

Ray Tracing: the Future of Refractive Surgery

Ray tracing has the potential to facilitate ultimate customization.

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The goal of refractive surgery is to provide the patient with his or her best possible visual performance. To obtain this optical quality, surgery (eg, corneal ablation, IOL implantation, etc.) must change the refracting structures of the eye. Accurate methods of calculation are required to achieve satisfactory surgical outcomes.

In ophthalmology, traditional planning methods for IOL power calculations or corneal laser ablation profiles are based on simplified formulas that are derived from paraxial optics. These formulas fail to consider the eye's multiple lenticular structures, or they may incorporate addition theorems for small aberrations in cases where they are not valid. Already somewhat theoretical, such formulations were found to incompletely correct some types of aberrations or to induce errors, specifically in eyes of atypical size or with preexisting aberrations.¹

Even the planning of refractive treatments using wavefront technology, which is known to measure the entirety of the eye's optical characteristics, is based on an approximation. It is presumed that the total measured wavefront aberration of a multilens system can be compensated for by applying the corresponding correction profile to a single refractive surface of the system without further adjustments of the profile. This is not exactly the case.¹ In fact, these assumptions limit the accuracy of today's planning methods and therefore limits their applicability for future fields of interest. Aspects of these calculations, however, can be addressed easily by the ray-tracing method.

RAY-TRACING METHOD

Ray tracing is a computer-based method used to calculate an ablation profile for a refractive laser by incorporating data derived from several types of measurements. By considering all optical surfaces of the eye, such as the back and front surfaces of the cornea and the crystalline lens, ray tracing offers the highest possible accuracy to improve the refractive predictability of corneal laser surgery or lens implantation.²

Optimal visual acuity cannot be achieved via a surgical plan that is calculated using a single diagnostic measure-

ment, such as that employed by existing methods. Even the individualized calculations of wavefront-guided ablation profiles use data from only one measurement method. Because a single type of measurement cannot provide all of the data that are required to achieve the utmost individualization, approximate and mean values taken from the literature are still used,^{3,4} which theoretically reduces the precision of treatment planning.

NECESSARY MEASUREMENTS

To achieve a maximum level of individualization for a treatment, the following measurements may be used: wavefront of the entire eye, corneal topography, topography of the cornea's back surface, and biometric data (ie, corneal thickness, anterior chamber depth, lens thickness, and ocular length). Today, only the shape of the lens, the retinal radius, and the refractive indices and their distribution in the lens cannot be measured directly and are therefore taken from the literature (they are approximations).

Using these described diagnostic data, the eye model obtained provides the best possible true-to-life reproduction of all of the refractive surfaces of the eye. The basis for any kind of calculation is optical ray tracing. In this method, the optical path of a bundle of light rays passing through the eye is calculated using Snell's law. The simulated wavefront of the total eye model calculated from the diagnostic data should be identical to the measured wavefront. Therefore, the shape of the surface of the anterior lens has to be adjusted by an iterative optimization algorithm.

OPTIMIZATION PROCESS

The optimization process has to be performed in an iterative manner. This is because the points of intersection of the tracked light rays with the crystalline lens' surface are the required starting point of the algorithm, yet this information is currently unknown. A lens from an average ocular model taken from the literature therefore serves as an initial guess for the iteration.

The goal of the intraocular optimization is to adjust a

specific refractive surface in such a way that the measured wavefront of the total eye equals the simulated wavefront from the model eye. A perfect eye has an ideal focal point on the retina (Figure 1), and the shape of a specific surface that should be optimized can now be adjusted until all beams reach the ideal focal point. In the case of an optimization of the front surface of the lens, as depicted in Figure 1, the measured wavefront in front of the eye has to be traced through the anterior and posterior surfaces of the cornea. This allows the calculation of the intraocular wavefront in front of the anterior surface of the lens (Figure 1, left). On the other hand, ray tracing from the retina's ideal focal point has to be performed through the posterior surface of the lens to calculate the intersection of the rays with the anterior surface of the lens (Figure 1, right). The shape of the anterior lens' surface is subsequently modeled in a way such that all wavefront rays from the anterior and posterior surfaces meet coaxially. A highly individualized shape of the surface has been created and can be used to provide the patient with the best possible treatment plan.

CLINICAL TRIAL DATA

Laser Ablation

In a clinical trial performed in 2009 and 2010, a standard LASIK ablation profile for a total of 127 eyes was calculated using the ray-tracing method.⁵ The investigation showed that this method was safe and effective, and the refractive outcomes were at least equal to those of conventional calculation. These results are promising and reveal that a precise and individualized treatment plan can be achieved.

IOLs and Contact Lenses

Using ray tracing, the diffraction limit or a maximal depth of focus can be targeted when optimizing IOLs. This means that the light rays of the targeted wavefront (plane or a specific type of higher-order aberration, Figure 2) are traced through the cornea's anterior and posterior surfaces to calculate the intraocular wavefront in front of the lens' anterior surface. An individualized profile for this surface can therefore be calculated. This procedure may lead to the customized production of IOLs that meet each patient's individual needs.

Because all optical structures of or on an eye can be taken into account, contact lenses may also be considered for a calculation by ray tracing. If one can optimize any surface of the eye using ray tracing, why not optimize a contact lens? Highly personalized shapes could be created for contact lenses' surfaces.

CONCLUSION

As development continues, a wide range of treatment plans will be calculated and customized by the ray-trac-

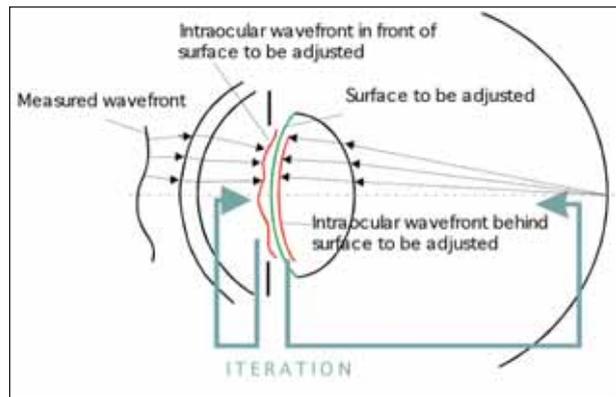


Figure 1. The customization process of the eye model. After implementation of the measured surfaces and the lengths, an intraocular surface such as the anterior surface of the lens is optimized so that the simulated total wavefront of the eye equals the measured wavefront. This optimizing process is performed iteratively from two sides.

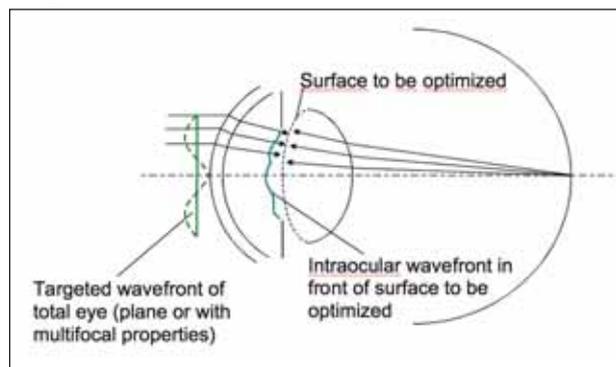


Figure 2. Schematic drawing of the optimization of an IOL's front surface by specification of a targeted wavefront. Iterative optimization is performed from two sides.

ing method. Ray tracing will allow surgeons to address the visual needs of individual patients. ■

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