can be related to the keratometric power by the following equation:

$$K_o = K_k * \frac{4/3 - 1}{1.3375 - 1} = K_k * \frac{1/3}{0.3375} = 0.98765431 * K_k. \quad [4]$$

This is the recommended "standard" method of converting the keratometric power (K_k) to the net optical power of the cornea (K_o). Since a few keratometers use a value other than the standardized keratometric index, clinicians should confirm the value used on their instrument. If the value is not 1.3375, then the actual value used (for example, 1.336) should be substituted for 1.3375 in equation 4 above.

In 1988, we first published the quadratic solution to the axial length vergence formula for the ELP_o.[1] Equations 5a through 5e give the reverse solution of the axial length vergence formula for the ELP_o given the stabilized actual postoperative refraction (APostRx) and the actual power of the implanted intraocular lens (IOL_e).

$$X = \frac{1336}{\dfrac{1000}{\dfrac{1000}{APostRx} - V} + K_o} \quad [5a]$$

$$A = IOL_e \quad [5b]$$

$$B = -IOL_e * (AL_o + X) \quad [5c]$$

$$C = 1336(AL_o - X) + IOL_e * X * AL_o \quad [5d]$$

$$ELP_o = \frac{-B \pm \sqrt{B^2 - 4A * C}}{2A}. \quad [5e]$$

In equation 5e there is a ± sign; the plus sign is used for negative IOL powers and the minus sign is used for positive IOL powers.

Every thick lens can be completely characterized

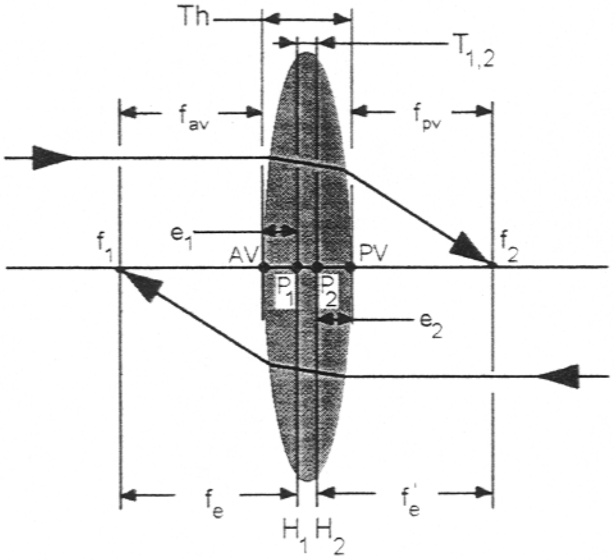

FIGURE 2. Primary and secondary principal planes and focal points. The diagram illustrates the location of the cardinal points of a thick lens: central lens thickness (Th), separation ($T_{1,2}$) of the principal planes (H_1 and H_2), anterior focal length (f_1), posterior focal point (f_2), anterior vertex of the lens (AV), posterior vertex of the lens (PV), the equivalent anterior and posterior focal lengths (f_e and f'_e), and the distances (e_1 and e_2) from the principal points (P_1 and P_2) to their respective vertexes (AV and PV).

optically by three pairs of cardinal points (Figure 2): two equivalent focal points (f_e and f'_e), two principal points (P_1 and P_2), and two nodal points (N_1 and N_2).[26] For intraocular lenses, the nodal points coincide with the principal points because the refracting medium (aqueous) is the same on both sides of the lens. The distances from the principal points to the respective anterior and posterior vertex of the lens (e_1 and e_2) provide all of the necessary information to relate the theoretical thin lens to the actual thick lens (for example, f_{AV}, anterior vertex focal length, and f_{PV}, posterior vertex focal length). The cardinal points are shown in Figure 2 for a biconvex intraocular lens.

Figure 3 illustrates the relationship of a thin lens with principal point ELP_o and a thick lens with principal points ELP_1 and ELP_2 in aqueous, each lens having an equivalent power of IOL_e. For distant objects (collimated light), the thin lens and the thick lens have the same effective focal length and will bring rays into the same focal point (f_e), when ELP_o is coincident with ELP_2.

Unfortunately, this relationship is only true when collimated light is incident on the IOL. When the rays incident on the intraocular lens are converging, such as those from the cornea, this relationship is no longer true. Binkhorst[24] and Jalie[27] overlooked this condition when generalizing their formulas for the thick lens equivalent. For plus lenses, the thick lens must be placed anteriorly to the thin lens equivalent, as shown in Figure 3, to bring the final rays into the same point of focus on the fovea. The amount of anterior displacement ($L_{2,0}$) of the thick lens secondary principal plane (ELP_2) with respect to the thin lens (ELP_o) is nonlinear and *depends* on corneal power (K_o), IOL power (IOL_e), the separation of the thick lens principal planes ($T_{1,2}$), and the position of the thin lens (ELP_o).

The value for ELP_2, the secondary principal plane of the thick lens, can be calculated by modifying equation 5a through 5e to incorporate a term related to the thickness of the lens. After a lengthy derivation, the only modification necessary in the calculation is to add a term representing the separation of the thick lens principal planes ($T_{1,2}$) to equation 5a ("the X" term). Equations 6a through 6e provide the formulas necessary to calculate the position of ELP_2 for a thick intraocular lens.

$$X = \frac{1336}{\dfrac{1000}{\dfrac{1000}{APostRx} - V} + K_o} + T_{1,2} \qquad [6a]$$

$$A = IOL_e \qquad [6b]$$

$$B = -IOL_e * (AL_o + X) \qquad [6c]$$

$$C = 1336(AL_o - X) + IOL_e * X * AL_o \qquad [6d]$$

$$ELP_2 = \frac{-B \pm \sqrt{B^2 - 4A * C}}{2A}. \qquad [6e]$$

The value for $L_{2,0}$ (Figure 3) is the difference between ELP_o and ELP_2.

$$L_{2,0} = ELP_o - ELP_2. \qquad [7]$$

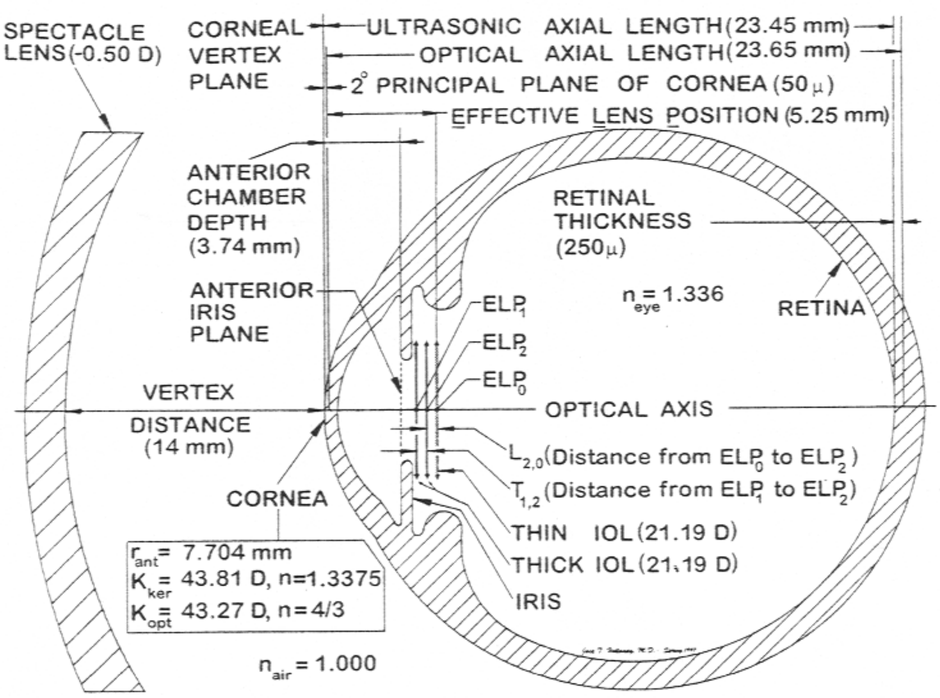

FIGURE 3. Standardized pseudophakic schematic eye (thick intraocular lens [IOL]). The values shown are the mean values for a pseudophakic eye: keratometric power of the cornea (K_{ker}), net optical power of the cornea (K_{opt}), and anterior radius of the cornea (r_{ant}). Using these values and a thick IOL power of 21.19 diopters (D), the anterior and posterior principal planes (ELP_1 and ELP_2) must always be anterior to the effective thin lens position (ELP_o). The distance ($L_{2,0}$) from the thin lens (ELP_o) to the thick lens secondary principal plane (ELP_2) is approximately equal to the separation ($T_{1,2}$) of the thick lens principal planes.

For example, using the thin lens in Figure 1, we have ELP_o of 5.25 mm, IOL_e of 21.19 diopters, K_o of 43.27 diopters, and APostRx of −0.50 diopters at vertex (V) of 14 mm. To find the equivalent position of a thick lens with principal planes separated by 0.1000 mm ($T_{1,2}$) and the same effective IOL power (IOL_e) of 21.19 diopters, we find from equation 6a through 7, $L_{2,0}$ must be 0.1001 mm. Therefore, the thick lens ELP_2 must be 5.15 mm (5.25 − 0.10) behind the secondary principal plane of the cornea (P_{C2}). Note that in this example $L_{2,0}$ and $T_{1,2}$ were virtually the same. This relationship is not always so close and must be determined by exact calculation. The exact values to eight decimal places are given in Table 2.

Once the location of the secondary principal plane ELP_2 of the thick lens is known, it is easy to determine the physical location of the anterior vertex (AV) of the thick lens to the actual vertex of the cornea (P_{C1}), as shown in Figure 3. If the lens in our example above were an equiconvex 21.19-diopter IOL with a 1.0-mm thickness (T_L) and a separation in principal planes of 0.10 mm ($T_{1,2}$), then the first and second principal planes (H_1 and H_2) must be 0.45 mm from the front and back vertex of the IOL (e_1 and e_2), respectively. In this example, the anterior vertex of the thick lens must be 0.65 mm anterior to ELP_o or 4.60 mm (5.25 − 0.65) posterior to the secondary principal plane of the cornea, P_{C2}. Since P_{C2} is 0.050 mm posterior to the anterior corneal vertex, the distance from the anterior vertex of the cornea to the anterior vertex of the thick IOL (AV_{PC1}) is 4.65 mm (4.60 +

TABLE 2. Schematic Eye Values for Thin and Thick Intraocular Lenses

Variable	Value	Units
DPostRx@specs	−0.50000000	Diopters
Vertex	14.00000000	mm
DPostRx@cornea	−0.49652433	Diopters
K_k	43.81000000	Diopters
K_o	43.26913580	Diopters
AL_u	23.45000000	mm
AL_o	23.65000000	mm
ELP_o	5.25000000	mm
IOL_e	21.19430164	Diopters
Th	0.99231156	mm
$T_{1,2}$	0.10000000	mm
ELP_2	5.14987887	mm
ELP_1	5.04987887	mm
$L_{2,0}$	0.10012113	mm

DPostRx@specs = desired postoperative refraction at spectacle plane; DPostRx@cornea = desired postoperative refraction at corneal plane; K_k = keratometric corneal power; K_o = optical corneal power; AL_u = ultrasonically measured axial length; AL_o = optical axial length; ELP_o = effective thin lens position; IOL_e = intraocular lens effective power; Th = central intraocular lens thickness; $T_{1,2}$ = distance between principal planes; ELP_2 = secondary principal plane of thick lens; ELP_1 = primary principal plane of thick lens; $L_{2,0}$ = difference between ELP_o and ELP_2.

0.05). Expressing these relationships in equation form, we have:

$$ELP_2 = ELP_o - L_{2,0} = 5.25 - 0.10 = 5.15 \text{ mm} \quad [8a]$$

$$AV_{PC2} = ELP_2 - T_{1,2} - e_1 = 5.15 - 0.10 - 0.45 = 4.60 \text{ mm} \quad [8b]$$

$$AV_{PC1} = AV_{PC2} + P_{C2} = 4.60 + 0.05 = 4.65 \text{ mm}. \quad [8c]$$

The value for AV_{PC1} can then be compared with the direct measurement (optical or ultrasonic) from the corneal vertex to the anterior vertex of the lens.

The relationship between the actual thick intraocular lens and the thin lens equivalent has been determined theoretically and demonstrated empirically. Two independent methods for determining the appropriate lens constant, ELP_o, for a specific style of IOL are available. The ability to validate the lens constant by two independent methods provides the manufacturer and surgeon added confidence and utility for lens constants used in intraocular lens power calculations and will continue to improve the refractive outcome of intraocular lens implantation. Improved accuracy in determining lens constants is directly correlated with our ability to achieve desired postoperative refractions.

REFERENCES

1. Holladay JT, Prager TC, Chandler TY, Musgrove KH, Lewis JW, Ruiz RS. A three-part system for refining intraocular lens power calculations. J Cataract Refract Surg 1988;14:17–24.
2. 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.
3. Hoffer KJ. The Hoffer Q formula: a comparison of theoretic and regression formulas. J Cataract Refract Surg 1993;19:700–712.
4. Holladay JT. Standardizing constants for ultrasonic biometry, keratometry and intraocular lens power calculations. J Refract Surg 1997;23:1356–1370.
5. Ray WA, O'Day DM. Statistical analysis of multi-eye data in ophthalmic research. Invest Ophthalmol Vis Sci 1985;26:1186–1188.
6. Rosner B. Statistical methods in ophthalmology: an adjustment for the intraclass correlation between eyes. Biometrics 1982;38:105–114.
7. Ederer F. Shall we count numbers of eyes or numbers of subjects? Arch Ophthalmol 1973;89:1–2.
8. Gauss CF. Dioptrische Untersuchungen. Göttingen: Druck und Verlag der Dieterichschen Buchhandlung, 1841.
9. Fedorov SN, Kolina AL, Kolinko AL. Estimation of optical power of the intraocular lens. Vestn Oftalmol 1967;80(4):27–31.
10. Fritz KJ. Intraocular lens power formulas. Am J Ophthalmol 1981;91:414–415.
11. American National Standard for Ophthalmics-Intraocular Lenses-Optical and Physical Requirements, ANSI Z80.7-1984. New York: American National Standards Institute, 1984.
12. Hoffer KJ. Biometry of 7,500 cataractous eyes. Am J Ophthalmol 1980;90:360–368.
13. Binkhorst RD. The accuracy of ultrasonic measurement of the axial length of the eye. Ophthalmic Surg 1981;12:363–365.
14. Binkhorst CD. Power of the prepupillary pseudophakos. Br J Ophthalmol 1972;56:332–337.
15. Colenbrander MD. Calculation of the power of an iris clip lens for distance vision. Br J Ophthalmol 1973;57:735–740.
16. Holladay JT, Waring GO. Optics and topography of the cornea in RK. In: Waring GO, editor. Refractive keratotomy for myopia and astigmatism. St Louis: Mosby-Year Book, 1992:62.
17. Javal E. Memoires d'ophtalmometrie. Paris: Masson, 1891:1–624.
18. Lowe RF, Clark BAJ. Posterior corneal curvature: correlations in normal eyes and eyes involved with primary angle-closure glaucoma. Br J Ophthalmol 1973;57:464–474.

19. Patel S, Marshall M, Fitzke FW. Shape and radii of the posterior corneal surface. J Refractive Surg 1993;9:173–181.
20. Rengstorff RH. Corneal refraction: relative effect of each cornea component. J Am Optom Assoc 1985;56:218–219.
21. Kampfer T, Wegener A, Dragomirescu V, Hockwin O. Improved biometry of the anterior eye segment. Ophthalmic Res 1989;21:239–248.
22. Patel S, Marshall J, Fitzke FW. Refractive index of the human corneal epithelium and stroma. J Refract Surg 1995;11:100–105.
23. Oslen T. On the calculation of power from curvature of the cornea. Br J Ophthalmol 1986;70:152–154.
24. Binkhorst RD. The optical design of intraocular lens implants. Ophthalmic Surg 1975;6:17–31.
25. Floyd G. Changes in the corneal curvature following cataract extraction. Am J Ophthalmol 1951;34:1525–1533.
26. Michaels DD. Visual optics and refraction: a clinical approach, 3rd ed. St Louis: Mosby, 1985:43–46.
27. Jalie M. The design of intra-ocular lenses. Br J Physiol Opt 1978;32:1–21.