Optical Quality in the Era of Wavefront Sensing

Interpreting optical aberrations and their effect on visual performance.

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The introduction of wavefront-sensing techniques to ophthalmology has redefined the clinical meaning of refractive error. Now, all imperfections in the components and materials within the eye that cause light rays to deviate from their desired path are referred to as *optical aberrations*. Lower-order aberrations (defocus and astigmatism) account for 90% of overall wave aberrations in the eye. Currently, lower-order aberrations can be well corrected with spectacles, contact lenses, or excimer laser surgery. Although higher-order aberrations make a smaller contribution to the eye's total aberrations, their correction can improve visual performance substantially.

The purpose of this article is to review methods of measuring wave aberrations in the eye and to illustrate the objective metrics that describe both optical and image quality.

Aberrometers allow detailed measurements of the eye's overall wave aberrations, as well as accurate measurements of the distribution and contribution of each higher-order aberration. However, the former metrics used to describe these aberrations, chiefly the Zernike polynomials, do not suitably depict visual quality because they do not directly relate to retinal image quality. New objective optical quality metrics could improve our ability to interpret the eye's aberrations. There are a variety of approaches for the description of complex optical performance, including objective metrics that quantify the quality of the optical wavefront in the plane of the pupil (ie, pupil-plane metrics) and others that quantify the quality of the retinal image (ie, image-plane metrics). These metrics are derived from the wave aberration of the individual eye, as measured by corneal or ocular wavefront sensors.

METHODS AND SYSTEMS

The ability to measure monochromatic aberrations of the eye has allowed clinicians to accurately describe the optical quality and the image-forming properties of the eye.[1-3] One relatively new approach to defining and reporting optical aberrations[4,5] is by measuring and expressing optical imperfections as wave aberration errors. The wave aberration defines how the phase of light is affected as it passes through the eye's optical system and can be defined mathematically by a series of polynomials such as the Zernike polynomials.[4] Several new objective metrics, derived from wave aberrations, are routinely used to describe the optical quality of the eye,[6,7] including the image- and pupil-plane metrics.

The Hartmann-Shack method[8] is the most frequently employed wavefront-sensing for measuring the optical quality of the eye and has been used in several areas of clinical research. Additional objective methods for wavefront-aberration sensing include laser ray tracing,[9] Tscherning aberrometry,[10] and skiascopy.[11] Subjective or psychophysical techniques include cross-cylinder[12] and the spatial resolved refractometry techniques.[13,14]

Alternative wavefront-sensing techniques have been designed for specific use in ophthalmology, including the curvature sensor, the pyramidal sensor, and the Talbot sensor. The first two techniques are based on phase diversity and depend on comparisons between phases in adjacent areas in the image or objective plane of an optical system.[15-17] The Talbot effect is a self-imaging phenomenon.[18,19] We have recently outlined the advantages and disadvantages of the various methods and systems for sensing wavefront aberrations[20]—a subject that is beyond the scope of this article.

DESCRIPTORS OF OPTICAL QUALITY

Optical aberration measurements cannot be comparable unless they are calculated with respect to the same reference axis and expressed in the same manner. Two reports define the conventions and standards for reporting optical aberrations of human eyes,[4,5,21] the ANSI Z80.28-2004 and the more recent ISO 24157:2008. It is recommended that ophthalmologists use the line of sight—the line passing through the center of the eye's entrance and exit pupils, connecting the object of regard to the foveola—as the reference axis for the purposes of calculating and measuring the optical aberrations of the eye (Figure 1).[22] Aberrations measured with respect to this axis will have the pupil center as

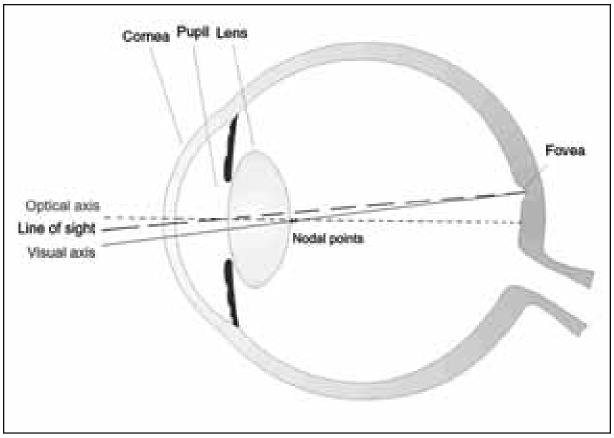

Figure 1. Schematically, the optical axis of the eye (dotted gray line) joins the center of curvature of all the optical surfaces. The appropriate and convenient axis describing the optical system of the eye is the line of sight (dashed black line). The visual axis (solid grey line) strikes the foveola but passes through the nodal points of the eye. These points correspond to the optical center of the refracting system. The axis ray passing through these points is not refracted; every ray directed to the first nodal point appears after refraction to come from the second point and continues in the same direction; the nodal points in the eye are situated approximately 7 mm behind the cornea (just behind the lens).

the origin of a Cartesian reference frame. Corneal topographers, which are centered at vertex normal, must therefore translate to the center of the entrance pupil to accurately draw corneal wavefront maps.

The ocular aberration is usually expressed in the entrance pupil in terms of the wave aberration: that is, defining how the phase of light is affected as it passes through the optical system. The wave aberration is defined as the deviation of a wavefront from a reference surface (ie, the ideal wave; Figure 2). The reference surface is defined as a surface of curvature near the wavefront whose origin is located at the Gaussian image point—where the light would be focused if the eye were perfect. If the Gaussian image is at infinity, then it follows that the reference surface is a plane. For the human eye, the natural choice for the reference surface would be a sphere with the center of curvature located at the photoreceptor outer segments in the retina, or at Bruch's membrane, where the reflex occurs.

TAKE-HOME MESSAGE

- Objective and subjective wavefront-sensing approaches can be used to measure the wavefront error of the eye.
- Optical aberrations cannot be compared unless they are calculated using the same reference axis.
- Surgeons require development of optimal measurements and representations of visual performance that can be done on an individual basis.

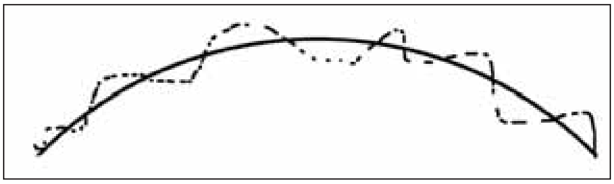

Figure 2. Definition of wave aberration error in the human eye. The solid curve represents the reference surface, and the dotted line represents the wave under study. The difference between the two represents the wave error of the eye.

The wave aberration is often defined by a series of polynomials, the most popular choice for ophthalmic optics being the Zernike polynomials. Generally, these polynomials can be used to represent any surface, and the quality of the fit is limited only by the number of polynomial terms that are used.

ZERNIKE POLYNOMIALS

The Zernike polynomials are a set of functions that can be used to describe the shape of an aberrated wavefront in the pupil of a complex optical system. Several normalization and numbering schemes are commonly used, including the double- and single-index schemes[4] and the magnitude/axis representation.[23] These schemes represent the eye's wavefront aberration by fitting the error between the actual and the ideal wavefronts with a Zernike expansion.

The orthogonality of the Zernike basis functions makes it easy to calculate the root mean square (RMS) wavefront error. Since the total variance in a wavefront is the sum of the variances of the individual Zernike modes, one can quickly identify the mode(s) having the greatest impact on the total RMS wavefront error by scanning the values of the coefficients. Furthermore, the wavefront error can be expressed as the sum of the RMS error when combining right and left eyes into a single population study.

There are some drawbacks of using Zernike polynomials. Although the normalized coefficients reveal the relative contribution of each Zernike mode to the total wavefront error of the eye, they do not reveal the relative impact of each Zernike mode on visual function. Additionally, when considering irregular ocular optics, such as eyes with keratoconus or after penetrating keratoplasty, the Zernike expansion method can be misleading because it cannot accurately represent the eye's surface optical properties,[24] resulting in an inadequate description of the image-forming properties of the eye. This is due to the fact that the Zernike expansion smoothes the data to find the best-fitting smooth surfaces (modes) to fit small (rapid) scale changes.

Several wave-aberration–derived metrics to quantify the optical quality of the eye have been proposed to overcome the disadvantages of the Zernike polynomial expansion. Image-plane metrics, which describe the effect of the eye's optical properties on image quality, can be further classified as metrics of image quality for point objects (eg, point spread function [PSF]) and for grating objects (eg, optical transfer function [OTF]).[1] The main difference between pupil-plane metrics and image-plane metrics is that the former describe the wavefront error in the plane of the pupil and the latter do so at the retina.

Pupil-plane metrics of optical aberrations can be used as a threshold indication that signifies if the aberration will affect image formation compared with a diffraction-limited case. Image-plane metrics, on the other hand, describe the optical image-forming properties of the eye under measurement. The most common pupil-plane metric of wavefront flatness is RMS wavefront error computed over the whole pupil (RMSw). Mathematically, this is the standard deviation of the values of wavefront error at various pupil locations. The peak-to-valley difference is a pupil-plane metric closely correlated to RMSw. It represents the difference between the maximum and minimum height of the eye's wave aberrations.

Optical aberrations can give rise to complex optical effects that cannot be simply quantified or mathematically characterized. It may be worthwhile to use the point-spread information calculated using the aberration information. The PSF and the scalar metrics of image quality of the PSF in aberrated eyes, such as Strehl ratio, are designed to capture the attributes of compactness and contrast. Unlike point objects, which can produce an infinite variety of PSF images depending on the nature of the eye's aberrations, grating objects always produce sinusoidal images regardless of the eye's aberrations.

There are only two ways that aberrations can affect the image of a grating; they can (1) reduce the contrast or (2) translate the image sideways to produce a spatial phase shift. The variation of image contrast with spatial frequency for an object is called modulation transfer function (MTF). The variation of image phase shift with spatial frequency is called phase transfer function (PTF). MTF and PTF can be derived by taking the magnitude of the OTF or its phase respectively. In practice, the magnitude of OTF is equal to the ratio of image contrast to object contrast, and the phase is equal to the spatial phase difference between image and object.[1]

WAVE ABERRATIONS

The relative contributions of the optical elements of the eye, such as the cornea and crystalline lens, to the total wave aberrations of the eye and the relative interindividual differences or age-related changes have been evaluated in

detail using either corneal or ocular wavefront sensors. Excluding lower-order aberrations from our discussion, it is known that the form of the ocular wave aberration varies substantially among individuals, depending on the eye's surface asymmetries and tilts between the optical components and their relative locations with respect to the pupil.

The contributions of higher-order aberrations to total wave aberrations in the eye are relatively low and are dominated by coma-like aberrations and spherical aberration. The range of absolute values decreases systematically for higher Zernike-mode numbers, meaning that the magnitude of aberration coefficients in an individual tends to be smaller for higher-order modes than for lower-order modes. However, the higher-orders can still negatively influence image quality when the pupil is large.[25]

The total optical performance of the normal eye is governed by the combination of aberrations among the corneal and internal optics. The total wave aberration of the eye is always less than the values for either the anterior cornea or the internal optics, and this is thought to be due to compensatory processing between the cornea and the lens. The overall result of this compensation process is a reduction of the magnitude of aberrations at the retinal plane with a possible improvement of optical quality at the foveola. In most young eyes, the magnitude of aberrations for both the cornea and the lens is larger than for the complete eye, indicating the importance of the lens' role in compensating for corneal aberrations and thus producing improved retinal images. However, in older eyes, the lens adds aberrations to the cornea, resulting in a complete system with poorer optical quality. The changes in the anterior cornea's shape and in the shape and size of the lens throughout life may explain the progressive lack of compensation between optics occurring in older eyes.

INCREASE WITH AGE

The amount of corneal, lenticular, and ocular higher-order aberrations (HOAs) increase approximately linearly with age.[26,27] In the normal corneas of young eyes, third-order Zernike terms are the most prevalent group of HOAs, followed by spherical aberration. Coma increases greatly with age, whereas, in general, corneal spherical aberration increases only slightly with age. The moderate increase in spherical aberration is related to a change in the asphericity of the cornea; the anterior cornea tends to become less prolate with age. The crystalline lens continues to grow throughout life; the central thickness increases and the surfaces become more curved, inducing changes in the asphericity of the anterior and posterior surfaces with a net increase in spherical aberration. The decoupling of aberrations between the cornea and the internal optics and the concurrent increase in magnitude of the total wave aberration with age results in a decrease in optical and visual performance, even in healthy eyes.

Recently, particular attention has been paid to the interocular (intraindividual) balance of optical aberrations.[28,29] Studies have shown mirror symmetry between the higher-order wavefront maps of the anterior cornea and the total optics between subjects' two eyes, especially for third- and fourth-order terms. Studies must elucidate the possible relationships between the interocular symmetry of wavefront aberration and cone orientation, which are also shown to be symmetric between eyes.[30] With the recent introduction of wavefront-related diagnostic and surgical approaches such as adaptive optics and wavefront-guided corneal laser surgery, ophthalmologists now require the development of optimal measurements and representations of visual performance on an individual basis. Objective metrics and predictors of image optical quality allow us to measure optical aberrations and to interpret how an induced change in aberration can influence visual performance.

However, optical quality metrics do not account completely for the real visual perception of the individual because vision involves many functions beside the optical properties of the eye, such as neural adaptation and compensation for optical aberrations.[31] Photoreceptor sampling is another factor that may influence the interpretation of predictors of visual performance because the foveal photoreceptor mosaic anatomically limits spatial resolution.[32] Consequently, one may theorize that personalized image and optical quality metrics are necessary for accurate prediction of visual performance, for example with the use of adaptive optics.

It may be unrealistic, however, to suppose that only one metric can capture all aspects of image optical quality; a series of metrics could be needed to adequately describe and predict the optical performance of an individual by measuring the optical properties of the eye. It remains to be investigated which particular combination of metrics will succeed in quantifying optical quality and visual performance for a variety of visual tasks under a variety of test conditions. A group of image-quality metrics that takes into account the importance of the range of spatial frequencies might be the best choice. Furthermore, because the natural condition of the human visual system is binocular and we live in a polychromatic world, novel approaches that measure visual performance using binocular functions[33] and polychromatic metrics may be the best predictors of everyday visual performance.[34] ■

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