Wavefront-Guided Treatments: Past, Present, and Future

An overview of wavefront basics and a personal account of one surgeon's experience.

BY A. JOHN KANELLOPOULOS, MD

It has been 10 years since ophthalmology was captivated by the ability not only to acquire wavefront measurements of the human eye but also to transfer these into a form of excimer laser treatment.[1-5] This development allowed us to enhance the wavefront of an eye by reducing higher-order aberrations (HOAs), either as a primary or secondary treatment.

It has been a fascinating journey to study the clinical use of wavefront-guided and other customized treatments. I have learned a lot from personal experience in our center in Athens, Greece, as well as through reading and hearing about the experiences of surgeons worldwide who use different wavefront platforms.[1-52] In some countries, wavefront-guided treatments achieve a high level of market penetration, preferred by surgeons and patients alike. Market penetration has been less in others, and these differences from country to country are puzzling.

Our experience with wavefront-guided treatments began in 2000 with the WaveLight Allegretto platform (now Alcon Laboratories, Inc., Fort Worth, Texas), which uses a Tscherrning wavefront analyzer, and was enhanced in 2006 with the WaveScan platform (Abbott Medical Optics Inc., Santa Ana, California). We began using these treatments for primary LASIK in 2002 and graduated to the secondary management of symptomatic LASIK cases in 2003.[40,44]

WAVEFRONT ANALYZERS

The basic principle of the Tscherrning aberrometer is to project a patterned series of laser beams onto the retina.[3] The image formed on the macula is affected by the total eye aberrations. An in-line camera captures the pattern projected on the retina, and the individual spots are identified. The created pattern is then analyzed against the projected pattern to provide the wavefront deviation data (Figure 1).

There are some differences between the Tscherning aberrometer and the Hartmann-Shack—the wavefront analyzer that most other platforms use—but comparative data are similar. A third type of wavefront analyzer, using ray-tracing data, is used in the iTrace aberrometer (Tracey Technologies Corp., Houston). However, no specific laser platform is coupled with this device for wavefront-guided treatments.

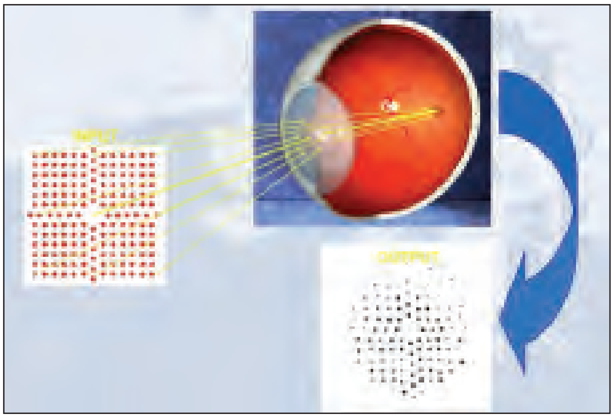


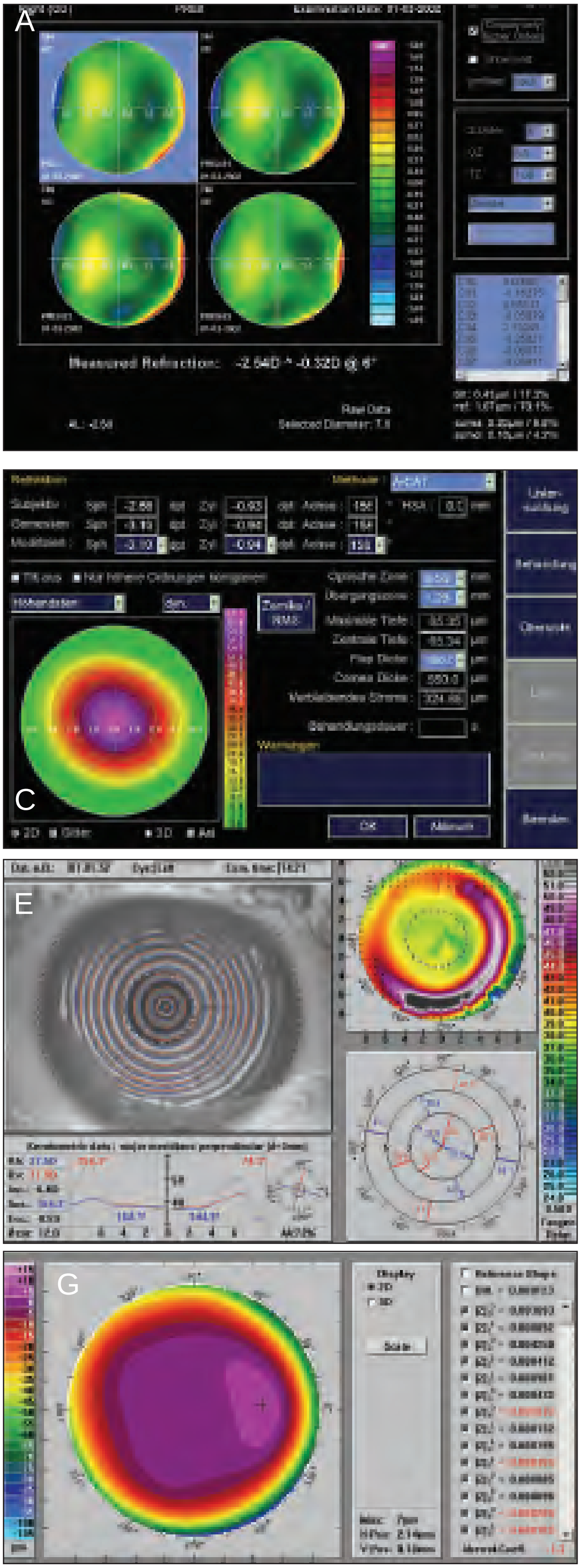
Figure 1. The wavefront measurement principle, in which wavefront deviation data is derived from created and projected patterns.

Some difficulties encountered when wavefront analysis of the human eye is used for treatments include the following:

- Selecting the optimal level of accommodation during measurement (far vision, intermediate vision, dilated pupil, or cycloplegia);
- Selecting the appropriate pupil size for the wavefront to be captured and the treatment delivered;[42] and
- Selecting among specific Zernike parameters and deciding which would be most beneficial for the human eye.

PARAMETERS THAT AFFECT TREATMENT

Applegate[9,10] reported that not all deviations in the Zernike polynomial are troublesome for human eyesight, and some may even enhance contrast sensitivity. This point was reiterated when wavefront analysis in fighter pilots[16] and professional baseball players[7] showed that many had excel-



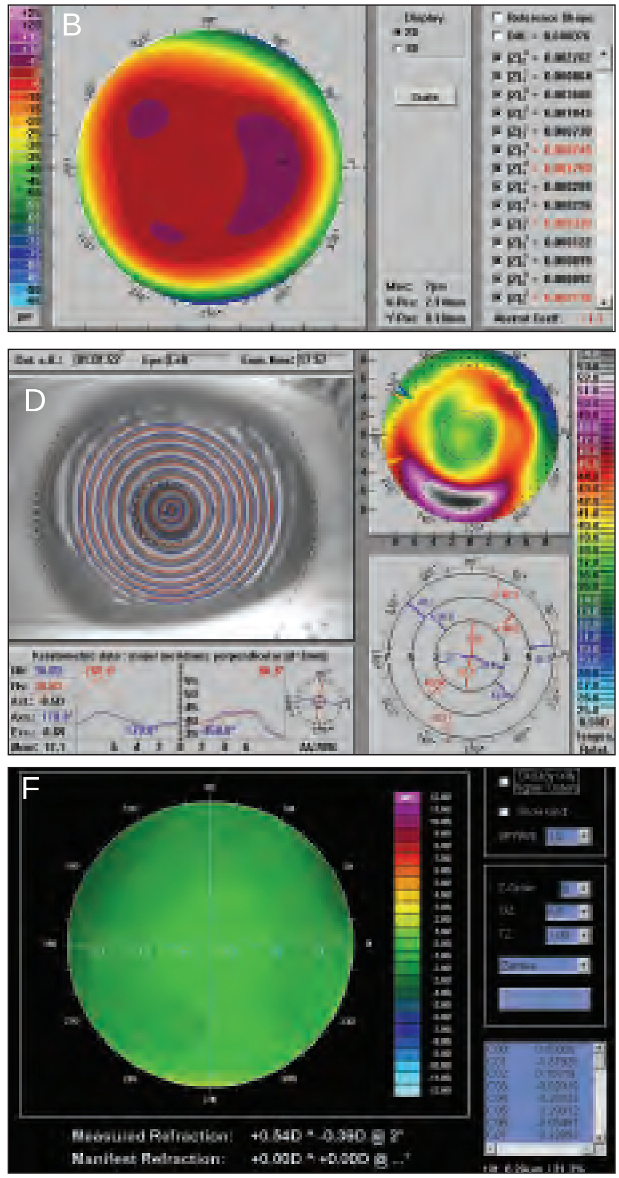


Figure 2. (A) Wavefront of an unhappy patient after LASIK. This eye has a high RMSh (1.2). (B) A topography-derived wavefront map that appears similar to the actual wavefront map. (C) The wavefront-guided enhancement plan. (D) Placido-disc–based topography of this unhappy patient. (E) Postenhancement topography. The optical zone has increased in both D and E. Note that the asphericity has improved,. (F) The wavefront map following the wavefront-guided enhancement. RMSh dropped to 0.3, and the patient was very happy. Of the individual Zernike polynomial values, some decreased and some increased, with C12 (spherical aberration) having the largest decrease. (G) Topography-derived wavefront map of the same eye following a wavefront-guided enhancement. This assessment correlates with the postenhancement wavefront map, supporting that the wavefront-guided procedure treated mainly corneal aberrations.

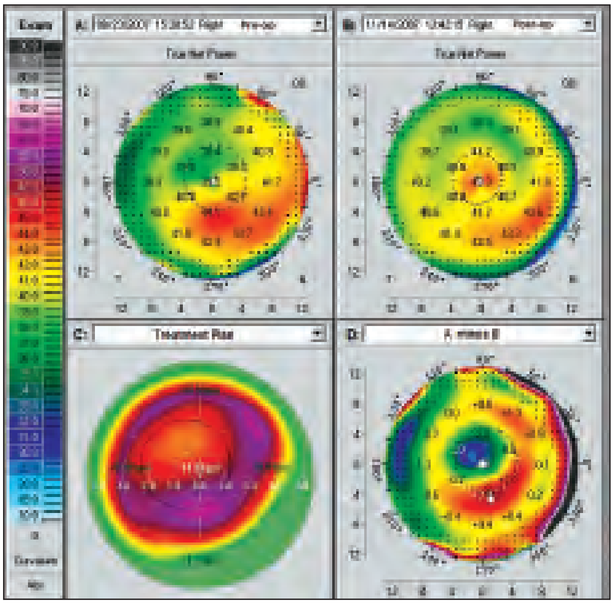


Figure 3. Summary of the clinical course of the right eye of a patient with post-LASIK ectasia. The patient was treated with the Athens Protocol (combined topography-guided PRK and CXL). (A) Topography of the right eye 3 years after LASIK. The eye had irregular astigmatism and marked inferior corneal steepening, and UCVA and BCVA were 20/40 with +1.50 -2.00 X 65º (20/20). (B) Topography 3 months later. A topography-guided PRK was performed followed by collagen crosslinking on the same day. The topography is flatter and normalized. UCVA is 20/25. (C) Topographic reproduction of the topography-guided PRK treatment plan. This platform is planning to remove tissue in an irregular fashion to normalize the corneal ectasia seen in 4A. (D) Comparison map (B minus A) represents the topographic difference in the first 3 months after the combined treatment. The paracentral flattening is self-explanatory, as the PRK and CXL have flattened the cone apex. The superonasal arcuate flattening represents the actual partial hyperopic correction that the topography-guided treatment achieved. The topography-guided treatment normalized the ectatic cornea by flattenning the cone apex and at the same time steepening the rest of the central cornea.

lent visual acuity and function despite the presence of coma.

Although most laser platforms can improve wavefront analysis after primary or secondary refractive surgery, the accuracy of correction is affected by several parameters, including the level of accommodation in the crystalline lens, the degrees of intraoperative cyclorotation,[43] and pupil centroid shift.[6] The latter is due to the difference between the dilated pupil when wavefront measurements are taken and the smaller size of the pupil during treatment.[41] An additional consideration is the change of normal wavefront aberrations that occurs with aging.[11] What is the optimal state that should be targeted by the treatment?

It has been our experience that, when used for enhancements, wavefront-guided treatments improve spherical aberration (C12 Zernike polynomial; Figure 2). For laser platforms that allow this, wavefront-guided treatment may be superior to standard treatment, mainly because it improves the spherical aberration profile of the cornea. It also provides better visual function under mesopic and scotopic conditions, whereas conventional excimer myopic ablations produce significant mesopic and scotopic spherical aberrations because they negatively affect corneal asphericity.

OPTIMIZED PROFILES

WaveLight's wavefront-optimized profile is a population-based aspheric correction that can be used to treat myopia, myopic astigmatism, hyperopia, and mixed astigmatism.[13] This profile preserves the natural aspheric shape of the cornea and neutralizes the laser-induced spherical aberration that typically accompanies conventional laser vision correction for myopia.[18] It reduces the most prominent and visually disabling HOAs without the need for wavefront customization in the majority of eyes.[14]

Most of the potential benefit of wavefront-guided treatments is afforded by wavefront-optimized profiles.[12] This theory was confirmed in the US Food and Drug Administration (FDA) trials of the WaveLight platform,[31] in which no significant difference was seen between wavefront-guided and wavefront-optimized treatments.

INDUCTION OF HOAs

One of the arguments regarding use of wavefront-optimized versus wavefront-guided treatments is that normal eyes do not usually have HOAs,[19,22,27,34] and therefore it would not make sense to employ wavefront-guided treatment, which could induce HOAs due to capture and/or delivery error. Potential parameters that may induce HOAs include the LASIK flap,[17,25] decentration of the excimer ablation,[24] and irregularities in the ablation. Flap-induced aberration has decreased over the years, and this may have positively influenced refractive outcomes in LASIK. It is possible that flap creation is a determining factor in the difference in induction of HOAs in LASIK versus surface ablation (PRK, LASEK, and epi-LASIK). The use of femtosecond lasers for flap creation has probably reduced wavefront deviations for most LASIK patients. The reduction in flap-related aberrations may be the strongest indication for the use of femtosecond lasers in flap creation in LASIK.

Laser centration is also a concern. The latest laser trackers have higher frequencies and therefore faster response times.[20,21,23] Centration, especially for myopic ablations, has been more important than matching pupil size in determining quality of vision in mesopic and scotopic pupils. A

TAKE-HOME MESSAGE

- Three types of aberrometer are used in ophthalmic applications:: Tscherning, Hartmann-Shack, and ray-tracing.
- Wavefront-guided treatments can improve the spherical aberration profile of the cornea and provide better visual function under mesopic and scotopic conditions.
- Potential parameters that may induce HOAs include the LASIK flap, decentration of the excimer ablation, and irregularities in the ablation.
- Unlike wavefront-guided treatments, topography-guided treatments do not appear to negatively change wavefront parameters.

decentration of more than 100 µm in myopic ablations starts to become significant and may induce mesopic and scotopic aberrations.

The WaveLight EX500 excimer laser (Alcon Laboratories, Inc.) employs a 1,028-Hz tracker with an effective 2 msec response time. We have experienced smaller deviation of ablations with this platform.[40] Our experience mirrors the improvements reported with tracker and cyclodeviation capabilities in most lasers. With fewer decentered ablations, we have seen a reduction in visual function side effects in patients with large pupils under mesopic and scotopic conditions.

TOPOGRAPHY-GUIDED PLATFORM

Since 2003, we have worked extensively with a topography-guided platform for laser vision correction in irregular corneas.[48] For a corneal surgeon, topography-guided ablation is valuable for several reasons. First, it can normalize even highly irregular corneas, such as those with keratoconus, pellucid marginal degeneration, or post-LASIK ectasia.[45-52] Second, the corneal surface does not change with different levels of accommodation or pupil size; therefore, it may offer a more stable medium to be imaged and treated.

Topography-guided treatments are not perfect, as the spherical equivalent is calculated automatically, and these treatments are based purely on corneal curvature, not the axial length of the eye. However, we have found that the results appear to be superior to wavefront-guided treatments. Topography-guided treatments do not appear to negatively change wavefront parameters, as wavefront-guided treatments may (Figure 3).

RAY TRACING

A new modality for customized refractive surgery, ray tracing, offers the reproducible value of topography-guided treatments along with consideration of wavefront and axial length data and expected changes in biomechanical response.

Mrochen and colleagues[30] reported the theoretical benefit of optical ray-tracing methods for planning complex refractive corrections. Using customized eye models generated from recentered topographic data (from the corneal apex to the pupillary center) with internal ray-tracing calculations, they showed that wavefront-guided correction may incompletely correct specific aberrations—and even increase them by a factor of two—due to the neglect of internal multilens complexities. Ray tracing, in theory, can compensate for these internal complexities to eliminate all residual aberrations, allowing the highest degree of customization.

PERSONAL EXPERINCE

Currently we employ wavefront, topography, corneal tomography, and axial length measurements in our standard preoperative evaluation of LASIK candidates.[44-50] When treating patients with myopia, we employ wavefront-optimized treatment. We use the WaveLight FS200 femtosecond laser (Alcon Laboratories, Inc.) to create the flap (8.5 mm in diameter and 120 µm depth) in 7 seconds, followed by ablation with the WaveLight EX500 excimer laser. For myopic eyes with aberrations measured greater than 0.4 µm, we consider wavefront-guided primary treatment. For eyes with hyperopia, we employ primary topography-guided treatment with a 9.5-mm flap at 130 µm. This treatment aims to center the hyperopic ablation on the visual axis, which is commonly nasal to the pupil center (angle kappa).

If retreatment is necessary, all custom modalities are considered (wavefront-guided, topography-guided, ray-tracing). It should be mentioned that our retreatment rate has been less than 1% for patients with myopia and less than 5% for patients with hyperopia over the past 3 years. ■

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