Very little attention was paid to the optical properties of the eye prior to the advent of wavefront guided laser vision correction. It is well known that the normal human eye suffers from many aberrations, which cause degradation of visual quality. Visual acuity is limited by diffraction, aberrations and photoreceptor density. Apart from these limitations, a number of factors also affect visual acuity such as refractive error, illumination, contrast and the location of the retina being stimulated.

Why are aberrations important?

For a long time clinicians have been searching for an answer as to why some patients with 20/20 Snellen corrected visual acuity were still unhappy? The answer to this lies in a cogent understanding of ocular wave front technology.

Aberrations generated by the eye can be divided into monochromatic and chromatic aberrations. Chromatic aberrations (dispersion) are traditionally divided into longitudinal and transverse. Chromatic aberrations limit retinal image quality because the real world is polychromatic.

Monochromatic aberrations are of two basic types of aberrations. Lower order and higher order aberrations. Zernike expansion of aberrations (Explained later in the article), are addressed as lower-order aberrations, with the Zernike radial order \( n < 3 \), and higher-order aberrations, with \( n \geq 3 \). This concept of division into lower and higher order is important for the ophthalmologist to understand as the lower-order aberrations (2nd order aberrations, defocus and primary astigmatism) significantly contribute to the total aberrations of the eye (remaining lower-order forms, piston and tilt, are usually ignored) and can be easily be corrected with glasses or contact lenses. Uncorrected higher order aberrations (HOA) can be the cause of many
symptoms such as double vision, halos, lack of contrast and even compromised far and near vision. The correction of higher order aberrations is believed to result in the so-called “super vision”, which has sparked the recent interest in wavefront-guided surgery (Figure 1).

The understanding of aberrations is important especially in refractive surgery. In wavefront guided LASIK the wavefront analysis is coupled with an excimer laser machine and excimer laser delivery is in accordance with the patients’ wavefront profile. In an optical system completely corrected using wavefront-guided treatment, image quality is only dependent on diffraction and scattering.

This article aims to review the basics of optical principles of aberrations.

What are aberrations?

In simplified terms aberrations can be defined as imperfections in the human optical system. The ideal definition of optical aberration is the deviation of the wavefront that originates from the measured optical system from reference wavefront that comes from an ideal optic system².

These aberrations may originate from any part of the human optical system starting from the tear film, the cornea, pupil, lens and even imperfections of the retina. (Figure 2). The cornea is the main source of ocular aberrations as it dominates the optical power of the eye. The pupil determines the amount of light entering the eye. Accommodation produced by the crystalline lens also significantly contributes to aberrations.

The normal human eye is aberrations are minimum at a pupil diameter of 2.5mm, as at this size diffraction of light at the pupillary margin is the only thing that governs image production on the retina. However as pupil size increases image quality decreases due to increase in aberration.

What do all these terms mean?

Visual quality is measured using certain technical terms. The following explanation provides a simplified overview to have a better understanding of these terms.

Point Spread Function (PSF)

When a point of light passes through an aberrated optical system it causes the beam to spread producing a blur from a point. In such a way, each aberration causes the point of light to take on a characteristic appearance when it hits the retina. The PSF of an aberration gives us an idea of what patients actually see.

Technically it is the image that an optical system forms of a point source of light. The PSF for a perfect optical system is an Airy disc, which is the Fraunhofer diffraction pattern for a circular pupil. The PSF is limited by diffraction and optical aberrations. If the pupil size increases, diffraction decreases but the aberrations will increase (Figure 3).

PSF and pupil size

Pupil size is extremely important when analyzing any wavefront data. The pupil size must be the same before any comparison between different maps is performed³.

Effects of pupil size

1. There is an increase in blur if either the refractive error (LOAs) or pupil size is increased (both are independent of each other, Figure 4).
2. Pupil size and HOAs are closely related to the depth of focus. Decrease in pupil size increases the depth of focus but the decrease in pupil size in turn causes a reduction in the available light which reduces visual quality and also amplifies the adverse effects of diffraction. It has also been seen that increasing certain higher order aberrations such as spherical aberration increases the depth of focus but again decrease visual quality.

The magnitude of HOAs that will allow an acceptable visual quality and the depth of focus while considering the influence of the pupil size have not been determined and may vary between subjects.

**Strehl Ratio**

Strehl ratio is defined by the ratio between the actual measured PSF peak height and the PSF peak height of a perfect optical system.
diffraction-limited optical system (minimal aberrations). It ranges from 0 to 1, where 1 is equal to a diffraction-limited system. The ratio usually decreases as pupil size increases.

Modulation Transfer Function (MTF)

MTF is a function that allows for the assessment of the degree of detail the human optical system is able to distinguish. When the quality of an optical system is degraded it is seen that higher spatial frequencies representing finer details are the first to be affected. MTF measures the contrast loss with increasing spatial frequency when transferring an object to an image through an aberrated optical system.

In other words, it evaluates the correlation between contrast in the image formed by the optical system being measured and the original contrast of the scene being observed. The contrast reduction is greater for high spatial frequencies (fine details and image contours). If the image contrast is the same as the object contrast, the MTF is highest i.e. 1.

When the spatial frequency increases, the MTF decreases because the image contrast is lower than in the object (Figure 5).

How can we measure these aberrations?

The purpose of wavefront analyses of the eye is to evaluate the optical quality of the eye by measuring the shape of its wavefront. For this, an aberrometer or wavefront sensor is used. All commercial available aberrometers work on similar principle by passing two or more parallel beams of light through the eye. A method is used to measure the extent to which those beams cease to travel in a visually optimal trajectory. Complex mathematical formulas then predict aberrations based on the altered angle of those beams.

Original aberrometers were based on the Hartmann Shack principle. It is a technique developed by Johannes Hartmann in 1900 and modified by Shack and Platt in the late 1960s. Numerous other methodologies and applications have since arisen. The first measurements of HOAs were conducted by Smirov using a psychophysical method, in 1961.

All aberrometers have three basic components.

1. An input light source (usually an infrared laser) that throws light onto the retina.
2. An emerging wavefront represents the optical properties of the eye.
3. The wavefront passes through a lenslet array made up of 200 – 1400 lenses depending on the instruments design. The light passing through individual lenslet is then focused on a charged coupled device (CCD) array, which is recorded by a computer.

Aberrometers are classified into three types (Figure 6). The first type is the outgoing wavefront aberrometer as in the Hartmann-Shack sensor, the second type is the ingoing

Figure 6: Classification of various aberrometry principles.

Figure 7: Principle of Hartmann Shack aberrometry.
retinal imaging aberrometer i.e. Tscherningaberrometer\textsuperscript{4} and the sequential retinal ray tracing method\textsuperscript{10}. The third type is the ingoing feed-back aberrometer as used in the spatially resolved refractometer\textsuperscript{12} and the optical path difference method\textsuperscript{13}. We shall deal with each of these in further detail.

**Hartmann Shack aberrometry**

**Principle**

A Hartmann-Shack device uses a narrow laser beam that is sent along the ocular line of sight into the eye, where it reflects from the retina. This reflection serves as a secondary source that illuminates the pupillary area from behind. When a plane or spherical wavefront is projected into a perfect optical system free of aberrations the returning wave should be aberration free i.e. plane or spherical. However if the system has optical aberrations the returning wavefront will reflect the aberrations of the system.

The outgoing light is then guided through a set of relay lenses that projects the pupil plane onto an array of tiny lenses that splits up the wavefront into a number of individually focused spots on a charged coupled device camera. Because of focal shift, the resulting spot pattern (figure inset) shows spot displacements compared with the reference positions. This way, the wavefront slopes are determined for the entire pupil at once\textsuperscript{14} (Figure 7).

**Machines using Hartmann Shack aberrometry (Figure 8)**

1. Zywave
2. iDesign
3. IRX3

The Zwave II aberrometer (Bausch and Lomb, Inc.) is part of the Zyoptix diagnostic workstation. It gives us the raw image, 2D analysis of the wavefront, variation of refractive power over varying pupillary diameters, higher order point spread function, 3D wavefront maps, Zernike amplitudes and summary with refraction. It provides total wavefront analysis up to the 5th order. Assists in establishing a refractive treatment plan to correct an individual’s particular aberration.

The iDesign is a part of the AMO wavescan studio. It uses a high definition Hartmann Shack sensor and analyzes 1250 data points. This data is fed to the STAR S4 IR Excimer laser before treatment. The iDesign display includes overview with eye image, corneal topography, and a Hartmann Shack image, a custom view with corneal wavefront map, axial power map, elevation map and the eye image, the Zernike coefficient display a wavefront map of total and higher order aberrations, the point spread function, and an eye image for the limbus to limbus diameter (Figure 8).

**Limitation**

1. Measurement of highly aberrated eyes and small pupil sizes is difficult. As the pupil gets smaller, the number of points diminishes because of the fixed lenslet array density.
2. However fast and uncomplicated (because no moving parts are required), the performance of this parallel method is limited to aberrations that are not too complicated. To determine the focal shift directly, each reference position is allocated a neighborhood in which the shifted spots are directly associated with a specific reference position (square grid in figure inset). For rapidly varying wavefronts with steep
slopes, this can result in focal shifts becoming so large that spots cross over to neighborhoods belonging to another reference position. This makes it impossible to determine the focal shift in these areas. Crossover can be partially prevented by using prefocus lenses that correct the ocular refraction.14

**Tscherning Aberrometry**

**Principle**

Contrary to the Hartmann-Shack method, the Tscherning aberrometer uses not 1 but a group of laser beams that enter the eye. These beams are generated using a wide laser beam passing through a screen with a large number of round holes. The lens projects an image of the Tscherning screen onto the retina, resulting in a spot pattern resembling a Hartmann-Shack pattern, where again spots are displaced due to focal shift. The Tscherning method projects a fixed pattern of spots onto the retina. The retinal image is then retrieved using a beam splitter and a second lens. The distortion of the light spots in relation to the light reference bundle is calculated as the wavefront error. This is then viewed externally using a CCD camera. The advantage is that it avoids inaccurate results from media opacities, which can produce false positives with a Shack-Hartmann device.14 (Figure 9).

**Machine using the Tscherning Method**

The WaveLight Analyzer Diagnostic Device (Allegro) gives a wavefront map, sagittal and tangential power maps, and analysis of Zernike coefficients. It automatically detects keratometric values during surface ablation procedures (Figure 10).

**Limitations**

It has similar limitations to the Hartmann Shack method. As all the spots are observed simultaneously highly aberrated eyes cause confusion as to the origin of the observed spots.

**Differential Skiascopy**

**Principle**

It is an automated streak retinoscopy done at 360 meridians. It utilizes a principle of skiascopic phase difference for refractive measurements. One slit of light is projected onto the retina and another detects light reflected back. As these systems continuously rotate around an axis each scans a meridian of 1 degree.

It uses focal shift in a different way, starting from the observation that the retinal image of a light beam coming
from a superior direction is located below the optical axis in a myopic eye and above the optical axis in a hyperopic eye. Because the retina can be considered a spherically concave mirror (reflecting about 4% of the incident light), the beam is reflected back in more or less the original direction in a myopic eye. In a hyperopic eye, however, the reflection is directed to the opposite side of the pupil. Moving the incident beam along a certain pupillary meridian (indicated by arrows in the figure) will result in a reflected beam that goes in the same or the opposite direction as the incident beam. The difference in direction and the ratio between the speed of the incident beam and that of its reflection can then be used to estimate the ocular refraction along this meridian.

The retina is scanned with an IR beam, and the time difference of reflected light is captured by an array of rotating photo detectors over the 360° of the retina. Therefore light passing through a scanning slit is compared to the reference light from a diode array.

**Limitations**

The scan area is an annulus of 2mm x 6mm. Therefore this does not analyze the central area of the optical system. Also, because the system measures along meridians the detection of radially symmetric modes are problematic. Thus the system either under or over estimates common modes such as trefoil, tetrafoil and pentafoil.

**Ray Tracing aberrometry**

**Principle**

Ray tracing employed most widely by iTrace (Tracey technologies) uses sequential ray tracing as a mechanism to analyze the aberrations of an optical system. In this instrument a thin laser beam is projected through the entrance pupil at a very high speed following a concentric matrix (Figure 12).

Each beam produces a spot on the retina the location of which is monitored by semiconductor photo detectors. Once the position of one spot is determined the laser beam moves to determine the location of another spot on the retina. This process is done till 256 points have been projected through the entrance pupil.

In this way the error distance (x,y) of each point from the fovea is determined. This helps find the theoretical conjugate focal points for each spot, which in turn tells us the transverse aberration for that point at the entrance pupil.

**Machine using the Ray tracing Principle**

iTrace measures aberrations over the whole eye over a flexible measurement zone of 2-8mm. It also provides, multi-zone refraction analysis, for day to night vision
assessment, over refraction with spectacle or contact lens, and in addition to a complete topographic analysis also measures accommodative volume (Figure 13).

Advantages

It makes measurements in highly aberrated eyes with a dynamic range of +/- 15D. The diameter of the 256-beam matrix can be adjusted according to the pupil size. One can select an area of interest however one must remember each spot is not immune to blurring by microaberrations.

An interesting point to note is that the technology used by this machine was initially used by the Institute of Biomedical Engineering of Kiev (Ukraine) for missile and satellite tracking!

How do we describe these deviations? What are Zernike Polynomials?

A wave front is an imaginary surface joining all points in space that are reached at the same time by a light wave propagating through a medium. A deviation of the wavefront that originates from the optical system, from a reference wavefront that comes from an ideal optical system constitutes a wavefront aberration.

In order to make the understanding of this data easy, the wavefront error is broken down into data and can be analyzed by using certain numerical terms called Zernike polynomials.

In 1934, Fritz Zernike published a paper describing a set of polynomials that could be used to expand the aberration data. Each polynomial represents a particular mode of optical aberrations. Thus the entire wavefront can be described by coefficients, which when taken as a whole reconstructs the wavefront map, but individually describe the relevant amount of each aberration mode. Different modes allow us to visualize the primary types of aberrations, which contribute to the overall deviation.

The first to sixth orders Zernike polynomials are shown graphically in this figure. The zero order has one term. The first order has two terms that represent tilt for the x and y axes. The second order includes three terms that represent defocus and regular astigmatism in the two directions. The third order has four terms that represent coma and trefoil, and similarly, the fourth order has five terms that represent tetrafoil, secondary astigmatism and spherical aberration. (Figure 14).

The polynomials can be expanded up to any random order if a sufficient number of measurements are made for the calculations. The unit for wavefront aberrations is microns or fractions of wavelengths and is expressed as the root mean square or RMS. Monochromatic aberrations can be evaluated quantitatively using the Zernike coefficients for each term.

References


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