Ray Tracing for IOL Power Calculations

This method uses different measurements than third-generation formulas to calculate IOL power.

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Ray tracing is a method for calculating the path of a single ray of light through a given optical system. As a ray passes through an optical system, starting at a given point and angle relative to the system's optical axis, it is refracted at each optical surface, causing the ray to change direction. The angles of these direction changes can be calculated according to Snell's law, although it is impossible to calculate the final direction of a ray that has passed through an optical system with more than one refractive surface using closed formulas.

The principles of ray tracing were developed in the early 17th century, but it was not until 150 years later, when Karl Friedrich Gauss developed a simplified calculation method, that optical calculations became practicable. In Gaussian optics, the sine is approximated by the first element of series expansion of the sine; that is, the angle (arc) itself. With this approach, for the first time, optical systems with more than one refractive surface could be calculated with a closed formula. These are principles that have been used in recent decades in the creation of IOL power calculation formulas.

This article reviews the differences between ray tracing and Gaussian optics in relation to IOL power calculation and lists reasons why ray tracing may offer a better method for IOL power calculation, especially in postrefractive surgery eyes.

GAUSSIAN OPTICS: BACKGROUND

The use of Gaussian optics is valid only if an optical system is centered relative to an optical axis and if the rays of interest have only very small angles relative to this axis. Therefore, spherical aberration, which causes a focus shift with changing pupil size, known in ophthalmology as *night myopia*, cannot be described with Gaussian optics.

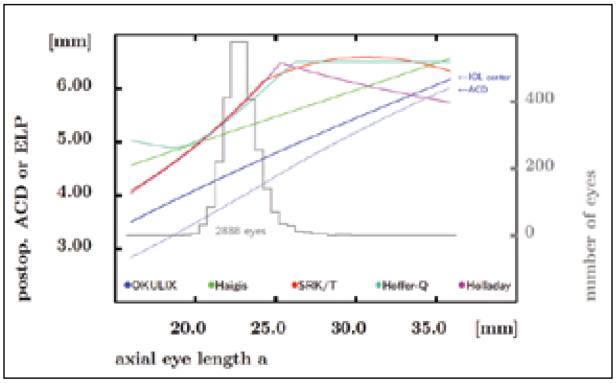

Figure 1. Differences in assumed IOL position for the Haigis, SRK/T, Hoffer Q, and Holladay formulas (as functions of axial length) as compared with the Okulix ray tracing formula (as functions of IOL center position in solid blue and anterior chamber depth in dotted blue).

Current third-generation IOL calculations do not even use the full capabilities of Gaussian optics. These formulas apply two additional simplifications to Gaussian optics: They combine anterior and posterior corneal surfaces into one surface, and they approximate the IOL as a so-called *thin lens*.

Combined surface. The combination of the anterior and posterior surfaces of the cornea into one surface requires certain assumptions about the ratio of the anterior and posterior radii of curvature. For a given ratio, a fictitious corneal refractive index, which is smaller than the refractive indices of the corneal material and aqueous humor, is calculated. This fictitious corneal refractive index differs in each IOL formula.

Thin lens. IOL formulas universally approximate the IOL as a thin lens; however, the assumed position of the IOL is different in each calculation method. Formula

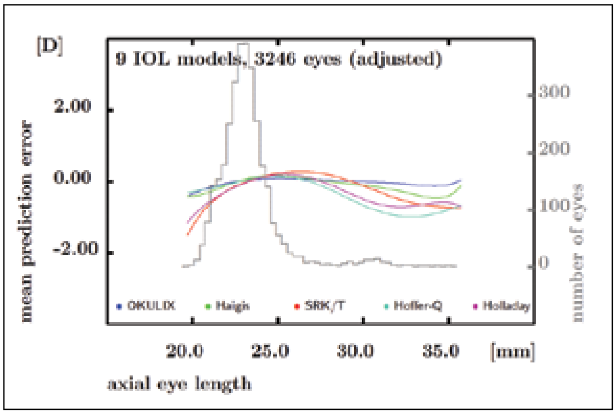

Figure 2. Prediction error of Okulix ray tracing and of the Haigis, SRK/T, Hoffer Q, and Holladay formulas, shown as functions of axial length. The distribution histogram is shown in grey, with scale on the right.

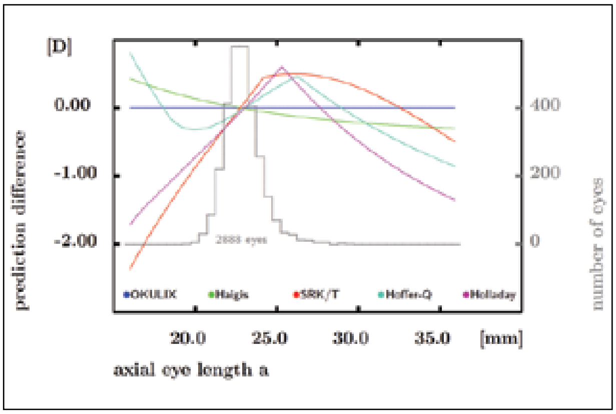

Figure 3. Theoretical differences in very short and very long eyes are confirmed by corresponding clinical data. Differences between ray tracing and the Haigis, SRK/T, Hoffer Q, and Holladay formulas are shown as functions of axial length (range, 16-36 mm). The distribution histogram is shown in grey, with scale on the right.

constants are used to calculate the position of a thin lens of a given appropriate power, and, if adjusted correctly, these constants will supply the required target refraction. This assumed position is often referred to as the *effective lens position* (ELP) and, just as with the fictitious corneal refractive indices of each IOL formula, the ELP varies among formulas. Therefore, the different IOL formulas are actually describing different physical systems (Figure 1).

RAY TRACING: A MODERN APPROACH

When applied to IOL formulas, as in the Okulix software (Tedics Peric & Jöher GbR; available at okulix.de), ray tracing uses a pseudophakic eye model, and ideally anterior and posterior corneal surfaces should be measured using topography. Okulix ray tracing has a software interface to all Tomey devices, to the Pentacam (Oculus Optikgeräte GmbH), and to the Lenstar (Haag-Streit), thus allowing the user a simple solution to use it with data from these devices.

In this power calculation strategy, anterior and posterior central curvature radii, asphericity of the surfaces, central IOL thickness, and index of refraction are all used to describe the IOL. The position of the IOL in this calculation is not some fictitious ELP but the true geometrical position, as defined by the anterior chamber depth (ACD): ie, the distance between the posterior corneal apex and the anterior IOL apex.

A problem for both strategies, Gaussian and ray tracing, is that the postoperative position of the IOL cannot be determined before surgery. Therefore, ray tracing is no more advantageous than third-generation IOL formulas to predict the accuracy of postoperative IOL position (Figure 2). However, prediction methods for postoperative ACD should be directly compared with corresponding ACD measurements, and this is possible with ray tracing but not with the fictitious ELP calculated with third-generation formulas derived by the principles of Gaussian optics.

With ray tracing, the postoperative ACD can be measured using partial coherence interferometry and directly compared with the preoperative estimation. With third-generation IOL formulas, the ELP can be back-calculated from the postoperative refraction; however, the latter is less accurate due to errors in subjective or objective refraction and IOL mislabeling. In short, the method used for preoperative ACD prediction should be consistent with partial coherence interferometry measurements of postoperative ACD.

ACD MEASUREMENTS

After IOL implantation, ACD measurements depend on the length of time after surgery, the size of the capsulorrhexis, IOL haptic angulation and thickness, and IOL material. Therefore, each of these parameters should be included in the calculation to produce a high-quality ACD prediction method. The size and position of the crystalline lens both have a predictive impact on postoperative ACD. Without accurate measurement of crystalline lens thickness, the preoperative ACD does not accurately depict the influence of the growth of the lens with age. Unfortunately, ultrasound lens thickness measurements have high measurement errors, and optical measurements are not available with most current equipment; they are, however, with the Lenstar LS 900.

Leaving aside lens thickness, there is good correlation between postoperative ACD and axial length or corneal radius. However, because all of these parameters cor-

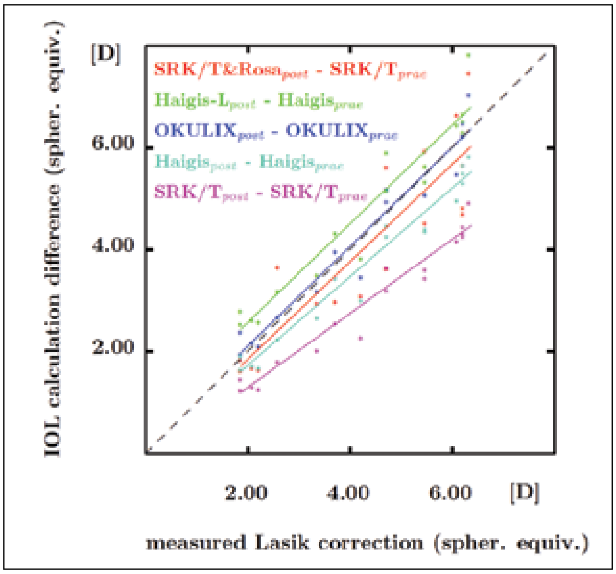

Figure 4. IOL calculation prior to and after LASIK was compared using ray tracing and third-generation formulas in 17 eyes.

relate, it can be dangerous to use one as an independent predictive variable in a multiple regression fit approach. The simplest method for ACD prediction, which is used in our ray tracing approach, is to employ the near-linear relationship between axial length and the distance from postoperative IOL center to posterior corneal apex. In this strategy, the postoperative ACD is calculated by subtracting half of the IOL thickness; this can be made more accurate by including optical measurements for crystalline lens position and lens thickness.

AFTER REFRACTIVE SURGERY

When used in average-sized (normal) eyes, ray tracing and third-generation IOL formulas produce similar results and prediction errors. In these cases, the position of the IOL after surgery produces the majority of errors. However, with eyes that are longer or shorter than normal eyes, as well as in postrefractive surgery eyes, prediction error with ray tracing and third-generation formulas differ significantly (Figure 3).

After refractive surgery, prediction errors can occur when corneal radii are measured with keratometry. Keratometers are calibrated assuming a spherical or moderately prolate aspherical corneal curvature, but the true shape of the cornea after refractive surgery is mostly oblately aspherical. If topography is used in place of keratometry, as is the case with ray tracing, these errors can be avoided by using an algorithm to extract the corneal vertex radii and corneal asphericity in the optical zone.

Another source of prediction error in postrefractive surgery eyes is the corneal refractive index, with its fictitiously assumed constant ratio of anterior and posterior corneal radii. To correct this error, Scheimpflug imaging or optical coherence tomography must be used to take an additional measurement of the posterior corneal curvature (Figure 4).

When topography is performed on both the anterior and posterior corneal surfaces, there is no need to distinguish between normal eyes and postrefractive surgery eyes. This is an advantage of using ray tracing for IOL calculations in these cases.

TAKE-HOME MESSAGE

- Ray tracing with the Okulix formula uses anterior and posterior central curvature radii, surface asphericity, central IOL thickness, and index of refraction to describe the IOL.
- Predictive methods for postoperative ACD should be compared with actual ACD measurements.
- The simplest method for ACD prediction is to employ the near-linear relationship between axial length and the distance from postoperative IOL center to posterior corneal apex.

CONCLUSION

The principles of ray tracing have existed since the 17th century, but only recently have they been applied to calculations for optical devices in ophthalmology. Although many surgeons rely on the use of third-generation IOL power calculation formulas such as the Haigis-L, Hoffer Q, Holladay 2, Olsen, and SRK/T, ray tracing is a modern technique, based on a different set of principles, that should be considered a potentially useful strategy. ■

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