# Highlights of the 1st International Congress of Wavefront Sensing and Aberration-free Refractive Correction

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The concept of wavefront customized correction, as collectively presented in the 1st International Congress on Wavefront Sensing and Aberration-free Refractive Correction on February 12, 2000, represents what has been referred to as "an inflection point in the history of eye surgery."[1] The Congress included papers on the optical and neural limits to vision, history of ocular wavefront sensing, the magnitude of ocular aberrations, the principles and function of clinical instrumentation, coupling wavefront sensors to lasers to create "super vision" clinical outcomes, and ended with future challenges to refractive surgery. Before embarking upon a selective proceedings of the 2nd Congress, we present the highlights of the 2000 Congress.

## BACKGROUND

### Optical and Neural Limits to Vision (Raymond Applegate, OD, PhD)

Non-invasive wavefront sensing of the human eye provides the necessary information to design corrections that minimize the monochromatic optical errors of the eye beyond simple sphere (defocus) and cylinder (astigmatism). These are known as "ideal" corrections. Although it is possible to design and implement compensating optics that reduce the eye's higher aberrations, the question remains: Can the neural retina capitalize on the increased image detail? To know if the retinal image can be improved, it is necessary to explore the limits imposed by the optical and neural design of the eye.

The exact limit to visual acuity is not as important as understanding that the visual acuity is limited by receptor diameter, receptor packing, and biological variation. For larger pupil sizes (>3-mm diameter), ideal corrections improve the optical quality of the retinal image beyond the limits imposed by photoreceptor spacing (Fig 1). Correcting the higher order aberrations will provide images with higher contrast and crisper edges. Under perfect "ideal" conditions, corrections could provide for high contrast visual acuity between 20/8 and 20/10.[2]

### History and Methods of Ophthalmic Wavefront Sensing (Howard Howland, PhD)

The primary methods of wave aberration detection and reconstruction have been based either on interferometry or ray tracing. In the interferometric method, Twyman-Green interferometry has not found much application in physiological optics, primarily due to difficulties in stabilizing the eye and construction of appropriate reference surfaces with which to compare corneal shape.[3]

All the other methods have been based on ray

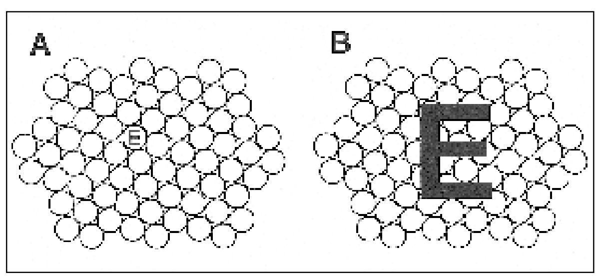


**Figure 1. A)** If a letter "E" is imaged such that it falls within the borders of a single photoreceptor, then the letter "E" cannot be differentiated from a period. **B)** To be seen as a letter, "E" must be sampled by enough photoreceptors to differentiate the letter's component parts.

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tracing. In physical optics, these methods were first realized by Hartmann in 1900, and clinically applied in ophthalmology by Liang and Bille in 1994. In 1894, Tsherning first introduced an apparatus that he named "aberroscope." Clinical application in ophthalmology using the principles of this device was first introduced by Howland in 1977.[3]

There exists today a variety of subjective and objective methods for assessing the wavefront aberration of human eyes; these methods span a wide range in cost, complexity, and accuracy. Due to the unique advantages of each method, we may expect to see their continued development in the near future.

### Magnitude of Ocular Aberrations (David Williams, PhD)

Higher order aberrations can be measured by a Hartmann-Shack wavefront sensor and can be corrected with an adaptive optics system. The benefits of correcting higher order aberrations are subjectively obvious. First, the benefits are maximized when the pupil size is large. This is greatest in younger patients, who typically have larger pupils, and in situations such as night driving. It is also important to recognize that the eye's higher order aberrations change substantially with accommodation. This means that a higher order correction for distance vision would not be appropriate for near viewing and vice versa. Also, the benefits of a higher order correction depend on accurate control of accommodation.[4]

### Understanding Aberrations Using Double-pass Techniques (Pablo Artal, PhD)

The double-pass technique has been used extensively in physiological optics. It is based on recording images of a point source projected on the retina and reflected back through the ocular media as a double-pass. From these double-pass images, the ocular modulation is calculated. The modulation transfer function yields the relationship between the contrast of an object and its associated image as a function of spatial frequency. This is a useful procedure to estimate ocular aberrations, although at present it requires a long computational time.[5]

The modulation transfer function measured using a double-pass system in a population of healthy patients of different ages declines with age. This indicates an increase in aberrations throughout life, which is further accelerated by the additional increment in intraocular scattering, noted in the 40s.

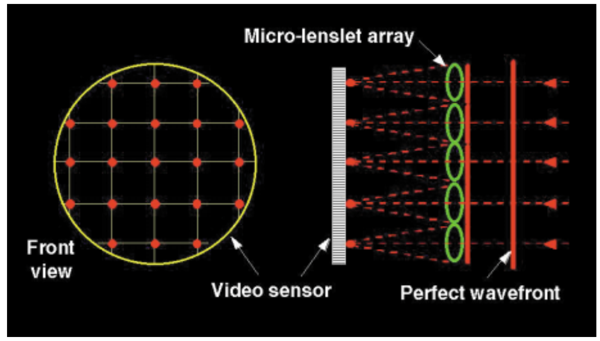


Figure 2A. Principles of Hartmann-Shack aberrometry

Another result predicted by the double-pass technique is the change of aberrations with accommodation. In general, aberrations are smaller and more compact for the accommodated eye.[5]

In a simple model, the aberrations for the complete eye can be assumed as the sum of those aberrations produced by the cornea and by the internal surfaces (mostly the lens). By measuring the aberrations of the complete eye and also the cornea using corneal topography data, the aberrations of the internal surfaces are estimated by direct subtraction. In general, in young subjects, the cornea is more aberrated than the complete eye. This suggests that the lens compensates, at least in part, for the corneal aberrations. Recent results suggest that this is not in general the case in older eyes.[5]

## CLINICAL MEASUREMENT TECHNIQUES AND UTILITY

### Principles of Hartmann-Shack Aberrometry (Larry Thibos, PhD)

The purpose of the Scheiner-Hartmann-Shack aberrometer is to measure the wavefront aberration function of the eye's optical system, which is the same as saying the purpose is to measure the shape of the wavefront of light that is reflected out of the eye from a point source in the fundus (Fig 2A).[6]

The shape of the aberrated eye's wavefront is a fundamental description of the optical quality of the eye called the "wavefront aberration function." This function lies at the heart of a rich theory that allows us to calculate the retinal image of any object, to assess the quality of that retinal image quantitatively, and ultimately to predict human performance on visual tasks.[6]

### Principles of Spatially Resolved Refractometry (Stephen Burns, PhD)

This is an instrument based on the Scheiner principle, which allows the rapid psychophysical

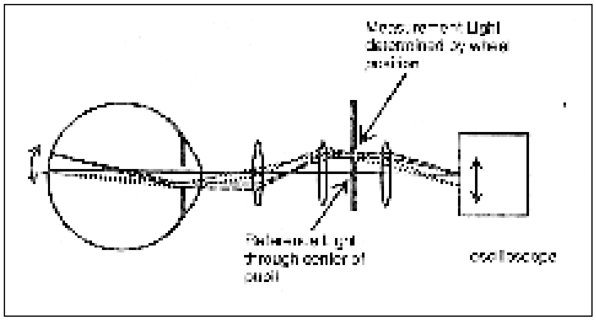

Figure 2B. Spatially resolved refractometry

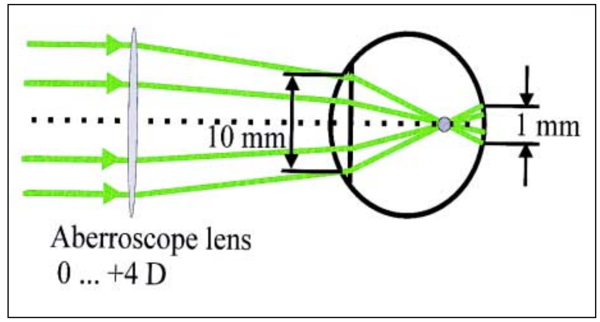


Figure 2C. Tscherning aberrometry

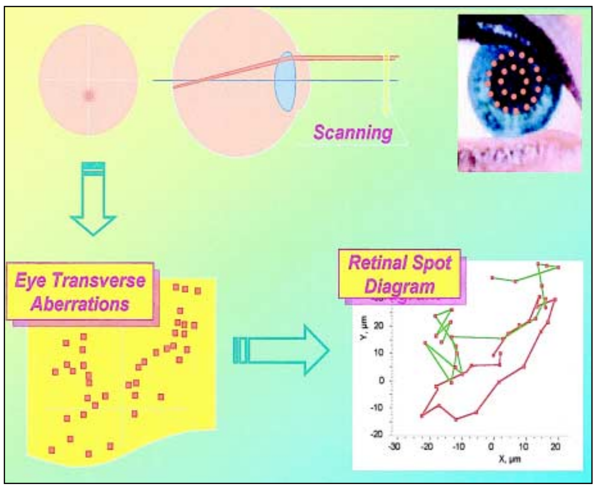


Figure 2D. Ray-tracing aberrometry

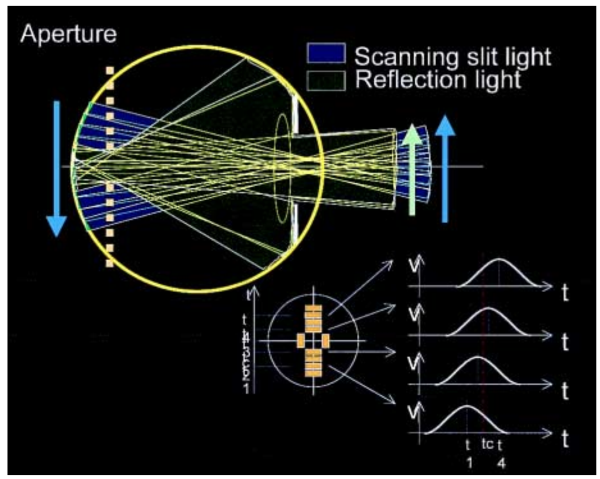


Figure 2E. Scanning slit refractometry

measurement of the complete wavefront aberrations of the eye (Fig 2B). The reproducibility of the measurements and the effect of static accommodation and wavelength of the eye can be investigated. In addition, the wavefront aberrations are combined with cone photoreceptor directionality to compute the modulation transfer function of the eye, at the retinal level. Results show significant changes in wavefront accommodation, with optimal image quality near the resting point of accommodation. Image quality for polychromatic (white) light is strongly affected by both longitudinal and transverse chromatic aberration.[7]

## Principles of Tsherning Aberrometry (Michael Mrochen, PhD)

The Tsherning aberroscope is based on retinal imaging optics. A collimated laser beam illuminates a mask with regular matrix pinholes that form bundles of thin parallel rays (in-going portion). These rays form a retinal spot that is more or less distorted according to the optical errors of the eye. This retinal spot pattern is imaged onto the sensor of a low light CCD camera by indirect ophthalmoscope (out-going portion). The deviations of all spots from their ideal regular positions are measured by means of a personal computer, and from these values the optical aberrations are computed in the form of Zernike polynomials up to the 8th order (Fig 2C).[8]

## Principles of Ray-tracing Aberrometry (Vasyl Molebny, PhD)

Like the Tsherning aberroscope, this technique measures the position of a series of thin laser beams projected onto the retina. The beams are directed into the eye parallel to the visual axis. Each entrance provides its own projection on the retina. A set of entrance point forms a set of projections. From these data, a refraction map is reconstructed as well as a point spread function of the eye (Fig 2D). Preliminary studies show high reproducibility of results.[9]

**Principles of Scanning Slit Refractometry (Scott MacRae, MD)**

The Nidek customized ablation system utilizes retinoscopic principles in the ARK 10000 (Scanning Slit Refractometer) system to give wavefront data (Fig 2E). This information is combined with corneal topography for preoperative and postoperative evaluation. The new Nidek EC-5000 laser delivery system combines the traditional scanning slit with a newer segmental area (1.0 mm) of ablation to maximize laser efficiency. It is anticipated that such combination strategies may be more common in the future.[10]

## CLINICAL EXPERIENCE

**CustomCornea Measurement Device (George Pettit, MD, PhD)**

The CustomCornea Measurement Device (CCMD) allows for accurate Hartmann-Shack wavefront sensing to be performed in the clinical setting. This measurement is a powerful tool for characterizing the eye prior to refractive laser surgery. Wavefront information is well correlated with the conventional technique of quantifying refractive error and also provides a measure of higher order aberrations that can compromise visual performance. These higher order aberrations are commonly present at detectable levels preoperatively, and are generally increased after surgical procedures. Accurate detection and reduction/elimination of high as well as low order aberrations is the goal of the Autonomous CustomCornea program. Initial clinical trials of wavefront-guided laser vision correction are underway.[11]

**Tsherning Aberrometer (Maik Kaemmerer, PhD)**

Studies performed over the last few years show that the Tsherning aberrometer is appropriate for routine clinical investigations on optical aberrations of the human eye. In the case of optically central opacities or large higher order ocular aberrations, which cause crossing over effects in the retinal image, it is difficult, and in some cases impossible to perform a correct measurement. This is a general problem of all ray tracing-based methods and is an object of further investigation. In a population of normal eyes undergoing analyses with the Tsherning device, a wide range of individual aberrations are observed (indicating that some individuals have bad optics). When considering the mean value, each aberration is very close to zero, with only a small amount of vertical coma and positive spherical aberration being prseent (overall good optics). This new device will be used in attempts to improve the aberrations associated with refractive surgery by performing wavefront-guided treatments based on the aberration measurements.[11]

**Tracey Aberrometer (Ioannis Pallikaris, MD)**

The Tracey Technology wavefront device provides information on the refraction distribution at the first principal plane of the ocular optical system. For the instrument to provide measurements that are directly applicable to clinical practice, the data can be transposed to the corneal plane. The Tracey device can be utilized for the measurement of accommodative amplitude and range.[12]

**Spatially Resolved Refractometer (Keith Thompson, MD)**

Using the spatially resolved refractometer, we have been able to directly measure all the major aberrations of the eye at the fovea, that is, the monochromatic wavefront aberrations, as well as both the longitudinal and transverse chromatic aberrations. Initial clinical work indicates that the technique can be readily performed.[7]

## METHODS OF CORRECTION

**CustomCornea Technology with the LADARVision System (Ronald Krueger, MD, MSE)**

The LADARVision treatment device employs a high-performance eye tracking system, a small-diameter excimer laser beam, and computer software capable of effecting complex customized corneal reshaping. Autonomous Technologies has coined the term “CustomCornea” to describe the combination of wavefront sensing of visual aberrations and LADARVision correction of these measured aberrations. The technology requirements for “CustomCornea” correction are: 1) a small spot scanning laser, 2) a fast eye tracking system, 3) an accurate and reproducible wavefront device, and 4) a wavefront laser interface, all of which are thoroughly represented by the Autonomous Technology platform.[14]

**Aberrometer Link-up with the Wavelight Laser (Theo Seiler, MD, PhD)**

The Wavelight laser treatment device is a scanning spot excimer laser with a small-diameter laser beam and an effective tracking system. The ablation pattern is derived from the reconstructed wavefront aberration map. In addition, the ablation profile includes correction factors that consider changes in the ablation rate due to laser tissue interaction, corneal curvature, and wound healing.[15]

### Retinal Imaging and Adaptive Optics (Austin Roorda, PhD—Founder's Award for Best Paper)

Retinal images in the human eye are normally degraded because we are forced to use the optical system of the human eye—fraught with aberrations—as the objective lens. The recent application of adaptive optics technology to measure and compensate for these aberrations has produced retinal images in human eyes with unprecedented resolution. The adaptive optics ophthalmoscope is used to take pictures of photoreceptors and capillaries and to study spectral and angular tuning properties of individual photoreceptors.[16]

Direct imaging is not the only use for adaptive optics. Since light can be imaged with high resolution, it follows that light can be delivered to the retina with the same precision. This opens a number of possibilities ranging from studying the perception of aberration-free retinal images to realizing the potential for pinpoint laser treatment of the retina. Using adaptive optics, aberration-free images can be projected on the retina. These methods are already being used to test the potential benefits of aberration-reducing refractive surgical techniques.[16]

### Preoperative Simulation of Outcomes Using Adaptive Optics (Josef Bille, PhD)

Recently, the application of wavefront sensing for preoperative evaluation of refractive surgical procedures has been proposed. Adaptive optical closed loop systems can be used to measure objectively higher order optical aberrations of the human eye. The patient can then be shown the resulting correction and be asked to adjust it to their preference. The final result of this process can be useful as a simulation of potential correction, and for planning the surgical procedure.[17]

Simulations are based on the application of multi-micromirror integrated active mirror matrices. Their application can also reliably simulate the diffraction limited performance of human eyes preoperatively, enabling the surgeon to test subjectively the influence of higher order optical aberrations on the visual performance of human eyes.[17]

## MODELING, OUTCOMES, AND THE FUTURE

### Modeling and Predicting Visual Outcomes With VOL-3D (Edwin Sarver, PhD)

The overall goal of the Visual Optics Lab - 3D (VOL-3D) project is to develop for clinical and research use, a user-friendly software program that models and evaluates the optics of a real and/or user-defined eye and stores the analysis in a relational database. The benefits of obtaining these

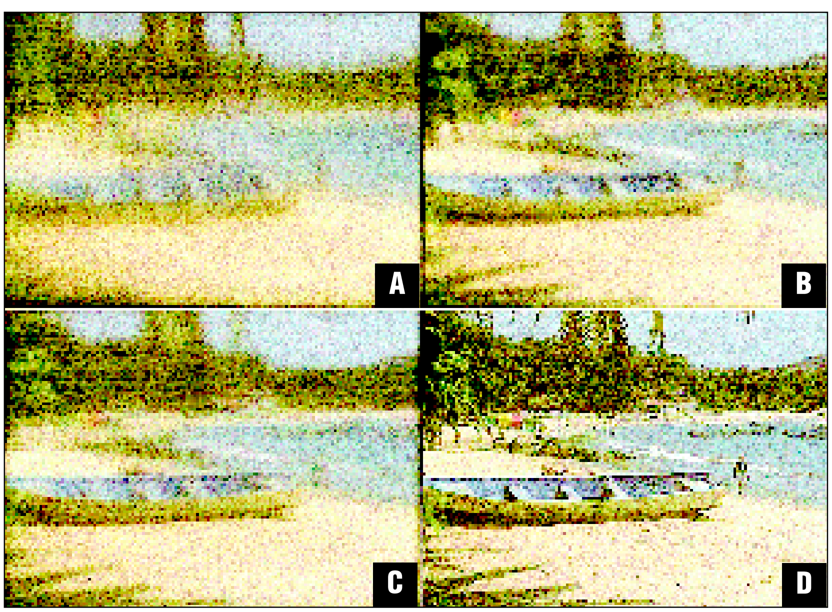


**Figure 3.** Retinal image simulation for **A)** uncorrected eye model, and spectacle lens corrected eye models with **B)** spherocylindrical back surface, **C)** spherical back surface, and **D)** b-spline back surface.

goals include designing new optical corrections, selecting the best available correction to meet a particular patient's needs, and demonstrating to the patient likely outcomes of various interventions (Fig 3).[18]

### Autonomous CustomCornea LASIK Outcomes (Marguerite McDonald, MD)

The US Food and Drug Administration (FDA) trial included 20 patients who underwent bilateral laser in situ keratomileusis (LASIK) and 20 patients who underwent bilateral photorefractive keratectomy (PRK). One eye was randomly selected for CustomCornea (Summit-Autonomous Technologies, Orlando, FL) and the other eye was selected for treatment with conventional LADARVision (Summit-Autonomous Technologies, Orlando, FL) surgery. Myopic, hyperopic, and astigmatic corrections have all been included. The average higher order root mean square (rms) error for the CustomCornea eyes was 0.28 µm, and 0.35 µm for the conventional LADARVision eyes. No eye lost more than one line of best-corrected visual acuity in either group.[19]

### Wavelight LASIK Outcomes (Theo Seiler, MD, PhD)

Visual acuity can be increased by operative improvement of the optical quality of the retinal image. At this point, however, it is not clear whether supernormal best-corrected visual acuity of approximately 2.0 (20/10), which was seen in 20% of eyes at 1 month, represents the real upper limit of visual acuity or whether we could not obtain better visual acuity because the correction of the wavefront error was incomplete. Even in patients whose best-corrected visual acuity improved, we achieved only up to 40% reduction of the wavefront errors in the best cases. Overall, the reduction of aberrations was significantly correlated with the increase in visual acuity, indicating that in many eyes, visual acuity is limited by higher order errors of the human optical system. The mean change after wavefront-guided correction was a 40% increase in wavefront error, which although disappointing at first glance, is promising when compared with the more then tenfold increase after standard excimer laser surgery.[15]

### Future Challenges to Aberration-free Ablative Correction (Cynthia Roberts, PhD)

The "shape-subtraction" model of refractive surgery does not predict all the corneal shape changes that occur after laser refractive surgery. Therefore, wavefront analysis cannot fully predict visual outcomes. A missing piece of the puzzle of corneal response is the biomechanical effect on visual outcome. What is the solution in order to produce an aberration-free outcome, or at least minimized aberrations? First, the biomechanical corneal response to laser refractive surgery should be characterized, in parallel to developing wavefront technology. Corneal topography offers a mechanism to measure the actual shape changes produced. With knowledge of the ablation algorithms, the biomechanical response can be separated from the change in shape produced by the ablation profile. Topographic changes can also be linked to the measured wavefront to more fully characterize both the corneal shape and the functional response. Ideally, the ultimate customized, "guided" procedure will use a combination of wavefront and corneal topographic analyses to provide a complete picture of corneal response and individual outcome. Predicting this complete response on an individual basis is one of the major challenges to the future of customized, aberration-reducing ablative procedures.[20]

## SUMMARY

As we review the many new and evolving techniques for treating patients with customized ablation, it is obvious that there is a rapid evolution of technology and thought. Newly refined diagnostic technology, such as wavefront sensing, and more sophisticated spot laser delivery systems with eye tracking gives the refractive surgical team greater flexibility in tackling challenging optical abnormalities. These highlights of the 2000 Congress now set the stage for further development, outlined in the following selected papers from the 2001 Congress.

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