Techniques in Ophthalmology 1(1):17–21, 2003

TECHNIQUE

Wavefront-Guided Refractive Surgery

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ABSTRACT

The latest in vision testing with wavefront analyzers, known as aberrometers, represents an exciting new technology for the ophthalmologist. These wavefront sensors will expand our understanding of the optics of the human eye. They will help us comprehend why our patients see what they see, with new knowledge about the parameters that affect the quality of vision. The equipment also makes available a new approach for improving outcomes of refractive surgery by using customized wavefront-guided excimer laser ablation. The implications for the future are exciting, and some encouraging results have already been obtained.

WAVEFRONT HISTORICAL DEVELOPMENT

Wavefront analysis of the human eye is based on an optical theory that was first developed in astronomy more than 100 years ago, with roots that date back almost 400 years. In the 1600s Scheiner described a disc with two pinholes that produced two retinal images. In 1900, Hartmann drilled several holes in such a disc and was able to trace the light rays that emerged from it. Light rays that went the wrong way were called “aberrated rays.” The Hartmann screen was a modification of the Scheiner disc and was a method for measuring the ray aberrations of mirrors and lenses. In 1971 Shack modified the Hartmann screen by using an array of tiny lenses. This became know as the Hartmann-Shack method of measuring aberrations, which was first used in the human eye clinically in 1994.

HOW WAVEFRONT WORKS

Light travels in flat sheets called wavefronts. If undisturbed, these waves remain parallel. The irregularities or aberrations in the cornea and the lens of the eye alter the light waves and create wavefront errors or distortions, as the light rays enter and exit the eye. That is the scientific principle that this technology uses.

The wavefront analyzer aims a diode laser into the eye and focuses it on the retina. As the light rays are reflected back out from the retina, they are subjected to aberrations as they travel through the eye’s optics. If the eye has no irregularities, these light rays will come out of the eye in a plane wavefront, or a perfect straight line. This is the optically ideal eye. However, if the eye has irregularities, the wavefront emerges not in a straight line, but with a unique shape specific for that eye.

This wavefront of light then passes through a tiny array of lenses, called the lenslet array, in the wavefront analyzer. The image created by the lenslet array is captured by a video camera (Fig. 1).

In a normal eye, the video image shows small dots of light in a symmetrical grid, aligned in a highly uniform pattern. In an eye with significant aberrations, however, the dots are blurred and the pattern appears distorted. The system compares the pattern seen in the eye being analyzed to an ideal pattern with no optical aberrations. The deviation of the spots from their ideal location provides information on the wavefront error. The system generates a series of equations that describe the complex shapes of the distorted wavefront measurements, called Zernike polynomials, for that particular eye (Fig. 2). For convenience it is useful to compute the average overall wavefront error. The statistic that is used is the RMS (root mean squared) wavefront error.

ABERRATIONS

There are two categories of aberrations. Second-order aberrations (basic spherocylindrical errors) can be corrected

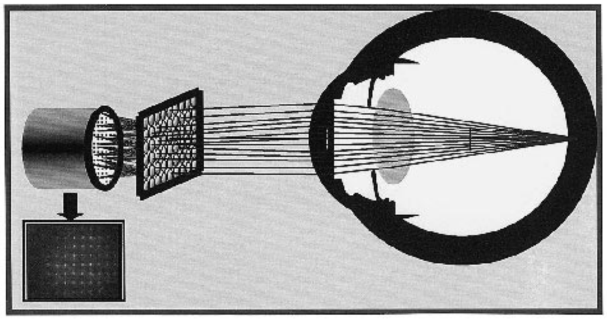

FIG. 1. Reflected laser beam in wavefront measurement.

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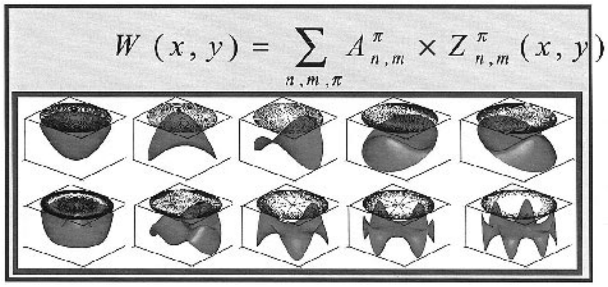

FIG. 2. Identification of the various higher-order aberrations is achieved though Zernike polynomials.

with spectacles, contact lenses, and conventional laser surgery. These include defocus and astigmatism. These have the largest impact on visual acuity. Then there exist higher-order aberrations that are third-order and above, the residual irregularities in the optical system. They can represent up to 10% to 15% of the total aberration error. They normally degrade retinal image quality only a small amount, and they also contribute to limiting the resolution of the human eye. These include trephoil, coma, spherical aberration, and others (Fig. 3). These occur naturally but are also induced by excimer laser refractive correction, where they may become more visually problematic.

Criteria to preselect patients for aberrometry include the following: high myopia (tissue saving), high astigmatism (tissue saving), thin corneal pachymetry (tissue saving), large pupils (tissue saving, night vision benefit), night vision complaints (possible aberrations), and patient interest in latest technology.

Coma is associated with streakiness of images, while spherical aberration smears out features of the image in a radially symmetric fashion, resulting in a ghosting halo around letters in a chart. Induced higher-order aberrations can be associated with complex visual complaints, such as glare, halos, and night driving difficulty. Spherical aberration in particular is often accompanied by night vision complaints.

■ WAVEFRONT ANALYZERS (ABERROMETERS)

The different ways of analyzing the optical system of an eye using wavefront technology employ relatively the same basic optical theory. Those measuring rays entering the eye include Emory's InterWave wavefront sensing system, Dynamic Skiascopy used by Nidek OPD, the Tscherning method found in the Schwind ORK Aberrometer, and the Allegreto Wave Anylyzer. The most common is the Hartmann-Shack method, which measures outgoing rays, used by the Bausch and Lomb Zywave, Alcon LadarWave, VISX Wavescan, WASCA Carl Zeiss Meditec, and KR-9000 PW Wavefront Analyzer by Topcon.

Wavefront Analysis Findings

Wavefront testing has allowed us to appreciate that the imperfect optics of "normal" eyes are not only related to the familiar second-order sphere and cylinder errors determined with a phoropter examination, but are also due to higher-order aberrations.

To date some information has come to light. Higher-order aberrations vary from person to person and are unique to a particular eye. They have an increased effect with pupil size: the larger the pupil, the more significant

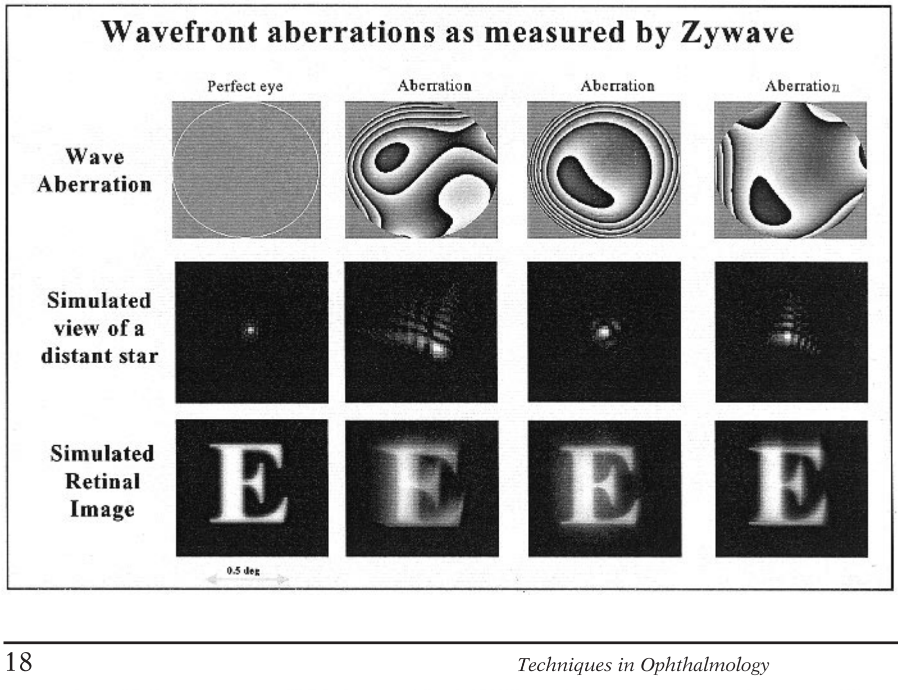

FIG. 3. Wavefront aberrations as measured by Zywave.

the effect on vision quality, since higher-order aberrations are more pronounced towards the periphery of the cornea. Higher myopes tend to have more aberrations, and aberrations tend to increase with age. They can change with accommodation and can fluctuate slightly from moment to moment with tear film changes.

Traditional refractive surgery increases higher-order aberrations anywhere from two to eight times preoperative measurements. Most of the change is induced by the laser ablation, and a minimal amount is induced by the creation of the flap. It is mostly spherical aberration that is induced.

One key finding from wavefront analysis research is that higher-order optical aberrations, in particular coma and spherical aberration, can have a detrimental effect on vision quality, even in eyes with optimal correction for sphere and cylinder refractive errors.

These observations suggest the potential for customized excimer laser ablation in not only correcting natural aberrations of the eye, but also for eliminating or decreasing the aberrations that are routinely induced by excimer laser surgery. The goal is to maximize vision quality.

■ WAVEFRONT-GUIDED LASIK PROCEDURE

The procedure is the same Lasik procedure that we have been performing for years, except that the laser ablation pattern is based on the measurement of all of the eye's optical aberrations from the wavefront analyzer (higher- and lower-order aberrations), and not simply on the eyeglass prescription.

To perform wavefront-guided Lasik, we first measure what we want to correct with the wavefront analyzer. After capturing the wavefront, the information is electronically transmitted to a small-spot precision excimer laser system used to create the intended custom ablation pattern. Finally, during the ablation, we need highly effective tracking of the eye. The eye tracker is for treatment alignment. As soon as we decide where to center the ablation, the eye-tracking system maintains this alignment during the ablation. Following eye movement is critical for wavefront-guided custom ablation.

Benefits and Results of Wavefront-Guided Lasik

The primary goal is the improvement of visual quality, especially in eyes with optical irregularities. The expected benefits of custom ablation include the reduction in natural and induced higher aberrations; improvement of visual quality (possibly even a gain in best-corrected visual acuity [BCVA]); a reduction or no worsening of preoperative symptoms, such as halos and night glare; and more accurate measurement and correction of lower-order aberrations.

Criteria for Zywave acceptance: Zywave refraction compared to manifest: sphere +/− 0.75D, cylinder +/− 0.50D, axis +/− 15 degrees, preoperative RMS value greater than 0.5 um.

The results have been encouraging to date. Preliminary studies show fewer induced higher-order aberrations when compared to traditional Lasik, and a reduction in higher-order aberrations from preoperative measurements in over 45% of patients. An increase is also seen in the percentage of eyes obtaining better than 20/20 vision and those gaining a line of BCVA, as compared to standard Lasik. Patients' subjective assessment of their postoperative vision is also excellent. While the technology is not yet perfected, the preliminary studies suggest an improvement over the already outstanding results with standard Lasik.

Limitations of Wavefront-Guided Lasik

We have all been hearing about wavefront technology and its tremendous potential. Our expectations have been growing. Wavefront's true potential, however, is just beginning to be explored. Even if we can figure out in theory how to correct the higher-order aberrations and measure them, we face the question of whether that task is achievable, given the limits of laser precision. Is it possible to make the laser treat as precisely as removing one or two or three microns, needed to correct those aberrations? Even if the laser can, the cornea is not a piece of inert plastic, but biological tissue; healing-associated changes might easily mask the subtleties of the wavefront treatment. A single layer of epithelial remodeling, or even slight biomechanical corneal "bowing," both known to occur after Lasik, would undermine the wavefront treatment effort. Also consider that the ocular aberrations change with age and due to changes in the crystalline lens. Furthermore, how accurate can wavefront-guided technology be without an absolute alignment and perfect match of the wavefront pattern measured to the ablation profile treated on the corneal surface? Even the slightest decentration or cyclotorsion will adversely affect the outcomes.

The future looks very bright. Not only does it hold the promise of wavefront-guided customized Lasik becoming the standard of care, but it also alludes to the possibility of one day customizing glasses, contact lenses, or even IOLs to improve vision quality.