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Visual Benefit of Correcting Higher Order Aberrations of the Eye

[Proceedings of the 1st International Congress on Wavefront Sensing and Aberration-free Refractive Correction]

Williams, David PhD; Yoon, Geun-Young PhD; Porter, Jason MS; Guirao, Antonio PhD; Hofer, Heidi BS; Cox, Ian PhD

Center for Visual Science, University of Rochester, Rochester, NY (Williams, Yoon, Porter, Guirao, Hofer) and Bausch and Lomb, Rochester, NY (Cox).

Correspondence: David Williams, PhD, Center for Visual Science, University of Rochester, Rochester, NY 14627. Tel: 716.275.8672; E-mail: david@cvs.rochester.edu

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ABSTRACT

There is currently considerable debate concerning the visual impact of correcting the higher order aberrations of the eye. We describe new measurements of a large population of human eyes and compute the visual benefit of correcting higher order aberrations. We also describe the increase in contrast sensitivity when higher order aberrations are corrected with an adaptive optics system. All these results suggest that many, though not all, observers with normal vision would receive worthwhile improvements in spatial vision from customized vision correction, at least over a range of viewing distances and particularly when the pupils are large. Keratoconic patients or patients suffering from spherical aberration as a result of laser refractive surgery as it is presently performed would especially benefit. These results encourage the development of methods to correct higher order aberrations.

Advances in the measurement of the eye's wave aberration ^{1,2} and the ability to accurately correct it with adaptive optics ³ have moved the wave aberration from an obscure academic concept to one that is central to efforts to improve vision. The power of the wave aberration is that this single function completely describes the aggregate effects of the cornea

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Visual Benefit of Correct... 

and lens on light passing through every location in the pupil. If you know the wave aberration, you know what must be done to light entering the pupil so as to create a perfect image on the retina, blurred only by diffraction and scattering. The wave aberration is the sum of individual aberrations including defocus and astigmatism as well as many other aberrations referred to as higher order aberrations. Of course, knowing a patient's refraction is also a prescription for improving retinal image quality. But the conventional refraction attempts to specify what is wrong with the eye using only three parameters (sphere, cylinder, and axis), whereas the wave aberration specifies the errors in the eye with many more parameters. Wave front sensors have been built that capture as many as 65 components in the wave aberration.² This article addresses the question whether correcting higher order aberrations as well as defocus and astigmatism can lead to real improvements in vision in everyday life. Do the visual benefits of correcting higher order aberrations warrant the refinement of technologies for vision correction, such as the development of customized laser refractive surgery or customized contact lenses?

Figure 1 illustrates the value of the wave aberration. It shows two wave aberrations, one for a patient following laser in situ keratomileusis (LASIK) and one for a typical, unoperated eye. The pupil diameter is 7 mm. The step size in the wave aberration plots is $0.55 \mu\text{m}$. The uncorrected spherocylindrical refraction of the unoperated eye was $-2.00 \text{ D } 0.00 \text{ D}$. The preoperative spherocylindrical refraction of the LASIK eye was $-3.00 \text{ D } 0.00 \text{ D}$ and the attempted LASIK correction was -3.00 D over an optical zone $\geq 7 \text{ mm}$. The postoperative LASIK eye has a relatively flat wave aberration in the central zone, similar to that of the unoperated eye, but exhibits severe aberrations near the pupil margin, as revealed by the high density of contour lines at the edge of the plot. This is due to the fact that the cornea is too steep there.⁴ From the wave aberration, it is possible to calculate the eye's point spread function, which is a succinct description of retinal image quality. We can convolve the point spread function (PSF) with any object, such as a letter E, to reveal the effect of the wave aberration on the retinal image. When the pupil is large, this patient will see poorly compared with the typical unoperated patient. This is not because of light scatter in the eye, it is because the corneal shape in the transition zone is not the correct one for good imaging. The higher order aberration illustrated by the LASIK patient is predominantly spherical aberration.^{4,5} This defect cannot be eliminated with any combination of sphere, cylinder and axis. Corrective technologies that can compensate for higher order aberrations are required.

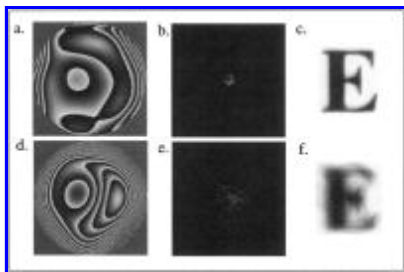


Figure 1. The wave aberrations of (a) an unoperated eye, and (d) a LASIK eye and their corresponding point spread functions (b) and (e). For both wave aberrations, the amount of defocus was adjusted to maximize the Strehl ratio of the point spread function as a method to approximate an optimized refraction. Values for astigmatism were small and not altered. (c) shows the convolution of the point spread function for the unoperated eye with the letter E, illustrating a typical loss in retinal image quality for this large, 7 mm pupil. (f) shows the inferior retinal image of the same E formed by the optics of the LASIK patient, in which considerable spherical aberration has been introduced by the procedure. The visual angle subtended by the E was 1 deg.

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RELATIVE CONTRIBUTION OF HIGHER ORDER ABERRATIONS TO WAVE ABERRATION



Even the unoperated eye in Figure 1 contains higher order aberrations that could be removed with customized correction. How important are these aberrations in the population of normal eyes? Figure 2 shows the distribution of monochromatic aberrations in a population of 109 adults, between 21 and 65 years of age.⁶ Criteria for inclusion in the study were spherical refraction between 6.00 and -12.00 diopters (D) and less than 3.00 D of astigmatism. These data were obtained by computing the Zernike decomposition of the wave aberration. Zernike decomposition breaks the wave aberration into its component aberrations. The ordinate of the graph indicates the average size of a particular Zernike component in the eye. Note defocus, which corresponds to Zernike mode Z_0^2 is by far the largest aberration. Since a large percentage of our population consisted of patients from a local clinic

who tended to be myopic, the magnitude of this defocus coefficient may be slightly larger than that for a purely randomly selected, normal population. The next largest contributor was astigmatism, which corresponds to the combination of Zernike modes Z^{-2}_2 and Z^{2}_2 . The higher order aberrations generally decline in size with increasing number, with some exceptions such as spherical aberration, Z^0_4 .

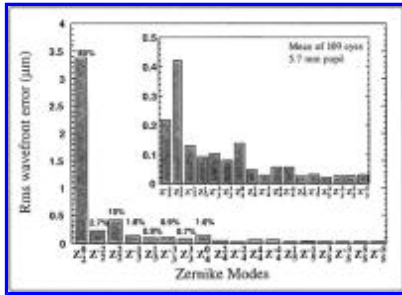


Figure 2. Mean absolute RMS values of the lowest 18 Zernike modes in a population of 109 human subjects measured with a Hartmann-Shack wavefront sensor. Pupil size was 5.7 mm. Inset excludes the Zernike mode corresponding to defocus (Z_0^2) and expands the ordinate to display values of higher order aberrations. The percentages listed in the Figure indicate the percentage of the variance accounted for by each Zernike mode.

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IMPACT OF HIGHER ORDER ABERRATIONS ON RETINAL IMAGE QUALITY

Although Figure 2 shows the relative contributions of different aberrations to the overall wave aberration, it does not inform us directly about the impact of higher order aberrations on the retinal image. The modulation transfer function (MTF) of the eye's optics, which can be computed from the wave aberration, provides a useful measure of retinal image quality. Figure 3 shows the MTF of the average eye in white light for a 3 mm and a 6 mm pupil when defocus and astigmatism have been corrected (dotted line), and when the higher order aberrations have been corrected as well (dashed line).⁷ Also shown for comparison is the aberration-free MTF of an ideal optical system in which diffraction by the pupil is the only source of image blur. The curve in which all monochromatic aberrations are corrected lies below that aberration-free curve because of the axial chromatic aberration of the eye.

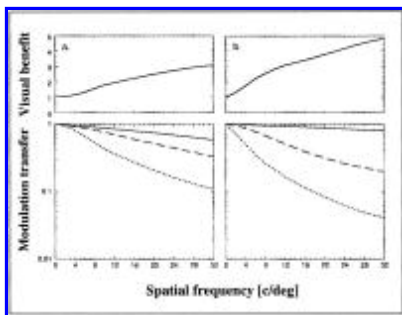


Figure 3. a) The modulation transfer function of the eye calculated from the wave aberrations of 17 eyes measured with a Hartmann-Shack wavefront sensor. Pupil size 3 mm, white light. The dotted curve shows the average MTF when a conventional refraction has been applied to the eye. The effect of the conventional refraction was approximated with an iterative procedure for identifying the amount of defocus that maximized the MTF at 16 c/deg. The values for astigmatism were chosen by zeroing the corresponding Zernike polynomials in the Zernike decomposition of the wave aberration. The dashed curve shows the modulation transfer function when defocus, astigmatism and higher order aberrations have been corrected. The solid curve shows the MTF for an aberration-free eye in which axial chromatic aberration has been eliminated and only diffraction remains. The transverse chromatic aberration was assumed to be 1 arc minute between 405 and 695 nm¹⁴ and the Stiles Crawford effect was assumed to have negligible effects on the MTF. The photopic luminosity function was used as the eye's spectral sensitivity. b) Same as image A but with a 6 mm pupil.

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Of particular interest is the ratio of the MTF when all the monochromatic aberrations are corrected to that when only defocus and astigmatism are corrected in white light. We define that ratio as the visual benefit of correcting higher order aberrations. It tells us how much retinal image contrast will increase at each spatial frequency with a customized ablation procedure or a custom contact lens that perfectly corrected all

monochromatic aberrations. A visual benefit of 1 corresponds to no benefit.

POPULATION VARIABILITY IN THE VISUAL BENEFIT OF CORRECTING HIGHER ORDER ABERRATIONS

It is also of some interest to know how much the visual benefit varies among normal eyes. Figure 4 shows, for a 5.7 mm pupil, a frequency histogram of the visual benefit of correcting higher order aberrations in the population of 109 normal eyes and 4 keratoconic eyes at a spatial frequency of 16 c/deg. This spatial frequency was chosen because it is among the highest frequencies that are detectable by normal subjects viewing visual scenes.⁸ Some normal eyes have a visual benefit close to 1, ie, show almost no benefit of correcting higher order aberrations. Clearly, customized correction of higher order aberrations isn't for everyone. However, the modal visual benefit in the normal population is nearly a factor of three, which would correspond to a subjectively obvious increase in the sharpness of vision. At the extreme, some normal eyes show a benefit of more than a factor of seven. These eyes are prime candidates for customized correction and the wave front sensor can efficiently single them out. We have also estimated the visual benefit in a small sample of keratoconic patients and have observed benefits as high as a factor of 25. Clearly, the development of technologies to correct the idiosyncratic higher order aberrations of such patients would be an especially valuable outcome of wave front sensing.

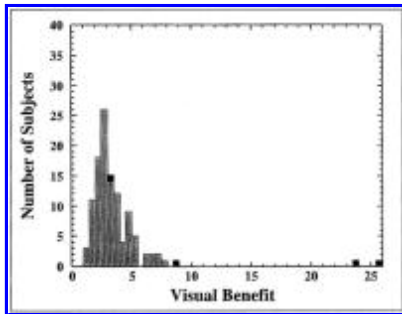


Figure 4. Histogram of the visual benefit of correcting higher order aberrations in white light for a population of 109 normal eyes (gray) and 4 keratoconic eyes (black). Pupil size was 5.7 mm. Visual benefit is shown for a spatial frequency of 16 c/deg. Benefit declines at lower spatial frequencies. For this calculation, the conventional refraction was assumed to correspond to zeroing the 3 Zernike modes corresponding to defocus and astigmatism. This probably slightly underestimates the optical quality that could be achieved by interactively adjusting defocus and astigmatism.

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VISION THROUGH ADAPTIVE OPTICS

The visual benefits of correcting higher order aberrations shown above are based on calculations from measurements of the wave aberration. But can such benefits be realized in practice? Liang and colleagues³ constructed an adaptive optical system at the University of Rochester that demonstrated for the first time that most higher order aberrations in the eye can be corrected. The adaptive optics system uses a wave front sensor to measure the eye's wave aberration. A computer then transforms the wave aberration into signals that control a deformable mirror. The deformable mirror bends the light at each point in the pupil in just the right way to correct the wave aberration. With this system, they showed that contrast sensitivity can increase as much as 6-fold when higher order aberrations are corrected. Moreover, we were able to image individual cones in the living human retina with a fundus camera equipped with adaptive optics.

More recently, Geun-Young Yoon in our laboratory has made additional measurements of contrast sensitivity of the eye when higher order aberrations are corrected, but in white light instead of monochromatic light.⁷ We chose to use white light because it more closely approximates the spectra of real scenes, and therefore includes the chromatic aberration of the eye. This more accurately captures the potential benefit of, for example, customized laser refractive surgery because it would leave the eye's chromatic aberration uncorrected.

Figure 5 shows contrast sensitivity functions for two eyes obtained with a 6 mm pupil. The lower curve was obtained when only defocus and astigmatism were corrected. The middle curve was obtained when higher order aberrations were corrected with adaptive optics. The upper panels show the ratio of the two contrast sensitivity curves, which is a measure of the psychophysical benefit of correcting higher order aberrations directly comparable to that computed from the optical MTF shown in Figure 3. The benefit for these two eyes rises to a

value of about 2 at high spatial frequencies. These data are consistent with the predictions from the modulation transfer functions discussed earlier. The visual benefit is not quite as great, presumably because the adaptive optics system is not capable of perfectly correcting all the higher order aberrations of the eye. Still, these results are probably a closer approximation of what can eventually be achieved with a refined laser surgical procedure or a customized contact lens, neither of which can be expected to be perfect.

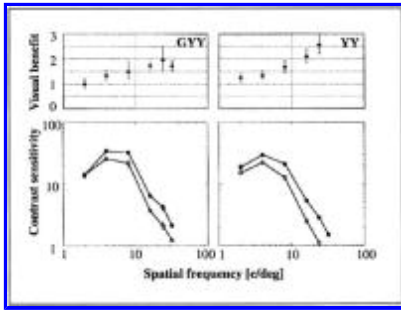


Figure 5. Contrast sensitivity functions (CSFs) for two observers (GY and YY) measured in white light with a conventional refraction (unfilled circles) and with higher order aberrations reduced with adaptive optics (filled circles). Pupil size was 6 mm and retinal illuminance was 57 Td. The upper panel shows the visual benefit of correcting higher order aberrations calculated by dividing the CSF with adaptive optics by the CSF with a conventional refraction.

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Figure 6 provides some insight into the visual importance of the improvement achieved with adaptive optics. It shows the wave aberration of one of the observers (YY, pupil diameter = 6.8 mm) whose data are plotted in Figure 5, with and without adaptive optical correction, the corresponding PSFs, and also the retinal images of the letter E, one deg in height, in monochromatic and white light. The images in white light were computed assuming the eye had the spectral sensitivity of the photopic luminosity function. There is a substantial improvement in the quality of the E even in white light, and an even more marked improvement in monochromatic light. The latter illustrates the important role that axial chromatic aberration plays when higher order monochromatic aberrations are corrected.

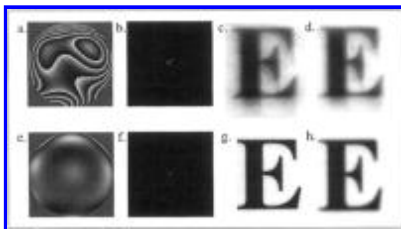


Figure 6. The wave aberration of a normal eye (a) without and (e) with correction of higher order aberrations with adaptive optics. The corresponding point spread function (b) without and (f) with adaptive optics. The corresponding retinal image in monochromatic light (c) without and (g) with adaptive optics. The corresponding retinal image in white light (d) without and (h) with adaptive optics. The visual angle subtended by the E was 1 deg.

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VISUAL ACUITY AND HIGHER ORDER ABERRATIONS

Visual acuity is a far less sensitive measure of the benefits of correcting higher order aberrations than contrast sensitivity. This is because the contrast sensitivity function is steep at the acuity limit and a large increase in contrast sensitivity slides the intersection of the function with the x axis only a short distance. Nonetheless, reliable improvements in letter acuity can be measured when higher order aberrations are corrected with adaptive optics. We find a mean increase in acuity of 1.4 across 7 eyes. The details of these experiments will be published elsewhere.

Another reason why visual acuity may underestimate the benefit of correcting higher order aberrations is that neural factors will ultimately limit acuity even when improvements in retinal image contrast can continue to provide improved vision at lower spatial frequencies. The spacing of foveal cones, which is approximately 0.5

minutes of arc 9,10 at the foveal center, ultimately imposes a limit on acuity of about 60 c/deg or half the reciprocal of the cone spacing 11 because aliasing by the cone mosaic occurs above this limit.12 Nonetheless, an increase in retinal image contrast at spatial frequencies below this sampling limit can still provide important improvements in the sharpness of vision, even if finer structure in the image cannot be resolved due to the grain of the mosaic.

DISCUSSION

These data illustrate that higher order aberrations can be measured with a Hartmann-Shack wave front sensor and they can be corrected with an adaptive optics system. The benefits of correcting higher order aberrations are subjectively obvious. Does this benefit warrant the development of customized laser refractive surgical methods, contact lenses, or other methods that could correct higher order aberrations? There are some important caveats about the visual benefit that can be realized in ordinary vision. First, the benefits are reduced when the pupil is small. The visual benefit would be largest in younger patients in which the pupil is large, 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 higher order correction depend on accurate accommodation. The failure to focus correctly on the target, which is commonplace due to accommodative lag, will diminish the visual benefit of higher order correction. Of course, there remain important questions about the accuracy with which customized, higher order correction can be delivered with laser refractive surgery. As just one example, there will be less tolerance to decentrations of the eye during surgery when higher order aberrations are corrected than when only defocus and astigmatism are corrected. Calculations suggest that the effects of decentrations that one might expect do not detract greatly from the benefit of correcting higher order aberrations.13

Nonetheless, the population data shown here reveal that the question isn't whether customized correction of higher order aberrations will be beneficial. The question is how many people will it benefit? The variability of the optical quality of the eye is very large, and some people will derive much more visual benefit than others. Abnormal eyes, such as those that suffer from large amounts of spherical aberration due to laser refractive surgery, or keratoconic eyes, stand to gain the most from customization methods. As these methods are refined, there is good reason to believe that many normal eyes, especially those with large pupils and large amounts of higher order aberrations, will see important improvements in visual performance with customized correction. With the rapid development of wave front sensing technology, we now have the tools to screen such patients easily. The remaining challenge is to perfect the correction methods to maximize the visual benefit for the largest number of patients.

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