Chapter 4

Advanced Intraocular Lens Power Calculations

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Core Messages

- Accurate IOL power calculations are a crucial element for meeting the ever increasing expectations of patients undergoing cataract surgery.
- Although ultrasound biometry is a well-established method for measuring axial length optical coherence biometry has been shown to be significantly more accurate and reproducible.
- The power adjustment necessary between the capsular bag and the ciliary sulcus will depend on the power of the intraocular lens.
- When the patient has undergone prior corneal refractive surgery, or corneal transplantation, standard keratometric and topographic values cannot be used.
- Several methods have been proposed to improve the accuracy of IOL power calculation in eyes following corneal refractive surgery; these can be divided into those that require preoperative data and those that do not.
- Because it is impossible to accurately predict the postoperative central power of the donor graft, there is presently no reliable method for calculating IOL power for eyes undergoing combined corneal transplantation and cataract removal with intraocular lens implantation.
- The presence of silicone oil in the eye complicates intraocular lens power measurements and calculations.

4.1 Introduction

Accurate intraocular lens (IOL) power calculations are a crucial element for meeting the ever increasing expectations of patients undergoing cataract surgery. As a direct result of technological advances, both our patients and our peers have come to view cataract surgery as not only a rehabilitative procedure, but a refractive procedure as well. The precision of IOL power calculations depends on more than just accurate biometry, or the correct formula, but in reality is a collection of interconnected nuances. If one item is inaccurate, the final outcome will be less than optimal.

4.2 Axial Length Measurement

By A-scan biometry, errors in axial length measurement account for 54% of IOL power error when using two-variable formulas [23]. Because of this, much research has been dedicated to achieving more accurate and reproducible axial lengths. Although ultrasound biometry is a well-established method for measuring ocular distances, optical coherence biometry has been shown to be significantly more accurate and reproducible and is rapidly becoming the prevalent methodology for the measurement of axial length.

4.2.1 Ultrasound

Axial length has traditionally been measured using ultrasound biometry. When sound waves encounter an interface of differing densities, a fraction of the signal echoes back. Greater differences in density produce a greater echo. By measuring the time required for a portion of the sound beam to return to the ultrasound probe, the distance can be calculated ($d = v \times t)/2$. Because the human eye is composed of structures of varying densities (cornea, aqueous, lens, vitreous, retina, choroid, scleral, and orbital fat), the axial length of each structure can be indirectly measured using ultrasound. Clinically, applanation and immersion techniques have been most commonly used.

4.2.1.1 Applanation Technique

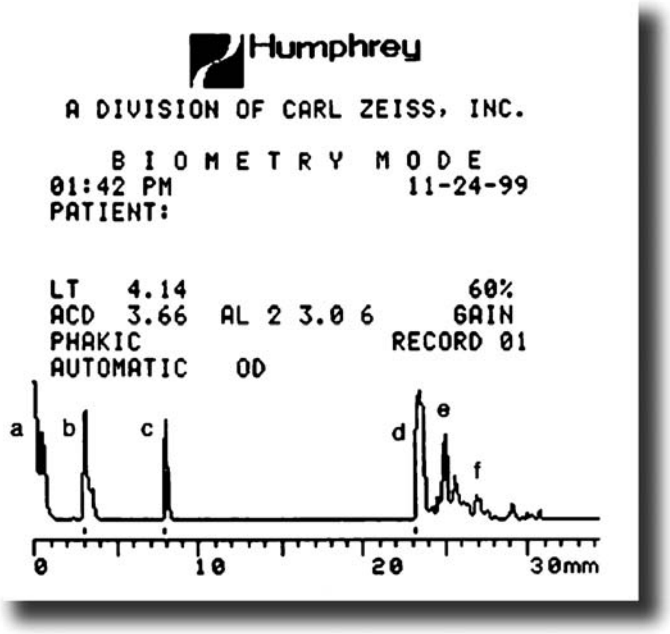
With the applanation technique, the ultrasound probe is placed in direct contact with the cornea. After the sound waves exit the transducer, they encounter each acoustic interface within the eye and produce a series of echoes that are received by the probe. Based on the timing of the echo and the assumed speed of the sound wave through the various structures of the eye, the biometer software is able to construct a corresponding echogram. In the phakic eye, the echogram has six peaks (Fig. 4.1), each representing the interfaces of:

1. Probe tip/cornea,
2. Aqueous fluid/anterior lens,
3. Posterior lens/vitreous,
4. Vitreous/retina,
5. Retina/sclera,
6. Sclera/orbital fat.

The axial length is the summation of the anterior chamber depth, the lens thickness, and the vitreous cavity.

The y-axis shows peaks (known as spikes) representing the magnitude of each echo returned to the ultrasound probe. The magnitude or height of each peak depends on two factors. The first is the difference in densities at the acoustic interface; greater differences produce higher echoes. The second is the angle of incidence at this interface. The height of a spike will be at its maximum when the ultrasound beam is perpendicular to the acoustic interface it strikes. The height of each spike is a good way to judge axiality and, hence, alignment of the echogram.

Because the applanation technique requires direct contact with the cornea, compression will typically cause the axial length to be falsely shortened. During applanation biometry, the compression of the cornea has been shown to range



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Humphrey
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PATIENT:

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ACD  3.66   AL 23.06        GAIN
PHAKIC                 RECORD 01
AUTOMATIC   OD
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Fig. 4.1 Phakic axial length measurement using the applanation technique. **a** Initial spike (probe tip and cornea), **b** anterior lens capsule, **c** posterior lens capsule, **d** retina, **e** sclera, **f** orbital fat from 0.14 to 0.33 mm [24, 29, 30]. At normal axial lengths, compression by 0.1 mm results in a postoperative refractive error toward myopia of roughly 0.25 D. Additionally, this method of ultrasound biometry is highly operator-dependent. Because of the extent of the error produced by direct corneal contact, applanation biometry has given way to noncontact methods, which have been shown to be more reproducible.

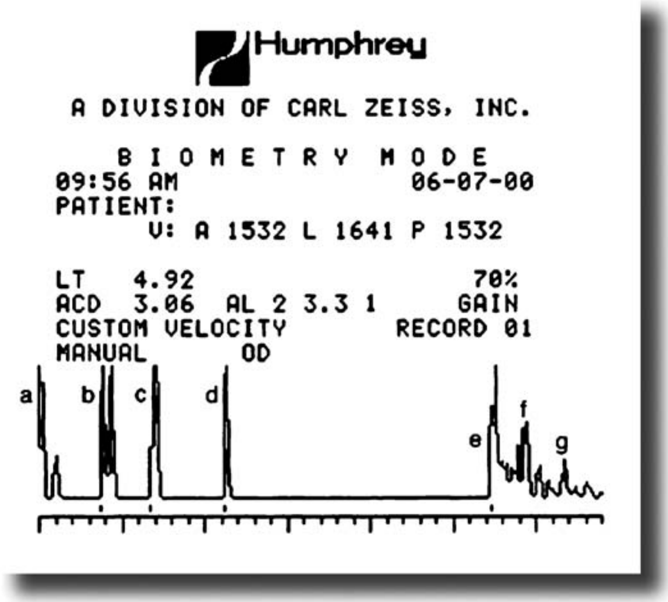
4.2.1.2 Immersion Technique

The currently preferred A-scan method is the immersion technique, which, if properly performed, eliminates compression of the globe. Although the principles of immersion biometry are the same as with applanation biometry, the technique is slightly different. The patient lies supine with a clear plastic scleral shell placed over the cornea and between the eyelids. The shell is filled with coupling fluid through which the probe emits sound waves. Unlike the applanation echogram, the immersion technique produces an additional spike corresponding to the probe tip (Fig. 4.2). This spike is produced from the tip of the probe within the coupling fluid.

Although the immersion technique has been shown to be more reproducible than the applanation technique, both require mindfulness of the properties of ultrasound. Axial length is calculated from the measured time and the assumed average speed that sound waves travel through the eye. Because the speed of ultrasound varies in different media, the operator must account for prior surgical procedures involving the eye such as IOL placement, aphakia, or the presence of silicone oil in the vitreous cavity (Table 4.1). Length correction can be performed simply using the following formula:

True length = [corrected velocity/measured velocity] × measured length

However, using a single velocity for axial length measurements in eyes with prior surgery is much less accurate than correcting each segment of the eye individually and adding together the respective corrected length measurements. For example, in an eye with silicone oil, the anterior chamber depth would be measured at a velocity of 1,532 m/s, the crystalline lens thickness at 1,641 m/s, and the vitreous cavity at either 980 m/s or 1,040 m/s depending on the



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   BIOMETRY MODE
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PATIENT:
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LT   4.92                    70%
ACD  3.06  AL 2 3.3 1       GAIN
CUSTOM VELOCITY        RECORD 01
MANUAL      OD
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Fig. 4.2 Phakic axial length measurements using the immersion technique. **a** Probe tip—echo from tip of probe, has now moved away from the cornea and becomes visible; **b** cornea—double-peaked echo will show both the anterior and posterior surfaces; **c** anterior lens capsule; **d** posterior lens capsule; **e** retina; **f** sclera; **g** orbital fat

Table 4.1 Average velocities under various conditions for average eye length [16]. *PMMA:* polymethyl methacrylate

Condition	Velocity (m/s)
Phakic eye	1,555
Aphakic eye	1,532
PMMA pseudophakic	1,556
Silicone pseudophakic	1,476
Acrylic pseudophakic	1,549
Phakic silicone oil	1,139
Aphakic silicone oil	1,052
Phakic gas	534

density of the silicone oil (1,000 centistokes vs. 5,000 cSt). The three corrected lengths are then added together to obtain the true axial length. Sect. 4.8 describes in greater detail IOL calculations in eyes with silicone oil.

For pseudophakia, using a single instrument setting may also lead to significant errors because IOL implants vary in sound velocity and thickness (Table 4.2). By using an IOL material-specific conversion factor (CF), a corrected axial length factor (CALF) can be determined using:

$CF = 1 - (VE/VIOL)$
$CALF = CF \times T$
where VE = sound velocity being used (such as 1,532 m/s),
VIOL = sound velocity of the IOL material being measured,
T = IOL central thickness.

By adding the CALF to or subtracting it from the measured axial length, the true axial length is obtained.

Another source of axial length error is that the ultrasound beam has a larger diameter than the fovea. If most of the beam reflects off a raised parafoveal area and not the fovea itself, this will result in an erroneously short axial length reading. The parafoveal area may be 0.10–0.16 mm thicker than the fovea.

In addition to compression and beam width, an off-axis reading may also result in a falsely shortened axial length. As mentioned before, the probe should be positioned so that the magnitude of the peaks is greatest. If the last two spikes are not present (sclera and orbital fat), the beam may be directed to the optic nerve instead of the fovea.

In the setting of high to extreme axial myopia, the presence of a posterior staphyloma should be considered, especially if there is difficulty obtaining a distinct retinal spike during A-scan ultrasonography. The incidence of posterior staphyloma increases with increasing axial length, and it is likely that nearly all eyes with pathologic myopia have some form of posterior staphyloma. Staphylomata can have a major impact on axial length measurements, as the most posterior portion of the globe (the anatomic axial length) may not correspond with the center of the macula (the refractive axial length). When the fovea is situated on the sloping wall of the staphyloma, it may only be possible to display a high-quality retinal spike when the sound beam is directed eccentric to the fovea, toward the rounded bottom of the staphyloma. This will result in an erroneously long axial length reading. Paradoxically, if the

Table 4.2 Velocities for individual intraocular lens materials [13]. *HEMA:* hydroxyethyl methylmethacrylate

PMMA	2,713 m/s (Alcon MC60BM)
Acrylic	2,078 m/s (Alcon MA60BM)
First generation silicone	990 m/s (AMO SI25NB)
Second generation silicone	1,090 m/s (AMO SI40NB)
Another second generation silicone	1,049 m/s (Staar AQ2101V)
Hydrogel	2,000 m/s (B&L Hydroview)
HEMA	2,120 m/s (Memory lens)
Collamer	1,740 m/s (Staar CQ2005V)

sound beam is correctly aligned with the refractive axis, measuring to the fovea will often result in a poor-quality retinal spike and inconsistent axial length measurements.

Holladay has described an immersion A/B-scan approach to axial length measurement in the setting of a posterior staphyloma [4, 33]. Using a horizontal axial B-scan, an immersion echogram through the posterior fundus is obtained with the cornea and lens echoes centered while simultaneously displaying void of the optic nerve. The A-scan vector is then adjusted to pass through the middle of the cornea as well as the middle of the anterior and posterior lens echoes to assure that the vector will intersect the retina in the region of the fovea. Alternatively, as described by Hoffer, if it is possible to visually identify the center of the macula with a direct ophthalmoscope, the cross hair reticule can be used to measure the distance from the center of the macula to the margin of the optic nerve head. The A-scan is then positioned so that measured distance is through the center of the cornea, the center of the lens, and just temporal to the void of the optic nerve on simultaneous B-scan.

Summary for the Clinician

- Because the applanation technique requires direct contact with the cornea, compression will typically cause the axial length to be falsely shortened.
- The speed of ultrasound varies in different media. To account for this, the operator must alter ultrasound speed settings for eyes that are pseudophakic or aphakic or that contain silicone oil in the vitreous cavity.
- In the setting of high to extreme axial myopia, the presence of a posterior staphyloma should be considered.

4.2.2 Optical Coherence Biometry

Introduced in 2000, optical coherence biometry has proved to be an exceptionally accurate and reliable method of measuring axial length. Through noncontact means, the IOL Master (Carl Zeiss Meditec, Jena, Germany) emits an infrared laser beam that is reflected back to the instrument from the retinal pigment epithelium. The patient is asked to fixate on an internal light source to ensure axiality with the fovea. When the reflected light is received by the instrument, the axial length is calculated using a modified Michelson interferometer. There are several advantages of optical coherence biometry:

1. Unlike A-scan biometry, the optical coherence biometry can measure pseudophakic, aphakic, and phakic IOL eyes. It can also measure through silicone oil without the need for use of the velocity cenversion equation.
2. Because optical coherence biometry uses a partially coherent light source of a much shorter wavelength than ultrasound, axial length can be more accurately obtained. Optical coherence biometry has been shown to reproducibly measure axial length with an accuracy of 0.01 mm.
3. It permits accurate measurements when posterior staphylomata are present. Since the patient fixates along the direction of the measuring beam, the instrument is more likely to display an accurate axial length to the center of the macula.
4. The IOL Master also provides measurements of corneal power and anterior chamber depth, enabling the device to perform IOL calculations using newer generation formulas, such as Haigis and Holladay 2.

The primary limitation of optical biometry is its inability to measure through dense cataracts and other media opacities that obscure the macula; due to such opacities or fixation difficulties, approximately 10% of eyes cannot be accurately measured using the IOL Master [21].

When both optical and noncontact ultrasound biometry are available, the authors rely on the former unless an adequate measurement cannot be obtained. Both the IOL Master and immersion ultrasound biometry have been shown to produce a postoperative refractive error close to targeted values. However, the IOL Master is faster and more operator and patient-friendly.

Though mostly operator-independent, some degree of interpretation is still necessary for optimal refractive outcomes. During axial length measurements it is important for the patient to look directly at the small red fixation light. In this way, axial length measurements will be made to the center of the macula. For eyes with high to extreme myopia and a posterior staphyloma, being able to measure to the fovea is an enormous advantage over conventional A-scan ultrasonography. The characteristics of an ideal axial length display by optical coherence biometry are the following (Fig. 4.3):

1. Signal-to-noise ratio (SNR) greater than 2.0.
2. Tall, narrow primary maxima, with a thin, well-centered termination.
3. At least one set of secondary maxima. However, if the ocular media is poor, secondary maxima may be lost within a noisy baseline and not displayed.
4. At least 4 of the 20 measurements taken should be within 0.02 mm of one another and show the characteristics of a good axial length display.
5. If given a choice between a high SNR and an ideal axial length display with a lower SNR, the quality of the axial length display should always be the determining factor for measurement accuracy.

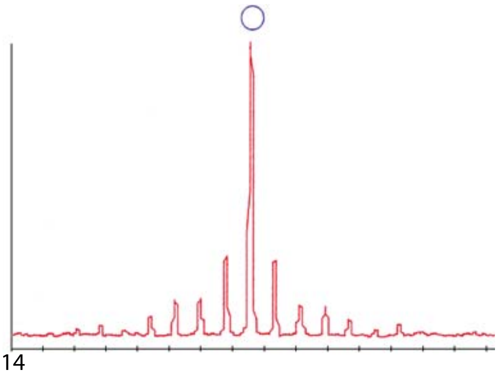


Fig. 4.3 An ideal axial length display by ocular coherence biometry in clear ocular media [12]

Summary for the Clinician

- Optical coherence biometry has proved to be an exceptionally accurate and reliable method of measuring axial length.
- The primary limitation of optical biometry is its inability to measure through dense cataracts and other media opacities that obscure the macula.

4.3 Keratometry

Errors in corneal power measurement can be an equally important source of IOL power calculation error, as a 0.50 D error in keratometry will result in a 0.50 D postoperative error at the spectacle plane. A variety of technologies are available, including manual keratometry, automated keratometry, and corneal topography. These devices measure the radius of curvature and provide the corneal power in the form of keratometric diopters using an assumed index of refraction of 1.3375. The obtained values should be compared with the patient's manifest refraction, looking for large inconsistencies in the magnitude or meridian of the astigmatism that should prompt further evaluation of the accuracy of the corneal readings.

Important sources of error are corneal scars or dystrophies that create an irregular anterior corneal surface. While these lesions can often be seen with slit lamp biomicroscopy, their impact on corneal power measurements can best be assessed by examining keratometric or topographic mires. The latter in particular give an excellent qualitative estimate of corneal surface irregularity (Fig. 4.4). In our experience, if the irregularity is considered to be clinically important, we try to correct it whenever feasible before proceeding with cataract surgery. Examples would include epithelial debridement in corneas with epithelial basement disease, and superficial keratectomy in eyes with Salzmann's nodular degeneration.

When the patient has undergone prior corneal refractive surgery, or corneal transplantation, standard keratometric and topographic values cannot be used. This topic will be further discussed in Sect. 4.6.

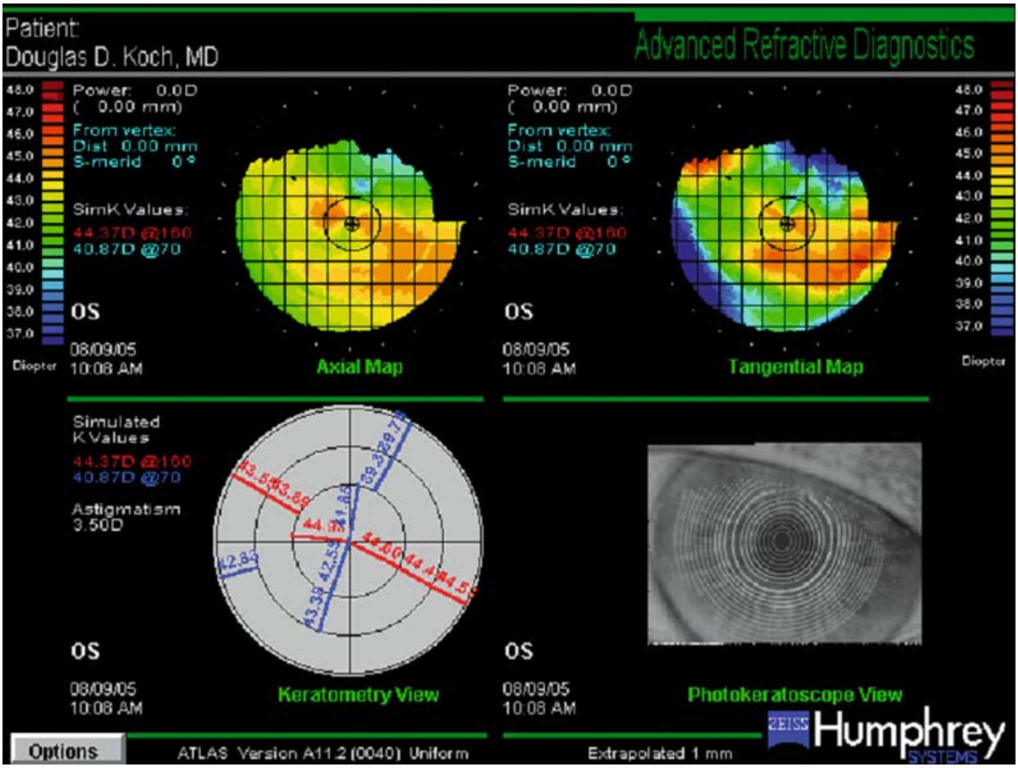
4.4 Anterior Chamber Depth Measurement

A-scan biometers and the IOL Master calculate anterior chamber depth as the distance from the anterior surface of the cornea to the anterior surface of the crystalline lens. In some IOL calculation formulas, the measured anterior chamber depth is used to aid in the prediction of the final postoperative position of the IOL (known as the effective lens position, or the ELP).

4.5 IOL Calculation Formulas

There are two major types of IOL formulas. One is theoretical, derived from a mathematical consideration of the optics of the eye, while the other is empirically derived from linear regression analysis of a large number of cases.

The first IOL power formula was published by Fyodorov and Kolonko in 1967 and was based on schematic eyes [7]. Subsequent formulas from Colenbrander, Hoffer, and Binkhorst incorporated ultrasound data [3, 5, 14]. In 1978, a regression formula was developed by Gills, followed by Retzlaff, then Sanders and Kraff, based on analysis of their previous IOL cases [8, 26, 28]. This work was amalgamated in 1980 to yield the SRK I formula [27]. All of these formulas depended on a single constant for each IOL that represented the predicted IOL position. In the 1980s, further refinement of IOL formulas occurred with the incorporation of relationships between the position of an IOL and the axial length as well as the central power of the cornea.


Patient:
Douglas D. Koch, MD

Power: 0.0D
(0.00 mm)
From vertex:
Dist 0.00 mm
S-merid 0°
SimK Values:
44.37D @160
40.87D @70
OS
08/09/05
10:08 AM

Simulated K Values
44.37D @160
40.87D @70
Astigmatism
3.50D

ATLAS Version A11.2 (0040) Uniform
Extrapolated 1 mm

Fig. 4.4 Corneal surface irregularity shown on the Humphrey topographic map of an eye with epithelial basement disease

4.5.1 The Second and Third Generation of IOL Formulas

The IOL constants in the second and third generation of IOL formulas work by simply moving up or down the position of an IOL power prediction curve for the utilized formula. The shape of this power prediction curve is mostly fixed for each formula and, other than the lens constant, these formulas treat all IOLs the same and make a number of broad assumptions for all eyes regardless of individual differences.

For example, two hyperopic eyes with the same axial length and the same keratometry may require different IOL powers. This is due to two additional variables: of more importance, the actual distance from the cornea that the IOL will sit in the pseudophakic state (i.e., ELP) and to a lesser degree, the individual geometry of each lens model. Commonly used lens constants do not take both of these variations into account. These include:

SRK/T formula—uses an “A-constant,”

Holladay 1 formula—uses a “Surgeon Factor,”

Hoffer Q formula—uses a “Pseudophakic Anterior Chamber Depth” (pACD).

These standard IOL constants are mostly interchangeable—knowing one, it is possible to estimate another. In this way, surgeons can move from one formula to another for the same intraocular lens implant. However, the shape of the power prediction curve generated by each formula remains the same no matter which IOL is being used.

Variations in keratometers, ultrasound machine settings, and surgical techniques (such as the creation of the capsulorrhexis) can impact the refractive outcome as independent variables. “Personalizing” the lens constant for a given IOL and formula can be used to make global adjustments for a variety of practice-specific variables.

Popular third generation two-variable formulas (SRK/T, Hoffer Q and Holladay 1) also assume that the distance from the principal plane of the cornea to the thin lens equivalent of the IOL is, in part, related to the axial length. That is to say, short eyes may have a shallower anterior chamber and long eyes may have a deeper anterior chamber. In reality, this assumption may be invalid. Short eyes and many long eyes typically have perfectly normal anterior chamber anatomy with normal anterior chamber depth. The error in this assumption accounts for the characteristic limited axial length range of accuracy of each third generation two-variable formula. The Holladay 1 formula, for example, works well for eyes of normal to moderately long axial lengths, while the Hoffer Q has been reported to be better suited to normal and shorter axial lengths [15].

4.5.2 The Fourth Generation of IOL Formulas

A recent exception to all of this is the Haigis formula [9]. Rather than moving a fixed formula-specific IOL power prediction curve up or down, the Haigis formula instead uses three constants (a_0, a_1, and a_2) to set both the position and the shape of a power prediction curve:

$$d = a_0 + (a_1 * \text{ACD}) + (a_2 * \text{AL})$$

where d is the effective lens position, ACD is the measured anterior chamber depth of the eye (corneal vertex to the anterior lens capsule), and AL is the axial length of the eye (the distance from the cornea vertex to the vitreoretinal interface). The a_0 constant basically moves the power prediction curve up, or down, in much the same way that the A-constant, Surgeon Factor, or pACD does for the SRK/T, Holladay 1, and Hoffer Q formulas. The a_1 constant is tied to the measured anterior chamber depth, and the a_2 constant is tied to the measured axial length. In this way, the value for d is determined by three constants, rather than a single number.

The a_0, a_1, and a_2 constants are derived by regression analysis from a sample of at least 200 cases and generate a surgeon and IOL-specific outcome for a wide range of axial lengths and anterior chamber depths. The resulting constants more closely match actual observed results for a specific surgeon and the individual geometry of an IOL implant. This means that a portion of the mathematics of the Haigis formula is individually adjusted for each surgeon/IOL combination.

The Holladay 2 formula uses another innovative approach, which is to use measurements of corneal power, corneal diameter, ACD, lens thickness, refractive error, and axial length to further refine the ELP calculation. The Holladay 2 formula is based on previous observations from a 35.000 patient data set and has been shown to be advantageous in both long and short eyes.

Summary for the Clinician

- The shape of the power prediction curve is mostly fixed for each second and third generation formula.
- Popular third generation two-variable formulas may also assume that the distance from the corneal vertex to the thin lens equivalent of the IOL is, in part, related to the axial length and/or central corneal power.
- The fourth generation IOL power formulas address these issues.

4.5.3 Capsular Bag to Ciliary Sulcus IOL Power Conversion

Intraocular lens power formulas typically calculate the power of the intraocular lens to be positioned within the capsular bag. Occasionally, this is not possible, as with an unanticipated intraoperative tear in the posterior lens capsule. In order to achieve a similar postoperative refractive result with an IOL placed at the plane of the ciliary sulcus, a reduction in IOL power is typically required.

The power adjustment necessary between the capsular bag and the ciliary sulcus will depend on the power of the capsular bag IOL (Table 4.3). The important concept is that for stronger intraocular lenses, the reduction in power must be greater. For very low IOL powers, no reduction in IOL power is required. Table 4.3 will provide good results for most, modern posterior chamber IOLs.

Table 4.3 Intraocular lens (IOL) power correction for unanticipated sulcus implantation [13]

Capsular bag IOL power	Ciliary sulcus power adjustment
+35.00 D to +27.50 D	−1.50 D
+27.00 D to +17.50 D	−1.00 D
+17.00 D to +9.50 D	−0.50 D
+9.00 D to -5.00 D	No change

4.6 Determining IOL Power Following Corneal Refractive Surgery

The true corneal power following corneal refractive surgery is difficult to obtain by any form of direct measurement. This is because keratometry and topography measure the anterior corneal radius and convert it to total corneal power by assuming a normal relationship between the anterior and posterior corneal curvatures. However, unlike incisional corneal refractive surgery for myopia, which flattens both the anterior and the posterior corneal radius, ablative corneal refractive surgery for myopia primarily alters anterior corneal curvature. Additionally, standard keratometry measures a paracentral region and assumes that this accurately reflects central corneal power. For these reasons, keratometry and simulated keratometry by topography typically under-estimate central corneal power following ablative corneal surgery for myopia and overestimate it for corneas that have undergone hyperopic ablation.

There is a second and less commonly recognized source of unanticipated postoperative refractive error. As a general rule, IOL power calculations following all forms of corneal refractive surgery should not be run using an uncorrected two-variable, third-generation formula because they assume that the effective lens position is, in part, related to central corneal power. By using axial length and keratometric corneal power to estimate the postoperative location of the IOL, or the ELP, the artifact of very flat Ks following myopic corneal refractive surgery will cause these formulas to assume a falsely shallow postoperative ELP and recommend less IOL power than required. To avoid this potential pitfall, the double K feature of the Holladay 2 formula allows direct entry of two corneal power values by checking the box “Previous RK, PRK…”; if the corneal power value before refractive surgery is unknown, the formula will use 43.86 D as the default preoperative corneal value. Another option is to apply Aramberri’s “double K method” correction to the Holladay 1, Hoffer Q or SRK/T formulas [1] or refer to the IOL power adjustment nomograms published by Koch and Wang [19].

Several methods have been proposed to improve the accuracy of IOL power calculation in eyes following corneal refractive surgery; these can be divided into those that require preoperative data and those that do not.

4.6.1 Methods Requiring Historical Data

4.6.1.1 Clinical History Method

The clinical history method [18] for corneal power estimation requires accurate historical data and was first described by Holladay as:

$$\mathrm{Kp} + \mathrm{SEp} - \mathrm{SEa} = \mathrm{Ka}$$

where Kp = the average keratometry power before corneal refractive surgery,
SEp = the spherical equivalent before corneal refractive surgery,
SEa = the stable spherical equivalent after corneal refractive surgery,
Ka = the estimate of the central corneal power after corneal refractive surgery.

4.6.1.2 Feiz-Mannis IOL Power Adjustment Method

Another method that is helpful to use when good historical data are available is the IOL power adjustment method of Feiz and Mannis et al. [6]. Using this technique, the IOL power is first calculated using the pre-LASIK (laser-assisted in situ keratomileusis) corneal power as though the patient had not undergone keratorefractive surgery. This pre-LASIK IOL power is then increased by the amount of refractive change at the spectacle plane divided by 0.7. This approach is outlined as follows:

$$\mathrm{IOLpre} + (\Delta \mathrm{D} / 0.7) = \mathrm{IOLpost}$$

where IOLpre = the power of the IOL as if no LASIK had been performed,
ΔD = the refractive change after LASIK at the spectacle plane,
IOLpost = the estimated power of the IOL to be implanted following LASIK.

4.6.1.3 Masket IOL Power Adjustment Method

Masket [22] has developed another method that adjusts the IOL power based on the amount of refractive laser correction. Instead of calculating IOL power with pre-LASIK data as above, this method modifies the predicted IOL power obtained using the patient’s post-laser correction readings by using the following formula:

$$\mathrm{IOLpost} + (\Delta \mathrm{D} \times 0.326) + 0.101 = \mathrm{IOLadj}$$

where IOLpost = the calculated IOL power following ablative corneal refractive surgery,
ΔD = the refractive change after corneal refractive surgery at the spectacle plane,
IOLadj = the adjusted power of the IOL to be implanted.

4.6.1.4 Topographic Corneal Power Adjustment Method

There are several approaches to modifying post-LASIK corneal power measurements:

1. To adjust the effective refractive power (EffRP) of the Holladay Diagnostic Summary of the EyeSys Corneal Analysis System by using the following formulas after myopic or hyperopic surgery respectively [11, 31]:

$$\mathrm{EffRP} - (\Delta \mathrm{D} \times 0.15) - 0.05 = \text{post-myopic LASIK adjusted EffRP}$$
$$\mathrm{EffRP} + (\Delta \mathrm{D} \times 0.16) - 0.28 = \text{post-hyperopic LASIK adjusted EffRP}$$

where ΔD = the refractive change after LASIK at the corneal plane.

2. To average the corneal curvatures of the center and the 1-mm, 2-mm, and 3-mm annular rings of the Numerical View of the Zeiss Humphrey Atlas topographer (AnnCP) and modify the result using the following formula [31]:

AnnCP + (ΔD × 0.19) − 0.4 = post-hyperopic LASIK adjusted AnnCP

3. To modify keratometry (K) values as follows [11]:

K − (ΔD × 0.24) + 0.15 = post-myopic LASIK adjusted K

This latter approach is not as accurate as the two above-mentioned topography-based methods.

4.6.2 Methods Requiring No Historical Data

4.6.2.1 Hard Contact Lens Method

This method does not require pre-LASIK data, but can only be used if the visual acuity is better than around 20/80 [34]:

Bc + Pc + SEc − SEs = Ka

where Bc = base curve of contact lens in diopters,
Pc = refractive power of contact lens in diopters,
SEc = spherical equivalent with contact lens in place,
SEs = spherical equivalent without contact lens,
Ka = estimated corneal power following refractive surgery.

Unfortunately, the literature now suggests that the hard contact lens method may be less accurate than originally thought following all forms of ablative corneal refractive surgery [2, 10, 17, 32]. Better results may require the use of contact lens designs with posterior curvatures that better fit the surgically modified corneal surface.

4.6.2.2 Modified Maloney Method

Another very useful method of post-LASIK corneal power estimation is one that was originally described by Robert Maloney and subsequently modified by Li Wang and Douglas Koch et al. [32]. Using this technique, the central corneal power is obtained by placing the cursor at the exact center of the Axial Map of the Zeiss Humphrey Atlas topographer. This value is then converted back to the anterior corneal power by multiplying this value by 376.0/337.5, or 1.114. An assumed posterior corneal power of 6.1 D is then subtracted from this product:

(CCP × 1.114) − 6.1 D = post-LASIK adjusted corneal power

where CCP = the corneal power with the cursor in the center of the topographic map.

The advantage of this method is that it requires no historical data and has a low variance when used with either the Holladay 2 formula or a modern third generation two-variable formula combined with the “double K method” correction nomogram published by Koch and Wang [19].

4.6.3 Hyperopic Corneal Refractive Surgery

For eyes that have undergone hyperopic LASIK, it is easier to estimate central corneal power than for myopic LASIK. This is presumably because the ablation takes place outside the central cornea. The average of the 1-mm, and 2-mm annular power rings of the Numerical View of the Zeiss Humphrey Atlas topographer can serve as an estimate of central corneal power following hyperopic LASIK. As an alternative, the adjusted EffRP of the EyeSys Corneal Analysis System proposed by Drs. Wang, Jackson, and Koch also works well (see Sect. 4.6.1.4) [31].

Remember that some form of a “double K method” is still required for IOL power calculations following hyperopic LASIK in order to avoid an inaccurate estimation of ELP.

Summary for the Clinician

- In eyes that have undergone ablative corneal surgery, IOL calculations are more complex due to difficulty in calculating true corneal refractive power and potential errors in estimating the effective lens position.
- A variety of approaches can be used to calculate corneal power (see Table 4.4).

4.6.4 Radial Keratotomy

Unlike the ablative forms of corneal refractive surgery (LASIK and PRK) in which only the anterior radius is changed, eyes that have previously undergone radial keratotomy experience flattening of both the anterior and posterior radii. This approximate preservation of the ratio between the anterior and posterior radii allows for a direct measurement of the central corneal power. Thus, any map that provides some average of anterior corneal power over the central 2–3 mm gives an accurate estimation of corneal refractive power. Examples include averaging the 0-mm, 1-mm, and 2-mm annular power rings of the Numerical View of the Zeiss Humphrey Atlas topographer and the EffRP from the Holladay Diagnostic Summary of the EyeSys Corneal Analysis System. It is important to remember that one still needs to compensate for potential errors in ELP by using the Holladay 2 formula or the double-K approach with third-generation formulas described in Sect. 4.6.

Patients with previous radial keratometry will also commonly show variable amounts of transient hyperopia in the immediate postoperative period following cataract surgery [20]. This is felt to be due to stromal edema around the radial incisions, which flattens the central cornea. Although usually transient, it may be as high as +6.00 D. It may be more likely to occur in eyes with eight or more incisions, an optical zone of less than 2.0 mm, or incisions that extend to the limbus. The hyperopia may take 8–12 weeks to resolve. Thus, we recommend following up these patients with refractions and topographic maps obtained at 2-week intervals, deferring surgical correction (IOL exchange or a piggyback IOL) until two reasonably stable refractions and topographies are obtained at the same time of the day.

Because of both the relative inaccuracy of IOL calculations in RK eyes and their tendency to experience a long-term hyperopic drift, we usually target IOL power calculations for −1.00 D. A detailed discussion with the patient regarding these issues is required. Finally, if more than 6 months passes before cataract surgery is required for the fellow eye, the corneal measurements should be repeated due to the fact that additional corneal flattening frequently occurs over time following radial keratotomy.

Summary for the Clinician

- Eyes that have previously undergone radial keratotomy experience flattening of both the anterior and posterior radii; this allows for a direct "averaging" measurement of the central corneal power.
- Patients with previous radial keratometry will commonly show variable amounts of transient hyperopia in the immediate postoperative period following cataract surgery.

4.6.5 Accuracy and Patient Expectations

It is important to explain to patients in that intraocular lens power calculations following all forms of corneal refractive surgery are, at best, problematic. In spite of our best efforts, the final refractive result may still end up more hyperopic or more myopic than expected. In addition, astig-

Table 4.4 Example of post-corneal refractive surgery intraocular lens calculation: a 50 year-old male underwent cataract extraction and posterior chamber IOL implantation in both eyes 5 years after myopic laser-assisted in situ keratomileusis (LASIK). The following data is from his left eye. *EffRP:* effective refractive power

Pre-cataract surgery data:

Pre-LASIK data:

- Pre-LASIK refraction: -8.50 D
- Pre-LASIK mean keratometry: 44.06 D

Post-LASIK data:

- Post-LASIK refraction: -0.50 D
- EffRP: 38.82 D
- Central topographic power (Humphrey Atlas): 39.00 D
- Contact lens over-refraction data: refraction without contact lens: -0.50 D, contact lens base curve: 37.75 D, contact lens power: +1.75 D, refraction with contact lens: -2.00 D

Post-cataract surgery data:

- An Alcon SA60AT lens with power of 23.5 D was implanted in this eye, and the manifest refraction after cataract surgery was +0.125 D

Corneal refractive power estimation:

Clinical history method:

- Pre-LASIK refraction at corneal plane (vertex distance: 12.5 mm): (-8.50)/{1-[0.0125*(-8.50)]} = -7.68 D
- Post-LASIK refraction at corneal plane: (-0.50)/{1-[0.0125*(-0.50)]} = -0.50 D
- Corneal power = 44.06 + (-7.68) - (-0.50) = 36.88 D

Hard contact lens method:

- Corneal power = 37.75 + 1.75 + [(-2.00) - (-0.50)] = 38.00 D

Adjusted EffRP:

- Adjusted EffRP = 38.82 - 0.15 * [(-0.50 - (-7.68)] - 0.05 = 37.69 D

Modified Maloney Method:

- Corneal power = 39.00 * (376/337.5) - 6.1 = 37.35 D

IOL power calculation (aiming at refraction of +0.125 D):

Clinical history method:

- IOL power using corneal power obtained from the clinical history method: 24.42 D

Hard contact lens method:

- IOL power using corneal power obtained from the hard contact lens method: 23.01 D

Adjusted EffRP:

- IOL power using Adjusted EffRP: 23.54 D

Modified Maloney method:

- IOL power using corneal power obtained from the Modified Maloney method: 23.94 D

Feiz-Mannis IOL power adjustment method:

- IOL power using pre-LASIK K: 14.55 D
- IOL power after LASIK: 14.55 + 7.18/0.7 = 24.81 D

Masket IOL power adjustment method

- IOL power using post-LASIK K (EffRP in this case): 20.19 D
- IOL power after LASIK: 20.19 + [-0.50 - (-7.68)] * 0.326 + 0.101 = 22.63 D

IOL power prediction error using different methods (Implanted – Predicted):

- Double-K clinical historical method: -0.92 D
- Double-K CL over-refraction: +0.49 D
- Double-K Adjusted EffRP: -0.04 D
- Double-K Modified Maloney method: -0.44 D
- Feiz-Mannis IOL power adjustment method: -1.31 D
- Masket IOL power adjustment method: +0.87 D

matism may be present and may not respond as expected to corneal relaxing incisions.

The higher order optical aberrations and multifocality that often accompany the various forms of corneal refractive surgery also remain unchanged following cataract surgery. For example, third- and fourth-order higher order aberrations produced by radial keratotomy can be as much as 35 times normal values. Elevated higher order aberrations are also seen following PRK and LASIK, particularly decentered ablations or older treatments with small central optical zones. Although the positive spherical aberration induced by myopic procedures may be partially ameliorated by implanting an IOL with negative asphericity, moderate to high amounts of positive spherical aberration usually remain. The visual consequence of these aberrations is loss of best-corrected acuity and contrast sensitivity and, understandably, some patients mistakenly expect that cataract surgery will alleviate these symptoms. Thus, it is important to discuss this prior to surgery so that their expectations will be realistic.

The active use of so many different methods of IOL calculation following corneal refractive surgery is eloquent testimony to how far we still have to go in this area. To minimize the risk of unexpected postoperative hyperopia, we generally recommend a refractive target of around −0.75 D, depending on the refractive status of the fellow eye.

See Table 4.4 for an example of an intraocular lens calculation following corneal refractive surgery.

4.7 Corneal Transplantation

There is presently no reliable method for calculating IOL power for eyes undergoing combined corneal transplantation and cataract removal with IOL implantation. This is because it is impossible to accurately predict the central power of the donor graft. There are several options:

1. Use a mean corneal power, based on evaluation of prior grafts, as a "best guess" of postoperative corneal power and proceed with IOL implantation. In eyes with an acceptable postoperative refractive error, additional lens surgery will not be required. For eyes with unacceptably high ametropia, options include IOL exchange, a piggyback IOL, or corneal refractive surgery.
2. Defer cataract surgery until the graft has stabilized, preferably after suture removal. Although more accurate, there would be a delay in visual rehabilitation and the second procedure may cause surgical trauma to the donor cornea.
3. Perform cataract extraction alone without IOL implantation in conjunction with the corneal graft. With this approach, there is minimal risk of trauma to the graft with the second procedure. However, it essentially eliminates the chance of implanting the IOL in the capsular bag.

Summary for the Clinician

- Because it is impossible to accurately predict postoperative central power of the donor graft, there is presently no reliable method for calculating IOL power for eyes undergoing combined corneal transplantation and cataract removal with IOL implantation.

4.8 Silicone Oil

For eyes containing silicone oil, A-scan axial length measurements are best carried out with the patient seated as upright as possible, especially if the vitreous cavity is partially filled with silicone oil. In the upright position, it is more likely that the silicone oil will remain in contact with the retina. In the recumbent position, the less dense silicone oil will shift away from the retina, toward the anterior segment. This can lead to confusion as to the correct interpretation of the position of the retinal spike.

The refractive index of silicone oil is also higher than that of the vitreous, requiring an adjustment to IOL power. To prevent the silicone oil from altering the refractive power of the posterior surface of the IOL, it is preferable to implant polymethyl methacrylate (PMMA) convex-plano lenses, with the plano side oriented toward the vitreous cavity and preferably over an intact posterior capsule. The additional power that must be added to the original IOL calculation for a convex-plano IOL (with the plano side facing toward the vitreous cavity) is determined by the following relationship, as described in 1995 by Patel [25]:

((Ns – Nv)/(AL – ACD)) × 1,000 = additional IOL power (diopters)
where Ns = refractive index of silicone oil (1.4034),
Nv = refractive index of vitreous (1.336),
AL = axial length in mm,
ACD = anterior chamber depth in mm.

For an eye of average dimensions, and with the vitreous cavity filled with silicone oil, the additional power needed for a convex-plano PMMA IOL is typically between +3.0 D and +3.5 D. However, if the silicone oil will not be left in the eye indefinitely, then it might be preferable to use an IOL that will provide the optimal refractive error after the oil has been removed.

As an alternative, if the length of time that the silicone oil will remain in place is uncertain, a low-power single-piece PMMA can be placed in the ciliary sulcus to correct for the additional power required while the silicone oil is in place. At the time the silicone oil is removed, this "temporary" piggyback IOL can then be removed, restoring the eye to its former refractive power.

For patients who may possibly undergo a silicone oil procedure at some point in the future, it is recommended that bilateral baseline axial length measurements be carried out. This would include any patient with a prior retinal detachment, high axial myopia, proliferative vitreoretinopathy, proliferative diabetic retinopathy, acquired immune deficiency syndrome, giant retinal tear, or a history of perforating ocular injury.

Summary for the Clinician

- The presence of silicone oil in the eye complicates IOL power measurements and calculations.
- The refractive index of silicone oil is higher than that of the vitreous, requiring an adjustment to IOL power.

4.9 Conclusion

The methodology for accurately calculating IOL power in normal and complex eyes has improved dramatically in recent years. Future advances are needed in all areas, including methods of measuring corneal power, predicting effective lens position, and perhaps even measuring axial length. The ultimate solution may be an IOL whose spherical and astigmatic power and higher order aberrations can be modified postoperatively. Ideally, such an IOL could be modified multiple times to adapt to the patient's changing visual needs and to compensate for aging changes of the cornea.

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