

Optical aberrations and the eye – Part 3

In the final part of our series, **Alejandro Cerviño** and **Dr Shehzad Naroo** discuss the methods of correction required for low and high order wavefront aberrations

THE WAVEFRONT IS DEFINED as the encircling surface where a wave reaches in a particular moment during its propagation. A ray is an imaginary line perpendicular to the wavefront.

Every alteration in the wavefront will cause the propagation to be less than ideal, and is called wavefront aberration. In other words, the variation on refractive power over different areas at the eye's entrance could be called wavefront aberration.

This wavefront can be described as a series of polynomials, called Zernike polynomials, which are normalised within an unitary circle (and are recommended by the Optical Society of America as the standard method for specifying the eye's wavefront).¹

The ametropias of the human eye are wavefront aberrations affecting the visual system, and even normal eyes have variations in the distribution of the optical power within the pupillary area, not affecting much of the patient's vision in most of the cases.

They can be divided into two groups: the low order wavefront aberrations, which are the common spherocylindrical ametropias and can be corrected with spectacles, and the high order wavefront aberrations, 'micro-aberrations' which have more to do with the detail on the image, and which cannot be corrected with traditional methods (Figure 1). These topics are discussed in detail in Part 1 of this series (OPTICIAN, April 25).

MEASURING ABERRATIONS

Originally, the correction of wavefront aberration produced by the optical



FIGURE 1. Simulation of the Snellen's E, as seen by an eye with low order aberrations corrected (myopia and astigmatism) and with mild higher order wavefront aberrations, mainly coma, (left), and after the coma was removed (right). The simulation of the Snellen E was provided by the WASCA(r) device (Wavefront Sciences Inc), a Hartmann-Shack based wavefront analyser

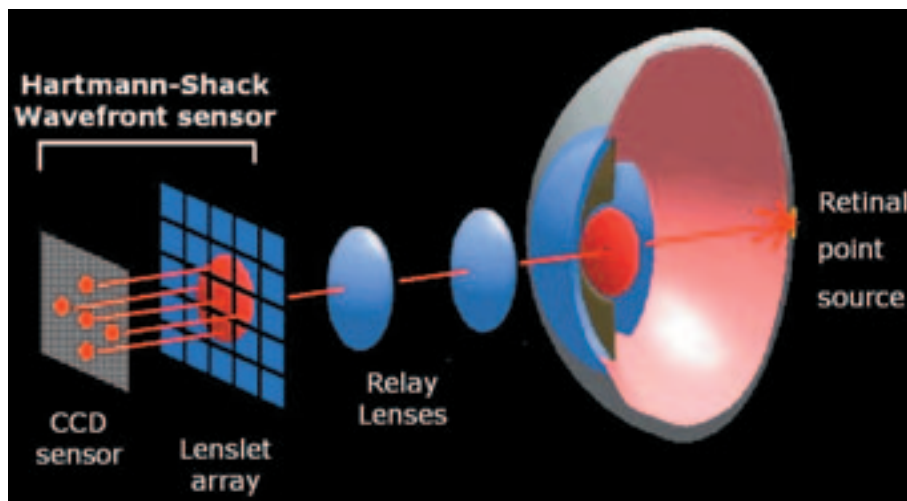


FIGURE 2. Schematic diagram of the behaviour of the Hartmann-Shack principle-based wavefront analysis systems (courtesy of Bausch & Lomb)

systems, known as 'adaptive optics', was developed in the field of astronomy, to compensate for atmospheric turbulence and to improve the imaging of bodies in outer space.

Adapting this technology, the correction of wavefront aberrations is now being applied to the eye.

The Tscherning-based instruments, such as the Allegretto (Wavelight Laser Technologies AG, Erlangen, Germany), Hartmann-Shack technology, as used by the Zywave (Bausch & Lomb, Rochester, New Jersey); the ray tracing with a scanning laser beam, as used by the Tracey (Tracey Technologies, Houston, Texas); or the skiascopy principle-based OPD/ARK-1000 (Nidek, Gamagori, Japan) are the current commercially available technologies used to measure the total wavefront

aberrations of the eye and, eventually, to aid a customised ablation.

They all analyse the behaviour of the light when passing through the optical system of the eye, but each of these technologies uses a different method of collecting data.

TSCHERNING PRINCIPLE-BASED

This apparatus uses an entire grid of laser spots. The image formed in the retina is captured and defined through a very small aperture, and it will be more or less deformed depending on the aberrations produced by the examined eye. The spot deviation is measured and processed to give the wavefront aberrations.

HARTMANN-SHACK PRINCIPLEBASED

This is the most popular technology for wavefront analysis. If a wavefront is divided spatially, then each one of those subdivisions can be approximated to a tilted perfect flat wave.

The reconstruction of the tilts of every division will result in an approximation to the original wavefront. That is the principle on which the Hartmann-Shack-based wavefront analysers rely.

The sensor consists on a lenslet array (like a compound insect eye) for wavefront decomposition and focusing of the

outgoing wavefront from each subaperture, and a detector (Figure 2).

RAY TRACING

This technique also uses a laser beam to measure the aberrations of the eye. This laser beam is projected on to the retina, parallel to the visual axis, at several points.

In a different way to the Tscherning devices, a laser beam is projected each time, making a rapid scan over several points, which give their corresponding projection (Figure 2). With the data obtained, a complete pattern is produced in just milliseconds. The system then generates maps showing the behaviour of the visual system.

These systems have shown a high reproducibility,² and have the advantage of measuring relatively high aberrations, as the sequential projection of the laser beam avoids the possibility of overlapping.

SKIASCOPY PRINCIPLE-BASED

These technologies use dynamic skiascopy, similar to that used by standard auto-refractors. An infrared slit scans through the pupil measuring the refractive power of the eye, generating auto-refraction data, as well as calculating wavefront aberration from the difference of refractive power between areas within the pupillary region. The main advantage of these

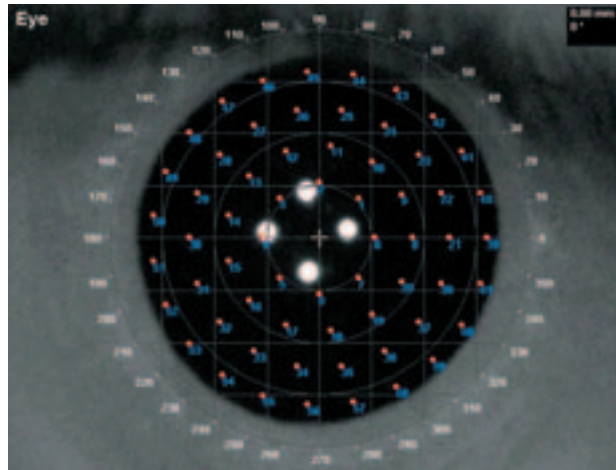


FIGURE 3. Image showing the point of entrance of the different laser beams in the Tracey System (Tracey Tec, Houston TX), as well as the order in which they are shot

systems is the large number of points measured.

The rapid development in the analysis of wavefront aberration can lead one to think that corneal topography analysis will become obsolete, but such a thing cannot happen as both measurements are strongly linked.

Knowledge of the corneal topographical profile is needed to alter the power of the anterior surface, and to differentiate an increased wavefront aberration produced by the anterior surface of the cornea (as the eye's main refractive element) from those produced in the other lenses of the visual system. Also, as stated by Klyce,³ at the present time, the spatial resolution of wave-

sensing technology is not capable of detecting the details of irregular corneal astigmatism.

CORNEAL ABERROMETRY

From topography analysis, a reference surface of known optical behaviour can be established so that the corneal topography can be expressed as elevation from that reference. This gives information, not just about how different the corneal surface is from that surface of known shape, but also about the behaviour of that surface when the light comes through.

Also, there are some software applica-

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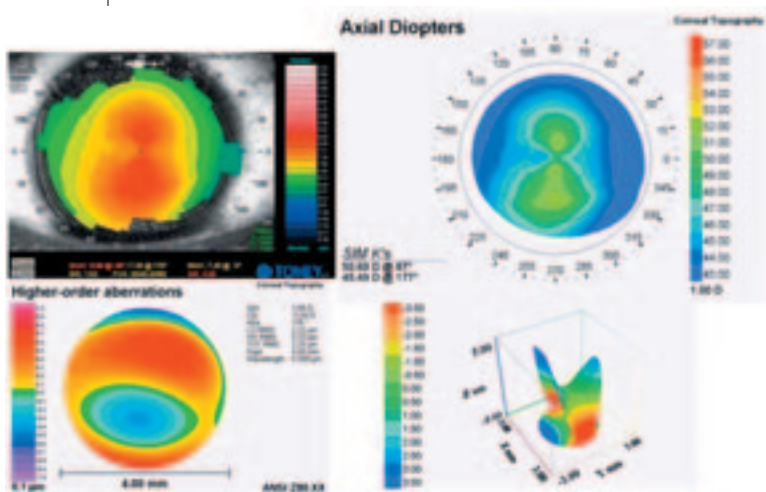


FIGURE 4. Image showing the original topographic axial map from the Tomey TMS (v.2.1) videokeratoscope (upper left) and the axial map (upper right), higher-order aberrations map (lower left) and the 3D representation of its Wavefront Error, WFE, (lower right), offered by the CTView software (v.5.0)

tions commercially available which allow the practitioner to obtain wavefront analysis from previously obtained topography exams. That is the case with the CTView (Sarver and Associates, Florida), which offers graphical displays for colour maps, spot diagrams, PSF, MTF, WFE and so on from the topographies obtained from a series of topography instruments (Alcon EyeMap, CSO, EyeSys, Humphrey, Keratron, Medmont, Nidek OPD, Orbscan and Tomey), supporting also the wavefront data obtained with the Nidek OPD, Tracey, WASCA and Zywave wavefront analysers (Figure 4).

It has been recently reported that the clinical repeatability of the videokeratoscope is enough to get reliable wavefront error in measurements at a single session, but may require several examinations and/or repeated independent measurements at the same examination to determine reliably some Zernike coefficients. This has significant practical implications for accurate customised correction of aberrations.⁴

RMS, PSF AND MTF – WHAT THESE ACRONYMS MEAN

The root mean square error (RMS) is used to describe two different concepts. The first quantifies errors in the wavefront reconstruction. The second relates to how the reconstructed wavefront differs from a perfect wave. In other words, the RMS provides a general estimate of the variation of the wavefront from the ideal.

The point spread function (PSF) represents the degradation suffered by the stimulus when it reaches the image plane as a consequence of the wavefront aberrations of the system. In other words, it represents how the image of a point source would be changed after going

through that optical system. There is usually an application available in clinical wavefront devices offering a representation of the retinal image of a point, given by the PSF (Figure 5).

The modulation transfer function (MTF) is defined as the modulation of the image divided by the modulation of the stimulus (Figure 6).

In a square wave grating there are dark bars and light bars. We can measure the amount of light coming from each. The maximum amount of light will

come from the light and the minimum from the dark bars. If the light is measured in terms of luminance (*L*) we can define modulation according to the following equation:

$$\text{Modulation} = (L_{\text{max}} - L_{\text{min}}) / (L_{\text{max}} + L_{\text{min}})$$

where *L*_{max} is the maximum luminance of the grating and *L*_{min} is the minimum.

When modulation is defined in terms of light it is frequently referred to as a Michelson contrast. Indeed, when one takes the ratio of the illumination from the light and dark bars one is measuring contrast. So, from this, we can say that the MTF represents the change in contrast from the stimulus to the final image.

CLINICAL APPLICATIONS

The clinical applications of wavefront aberration analysis can be grouped into two wide fields:

- ◆ The imaging of the internal eye structures
- ◆ The analysis and correction of the visual performance.

The difference lies in the direction of the light analysed. For the second group, the direction has to be reversed, so that the object plane is on the retina, and the light analysed comes out from the eye.

IMAGING OF THE INTERNAL STRUCTURES OF THE EYE

This first group comprises all the optical improvement in terms of lens design and system filtering, computing and so on, in order to get better resolution when observing the inner structures of the eye. In other words, it is the direct application of adaptative optics to the eye.

Once the low and high order aberrations are measured, the next step is to compensate for them in order to get the best image possible.

Wavefront analysis systems have a very important role, as they will give information about the changes needed to make the observation system perfect for imaging of an individual eye. In fact, Barry Thibos *et al.*⁵ have described the Hartmann-Shack aberrometer essentially as a modified fundus camera which takes multiple pictures of a single spot of light on the retina. This description can be extended in some ways to all clinical wavefront analysers.

The improvement of systems for imaging the internal structures of the eye has a direct and very important clinical relevance in the early detection of pathological and progressive conditions. Changes such as oedema in the optic nerve head, or retinal spots in diabetic retinopathy could be detected earlier, so that the patients may have a better prognosis.

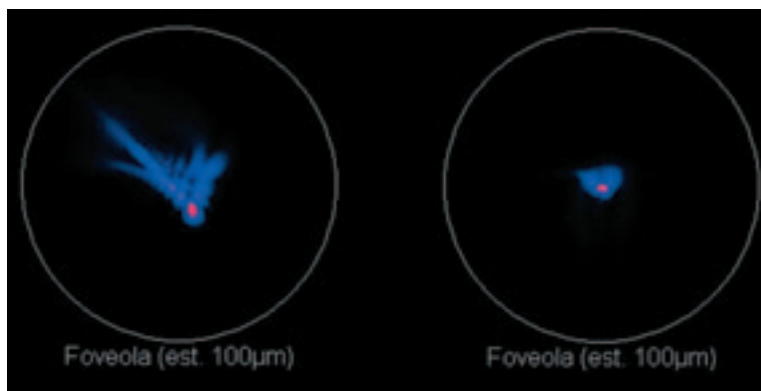
ANALYSIS AND CORRECTION OF THE VISUAL PERFORMANCE

This second group comprises all the techniques developed to study and improve the visual performance of the human eye. This may influence several clinical areas.

Refractive surgery

In fact, the preoperative wavefront

FIGURE 5. Representation of the retinal image of a point on the retina of an eye suffering from higher-order aberrations, mainly coma (left), and the improvement with the correction of the primary coma aberrations (right), Images obtained using the Zywave (B&L, Rochester NY)



aberrometry examination should help to decide whether a traditional refractive surgery procedure would solve the visual problems of the patient, or if an ablation profile customised by the wavefront aberrations is indicated. Traditional refractive surgery corrects the main components of the wavefront aberrations (defocus and astigmatism) but it has been widely recognised by several investigators as resulting in an increase in the third order aberrations,^{6,7} which do not usually affect the optical performance of the eye substantially.

These aberrations can leave a healthy eye which has been treated by traditional surgery with success (so no residual myopia, hyperopia or astigmatism is left), unable to perform as well as expected, especially with low contrast targets or in a scotopic environment.⁷⁻⁹

However, it has been reported that the change is small and within the normal range of contrast sensitivity.¹⁰ Also, it is critical to be able to quantify these aberrations in patients with irregular astigmatism due to keratoplasty, topographically asymmetrical astigmatism, congenital corneal irregularities and so on.

In irregular corneas, or irregularities in internal lenses (posterior corneal surface and crystalline lens), traditional refractive surgery does not solve the visual problem, or at least not completely, and most of the times the surgery itself is contra-indicated.

Currently, the customised corneal ablation is becoming popular, being applied not just to specific cases of irregularities in the visual system, but also in the traditional refractive surgery candidate, giving results that in most of cases leave better acuities than 1.0 (6/6).¹¹

In recent years, an increase in devices used to quantify wavefront aberrations has occurred, and a more in depth study of the ablation itself is beginning to be developed for each patient, due to the previously reported relation between the corneal parameters, the total wavefront aberrations of the eye, the ablation size and depth, and the possible complications^{12,13} prior to surgery.

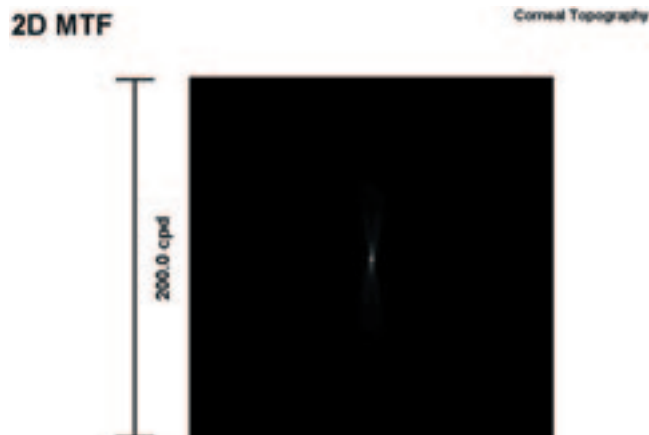
Furthermore, an evaluation of the post-operative corneal aberration can be performed, so, in case an enhancement is needed, the correction over the first ablation can be customised to make the best compensation of the total aberration of the eye and get an optically close-to-perfect ocular system¹². Complete compensation is not possible, however, as the aberrations are not constant but vary with accommodation, age, tear film and so on.

Contact lens practice

The use of contact lenses for correcting wavefront aberrations of the eye is a developing area of research.

The wavefront aberrations produced

FIGURE 6. Image showing the bidimensional representation of the MTF corresponding to the topography map shown in Figure 4. The representation was obtained through CTView



by contact lenses seem to be relatively predictable, depending on the material and parameters of the contact lens.^{14,15} Vision has shown improvement when the lens design is modified according to the wavefront aberration (especially spherical aberration).

Nevertheless, the rotation of the lens on the eye reduces the possibility of aberration correction.¹⁶ As the contact lens seeks to correct the lower and higher order aberration, the translational and rotational movement of the lens should be more accurate and predictable.

As it is widely known, contact lenses have several advantages over surgery, mainly based on reversibility. Also, the possibility of compensating wavefront aberrations of the eye with contact lenses benefits from adjustments in their parameters when the desired performance is not achieved by the patient because of changes in the aberrations of the eye (effect of ageing,¹⁷ surgeries, trauma and so on), so the optical performance can be maintained. Also, in cases where refractive surgery is contra-indicated, the contact lens is the only solution and great aberrations may be compensated.

Ocular pathology

Besides all the benefits that adaptive optics in imaging systems would give in retinal pathology detection, wavefront analysis may help in other diagnosis and evaluation of some ocular anomalies.

There are many pathologies which produce a change in wavefront aberrations of the eye. Anterior pole pathologies, such as those which occur with morphometrical alterations of the cornea (keratoconus, marginal degeneration, or ectasias in general) produce a noticeable increase in the third order wavefront aberrations, and result in irregular astigmatism that cannot be corrected with spectacles.

Also, pathologies affecting the inner lenses of the eye produce these increases in wavefront aberrations. It has been stated that cataracts increase the wavefront aberration co-efficients, but the polarity

has been shown to be negative in nuclear cataract and positive in cortical cataract.^{18,19}

Wavefront aberration analysis systems may also help in other conditions affecting the most anterior optical element of the eye, namely the tear film. It is known that the tear film has an important role in the smoothing of the optical quality of the anterior cornea, so it is easy to understand that alterations in the tear film will affect wavefront integrity.

Thibos *et al* demonstrated that the good state of the tear film has great importance when trying to image the inner structures of the eye,⁵ and it has been also referred as a possible application of the Hartmann-Shack aberrometers as an aid for evaluating ocular dryness (Figure 7).²⁰

Right now, there are studies going on trying to determine what is the contribution of the tear film to minimise those aberrations.

IOL lens selection

It has been recently demonstrated that the implantation of an intraocular lens (IOL) can produce more wavefront aberrations than Lasik, increasing mainly the spherical aberration.²¹ IOL design has experienced many improvements in the last few years, making possible an accommodative IOL, and improving the optical performance. By designing a more prolate anterior surface, spherical aberration is significantly reduced.²²

The refractive surgery technique known as 'bioptics', could soon be a beneficiary of the advance in wavefront technology. It can be expected that, with the increasing development of wavefront analysis systems and lasers, in patients with high ametropias, an intraocular lens can be inserted to correct the largest part of the ametropia leaving the reshaping of the cornea for a later adjustment and total wavefront aberrations correction.

This would increase the chances of a better-than-6/6 vision in patients over 10D without the need for deep ablation (which would require really thick original corneas

and involves more risks) and the possibility of performing an easier and quicker customised ablation that would be really hard to achieve if full correction is performed over the cornea.

WHAT IS NEXT?

With the technology available at this time, an in-depth knowledge of the corneal morphometry can be achieved for various applications: refractive surgery, contact lens fitting, orthokeratology, IOL and so on, but wavefront technology will be able to provide information of every change to the optical properties of the ocular system.

Customised refractive surgery for monovision, where the distance eye is corrected for the wavefront aberrations in distance, and the eye for near is corrected for its aberrations in close vision, or monovision with contact lenses, or aberration free accommodative IOL lenses and so on may all be achievable.

In the field of ocular imaging, systems which include real time wavefront analysis and adaptive optics will be available for ophthalmoscopes, retinographs, and any other system for internal imaging, providing a wonderful tool for the early diagnosis of retinal pathology.

At the current rate of development, it is to be expected that corneal wavefront sensing systems will allow a point by point analysis of the wavefront aberrations of the eye, getting information of the optical behaviour of the eye over as many points as corneal topographers do.

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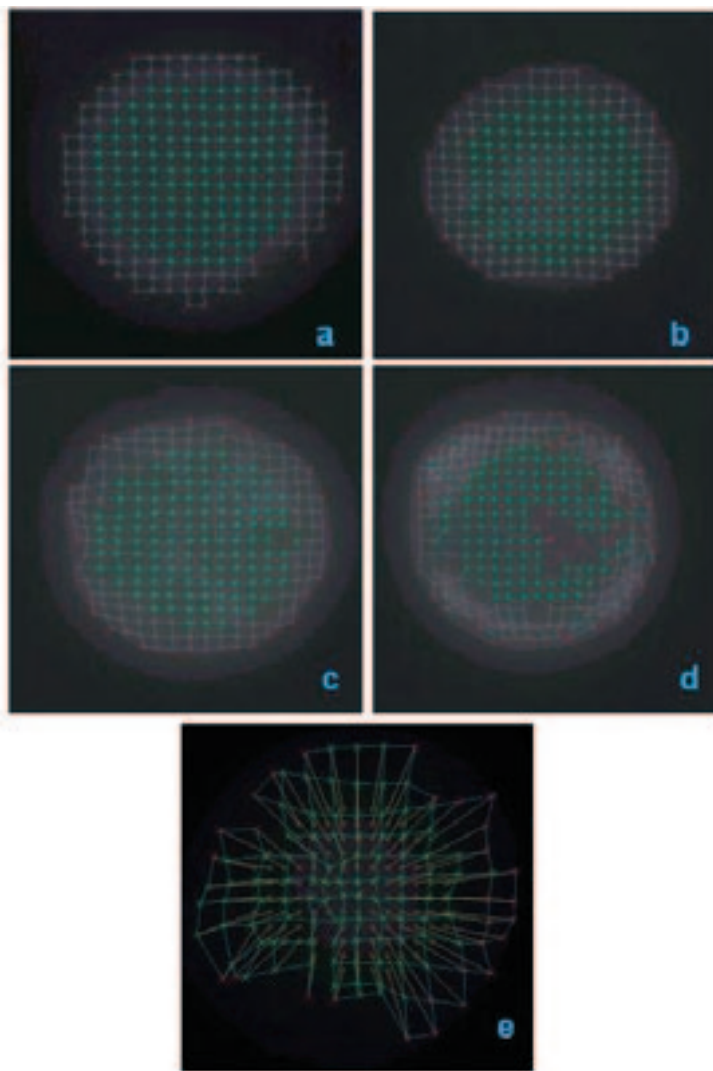


FIGURE 7. Suggested standards for SH aberrometry patterns in dryness evaluation: (a) Grade 0: Flat grid, parallel lines, without distortion; (b) Grade 1: Trace distortion of the lines, trace peripheral 'curvature effect'; (c) Grade 2: More evident distortion and 'curvature effect', 1-2 blank spots, or grid 'breaks'; (d) Grade 3: Severe distortion and 'curvature effect', more blank spots; Grade 4: The grid is highly distorted

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