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Correction of the Eye's Wave Aberration

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1. Introduction

We have seen in the previous two chapters that the human eye is not a perfect optical system and contains a host of different aberrations. If the eye's optical quality is poor, i.e. if the images formed on the retina are blurred or have low contrast, vision will be deficient even if the rest of the visual system were perfect. Several methods to improve the optics of the human eye have been proposed and developed, the earliest written reports of which originated at least 700 years ago. Spectacles that corrected defocus were invented as early as the 13th century (Willoughby Cashell, 1971; Rubin, 1986) while spectacles that corrected defocus and astigmatism were conceived in the 19th century (Helmholtz, 1924). Since then, there has been relatively little work on exploring techniques to correct additional aberrations in the eye. In 1961, Smirnov suggested that it might be possible to manufacture customized contact lenses that would compensate for the higher order aberrations found in individual eyes. Recently, technological advances in measuring and compensating for the aberrations of the human eye have made it possible to provide the eye with unprecedented optical quality (Liang *et al.*, 1997). An observer viewing the world through a "super-correcting" device can see sharper, higher-contrast images than they have ever seen before. In this chapter, we describe several methods for correcting the eye's higher order aberrations, including adaptive optics. In addition, the benefits of correcting higher order aberrations and the constraints imposed by the higher order correction method will also be discussed.

2. Methods for Correcting Higher Order Aberrations

The most conventional methods used to correct the aberrations of the eye have been spectacles and contact lenses. Traditionally, these methods have only compensated for defocus and astigmatism (or known in the trade as sphere and cylinder). Now recent developments in technology have made it possible to investigate the prospects for eliminating higher order aberrations as well. In this section, we will briefly explain several methods for correcting higher order aberrations.

2.1. Contact lenses

Conventional contact lenses correct refractive errors by adding or subtracting focusing power to the eye. While these lenses typically correct for only three constituent aberrations (one defocus and two astigmatic Zernike modes), wave aberrations have been measured using a Hartmann-Shack wavefront sensor that include as many as 65 different Zernike aberrations (Liang *et al.*, 1997). With the development of lathing and laser ablative techniques that can sculpt arbitrary surfaces on contact lenses, it may be possible to create a customized contact lens having an aberration profile that exactly compensates for the wave aberration of an individual eye. The performance of a customized lens will be sensitive to slight rotations and decentrations of the lens as it moves on the eye. However, early studies have theoretically shown that image quality is only slightly reduced when a customized contact lens experiences rotations and decentrations of the same magnitude as those typically found in soft contact lenses (Guirao *et al.*, 2000a, 2001).

2.2. Laser refractive surgery and intraocular lenses

Another way to correct the eye's aberrations, instead of adding a complementary optical system to it, is to physically change the eye's optics. Laser refractive surgery is a general term for a surgical procedure that can alter the eye's optics by permanently changing the shape of the cornea. Photorefractive keratectomy, or PRK, and laser-assisted in situ keratomileusis, or LASIK, are the most popular methods in laser refractive surgery. These techniques, shown in Fig. 1, are currently used to remove defocus (myopia and hyperopia) and low to moderate degrees of astigmatism. The principle of these methods is to eliminate corneal tissue and change the curvature of the cornea so that light can focus exactly on the retina. PRK is done by the use of a laser which precisely reshapes the cornea's front surface. In LASIK, the surgeon uses a micro-keratome to cut a thin corneal flap and pulls this flap off of the cornea, exposing the underlying tissue. The surgeon then uses an excimer laser to remove this underlying tissue and reattaches the flap after the ablation.

There is an ongoing effort to refine laser refractive surgery to correct other defects besides conventional refractive errors (MacRae *et al.*, 2000). With wavefront sensing and corneal topography (a technique that determines the shape and thickness of the cornea), it's possible to determine how to alter the shape of cornea in order to minimize the residual wave aberration of the eye. Thus, refractive surgery provides an alternative method for correcting the higher order aberrations of the eye. In contrast with a contact lens, the effects of this surgical treatment are permanent. However, the cornea is a living structure and will change shape after surgery due to healing mechanisms that are not entirely understood.

Instead of reshaping the cornea of the eye, it is also possible to replace the eye's lens with an intraocular lens that compensates for the aberrations caused by the entire optical system. In this method, it is possible to measure all the aberrations and make an artificial lens that compensates them to minimize the residual aberrations.

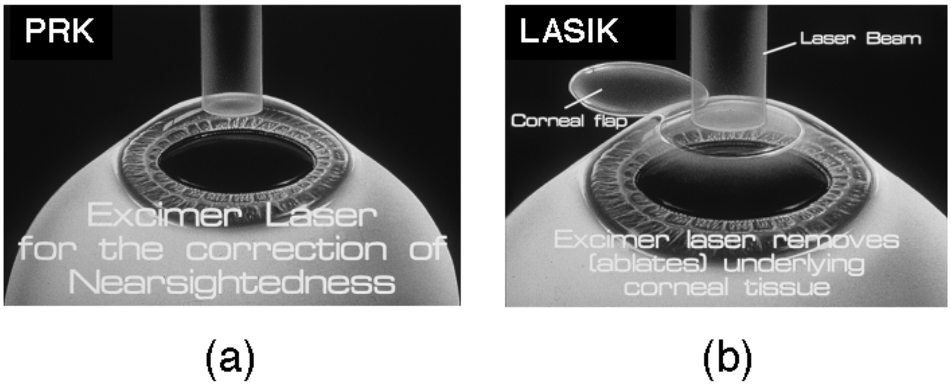

Figure 1. Schematic illustration of two types of refractive surgeries, (a): PRK, in which an excimer laser directly ablates the first surface of the cornea, and (b) LASIK, in which a corneal flap is cut and lifted, allowing the excimer laser to ablate the underlying corneal tissue (cited from Gimbel Eye Centre web page).

2.3. Adaptive optics

All of the aforementioned techniques provide a static correction of the eye's aberrations, usually for distance vision. Real-time correction of higher order aberrations can be reliably achieved using adaptive optics, a technique first introduced to vision by Liang and Williams (Liang & Williams, 1997). A deformable mirror is used to correct the eye's wave aberration without physically altering the cornea or any of the eye's optical components. Once the eye's optics are corrected, one may non-invasively image the retina at a microscopic scale or experimentally measure the improvement in visual performance that subjects experience when their higher order aberrations are corrected.

3. Adaptive Optics for the Human Eye

3.1. System design

Fig. 2 shows the schematic diagram of the adaptive optics system for the human eye at the University of Rochester. The system contains a Hartmann-Shack wavefront sensor used to measure the wave aberration of the eye and a wavefront corrector used to compensate for these aberrations. In addition, the system has two separate arms that allow for vision testing and retinal imaging. The adaptive optics part of the 1st generation system is a deformable mirror (Xinetics, Inc.) with 37 actuators that can independently push and pull on the mirror to warp it's surface into an appropriate shape to compensate for the eye's aberrations. The stroke of each actuator is ± 2 μm, allowing for a total wavefront shift of 8 μm upon reflection. Because the eye is not a perfect optical system, light exiting the eye's pupil from a point source on the retina does not emerge as a

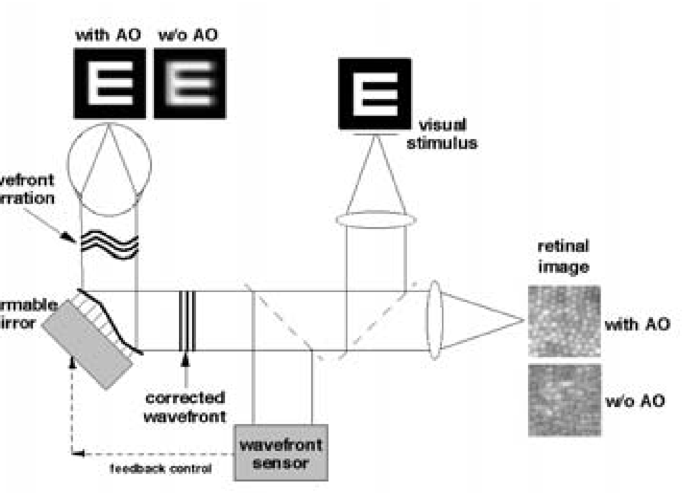

Figure 2. Schematic illustration of an adaptive optics system for vision.

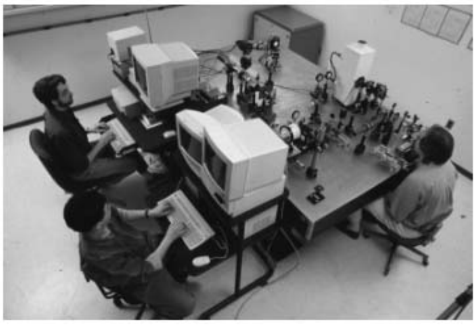

Figure 3. Adaptive optics system at University of Rochester.

planar wavefront, but as an aberrated wavefront. The shape of this aberrated wavefront, which varies from eye to eye, can be measured with a Hartmann-Shack wavefront sensor. A computer then converts the spot positions obtained with the wavefront sensor into a control signal for the deformable mirror.

Aberration compensation is achieved with a closed-loop feedback control at frame rates of up to 30 Hz using a direct-slope algorithm. In each loop, the mirror stroke is directly computed from the local slopes of the wavefront, as determined by the wavefront sensor. Wavefront correction is performed until the root-mean-square (RMS) wavefront error is reduced to a pre-determined value, or levels off at a minimum value. 10 to 20 loops are usually needed to achieve the best correction and an entire closed-loop correction requires less than 1 second. Fig. 3 shows a picture of the adaptive optics system used at the University of Rochester.

3.2. System performance

Wave aberrations and their associated point spread functions (PSF) are shown in Fig. 4 for an aberration-free, or perfect, eye and for three normal subjects over a 6.8 mm pupil. As illustrated in this figure, both the wave aberration and PSF can vary tremendously from person to person. Fig. 5 illustrates the benefit of using adaptive optics on the wave aberration for two subjects before and after adaptive compensation. The wavefront after compensation is much flatter after compensation, though still not completely perfect, indicating the presence of small amounts of residual higher order aberrations. Fig. 6 shows the corresponding PSFs calculated from the wave aberrations presented in Fig.

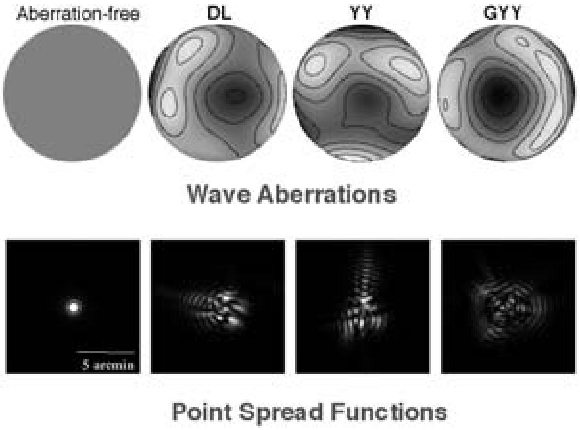

Figure 4. Wave aberrations and the PSF calculated from the wave aberration for three subjects (6.8 mm pupil). For comparison, the diffraction limited case, shown on the left of the figure, represents an aberration-free, or perfect, eye.

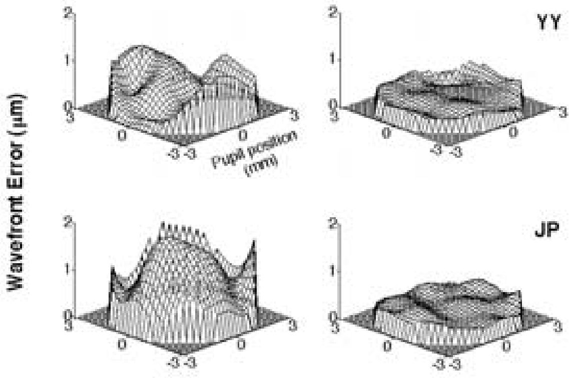

Figure 5. Wave aberrations of two subjects before (left panels) and after (right panels) adaptive compensation across a 6 mm pupil. Defocus and astigmatism have been removed from the wave aberration.

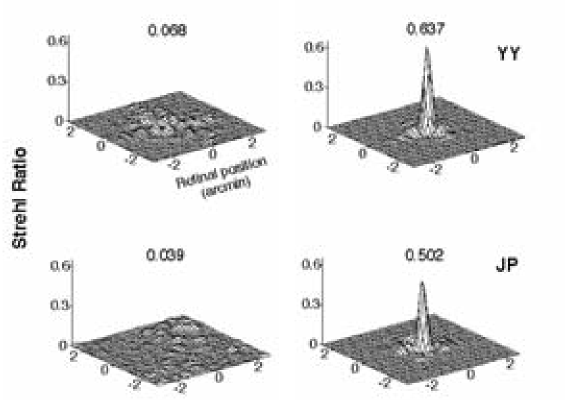

Figure 6. 3-dimensional plots of the PSFs of the subjects from Fig. 5 before and after adaptive compensation. The number above each PSF is the Strehl ratio for that particular subject and condition.

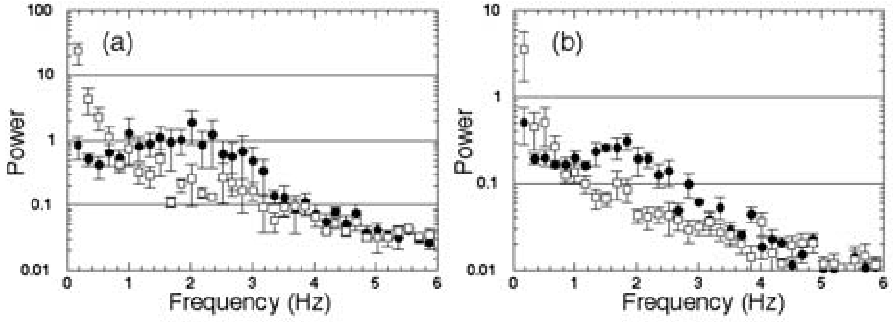

Figure 7. The power spectra of (a): 2nd and (b): 3rd order Zernike modes during an open (squares) and closed-loop (circles) correction. The results shown here are the average of 8 trials in each condition.

5 at a wavelength of 550 nm. For the best correction for these eyes shown here, adaptive compensation increased the Strehl ratio from 0.04 to 0.50 for subject JP and from 0.07 to 0.64 for subject YY. The total improvement in optical quality, as indicated by the Strehl ratio, is a factor of 10 after adaptive compensation. The actual visual benefit achieved by this higher order aberration correction will be described in the next section.

The advantage of running the system in a closed-loop fashion is shown in Fig. 7 and 8. Fig. 7 shows the power spectra of the 2nd and 3rd order Zernike modes obtained from an open (squares) and closed-loop (circles) correction of the eye's wave aberration on a semi-log plot. These results were measured from one subject, and are the average results of 8 trials measured over 5 seconds in each condition. These results show that the closed-loop control has a better performance than open-loop correction. The power is reduced in frequencies less

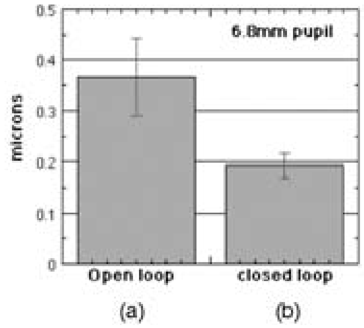

Figure 8. Time-averaged residual RMS wavefront error obtained in (a) open loop and (b) closed loop control for one subject over 8 trials.

than about 0.8 Hz in closed-loop control, but increases somewhat in the higher frequencies, indicating that the control process requires further refinement. The overall power is reduced in a closed-loop correction for Zernike orders up to 5th order. The time-averaged residual RMS wavefront errors of one subject for both an open and closed-loop control system are shown in Fig. 8. The closed-loop correction provides an improvement in the residual RMS of nearly a factor of two when compared with an open-loop correction.

4. Benefit of Correcting Higher Order Aberrations

Adaptive optics can dramatically improve the point spread function and the Strehl ratio by correcting the eye's higher order aberrations. The eye's modulation transfer function (MTF), which can be computed from the wave aberration, gives a useful measure of retinal image quality which is dictated by the optical quality of the eye. Of particular interest is whether improvements in optical performance will be reflected in the visual performance as well. What is the visual benefit that one can expect from a customized correction of the eye's higher order aberrations? (Williams *et al.*, 2000) Here we define visual benefit as the ratio of the polychromatic MTF obtained when all of the eye's monochromatic aberrations are corrected to that when only defocus and astigmatism are corrected in white light.

4.1. Improvement of contrast sensitivity

As earlier described, contrast sensitivity is one method of assessing visual performance. The contrast sensitivity function (CSF) is a measure of a subject's sensitivity to gratings of different spatial frequencies. The lower the contrast sensitivity, the higher the contrast a subject would need to detect a given spatial frequency grating. The CSF, when plotted as a function of spatial frequency, has a shape similar to that of a band-pass filter. Subjects require the least amount of contrast to detect low frequency information (i.e., have a high contrast sensitivity to low spatial frequencies) and require higher contrast (or have a low contrast sensitivity) to detect fine structures and spatial frequencies. What happens to a subject's CSF when their higher order aberrations are corrected? As the retinal

image becomes sharper, the visual system may become more sensitive to lower contrast gratings, and as a result, contrast sensitivity would be improved.
To test this hypothesis, we measured the contrast sensitivity of the eye to gratings of different spatial frequencies after adaptive compensation with the contrast sensitivity of the eye after a conventional refraction (or correction of defocus and astigmatism). The experiment was conducted using the adjustment method, in which a subject could manually set the contrast of the grating to a level at which the grating was no longer visible (Yoon *et al.*, submitted).

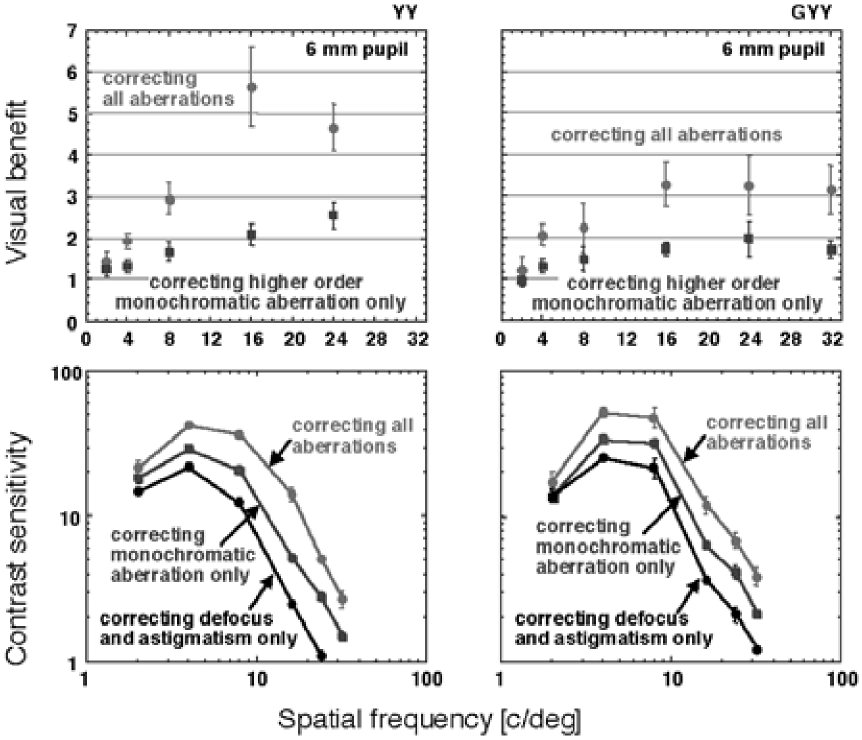

Figure 9. Contrast sensitivity functions (lower panels) and visual benefit (upper panels) with and without higher order aberration correction.

Fig. 9 shows the CSF and visual benefit for two subjects with only defocus and astigmatism only corrected, after correcting the higher order monochromatic aberrations as well as defocus and astigmatism, and after correcting both monochromatic aberrations and chromatics aberration (filled circles). The results are similar for both subjects. The contrast sensitivity when correcting the monochromatic aberrations with a deformable mirror is higher than when defocus and astigmatism alone are corrected. This illustrates that higher order aberrations in normal eyes reduce visual performance. Moreover, correcting both chromatic and monochromatic aberrations provides an even larger increase in contrast sensitivity. That is, leaving chromatic aberration uncorrected reduces the benefit of correcting the monochromatic aberrations of the eye.

Fig. 9 also shows the visual benefit, defined as the ratio of contrast sensitivity when correcting monochromatic and chromatic aberrations, or when correcting monochromatic aberrations only, to that when correcting defocus and astigmatism only. Contrast sensitivity when correcting monochromatic aberrations only is improved by a factor of 2 on average at 16 and 24 c/deg. The maximum benefits for the two subjects are approximately a factor of 5 (YY) and 3.2 (GYY) at 16c/deg when both monochromatic aberrations and chromatic aberration were corrected.

4.2. Improvement in retinal image quality

The improvement in contrast sensitivity with a higher order correction results from a sharpening of the retinal image when using adaptive optics. In order to show the improvement obtained with adaptive optics, we will consider image quality with and without adaptive optics. Fig. 10 shows the wave aberration of one observer (YY, pupil diameter = 6.8 mm) before and after adaptive optical correction, and the retinal images of the letter E, one degree in height, in both 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 with a higher order correction in white light with an even more marked improvement in monochromatic light, illustrating the important role that axial chromatic aberration plays when higher order aberrations are corrected.

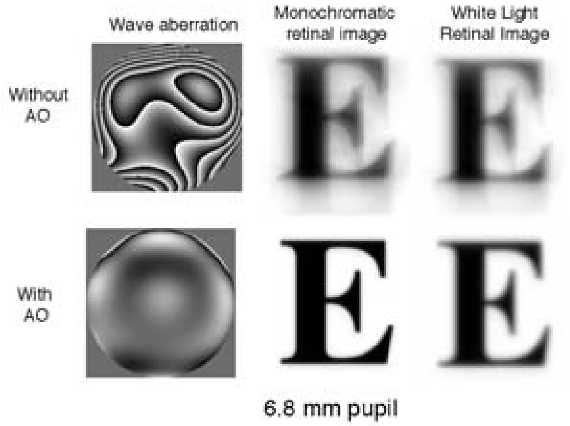

Figure 10. The improvement in the wave aberration and retinal image quality of a normal eye for monochromatic light ($\lambda = 550$ nm) and white light across a 6.8 mm pupil after correcting the higher order aberrations in a normal eye using adaptive optics.

4.3. Estimated population statistics of visual benefit

The distribution and magnitude of the monochromatic aberrations in the population of normal human eyes shown in the last chapter does not directly inform us about the impact of their correction on retinal image quality. What fraction of the population could derive a significant visual benefit from a customized correction of their eye's higher order aberrations? The variability of the optical quality of the eye is very large, and some people derive more visual benefit than others. The frequency histogram in Fig. 11 shows how much the visual benefit, for a 5.7 mm pupil, varies among eyes in the normal population of 109 normal subjects and in 4 keratoconic patients. The distributions of visual benefit at spatial frequencies of 16 c/deg are shown, because it corresponds to the nearly highest frequency that is detectable by normal subjects viewing natural scenes. Some normal eyes have a visual benefit close to 1 and show almost no benefit of correcting higher order aberrations. (A visual benefit of 1 would indicate that there is no benefit in correcting higher order aberrations since the eye's MTF with all of the monochromatic aberrations corrected would have to be the same as the MTF in which only defocus and astigmatism are corrected.) On the other hand, some normal subjects could experience a substantial visual benefit of more than a factor of four or five. The modal visual benefit in the normal population is nearly a factor of 2.5, indicating an obvious increase in the sharpness of vision as a result of the higher order correction.

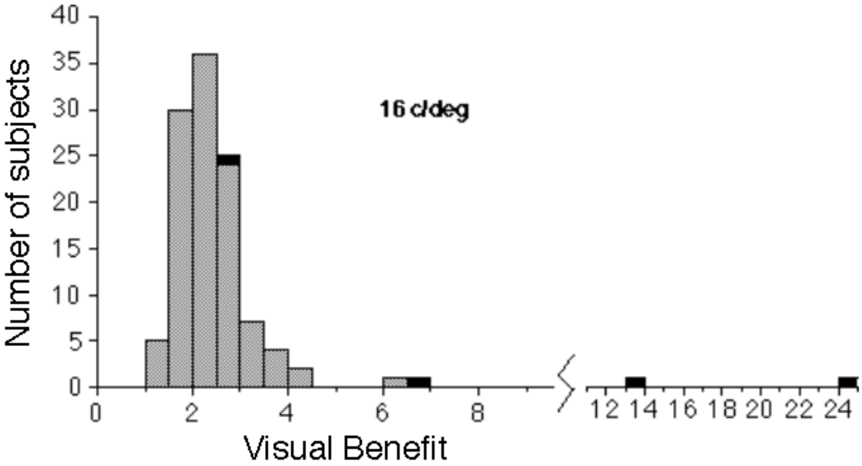

Figure 11. Expected visual benefit of higher order aberration correction in white light for 113 human subjects across a 5.7 mm pupil at 16 c/deg. Normal subjects are shown in grey while keratoconic subjects are shown in black.

The visual benefit in the keratoconic patients is much larger. One of these subjects, in the early stages of keratoconus, presents a visual benefit similar to those for normal subjects. The other three, however, show larger benefits than any normal subject does in the population (one as high as a factor of 25). These results suggests that abnormal eyes, such as a keratoconic eye that suffers from large amounts of aberration, stand to gain the most from a customized method that corrects higher order aberrations. Moreover, a large portion of the normal subjects in our population could reap significant improvements in vision, especially for large pupils.

5. Constraints on the Visual Benefit of Higher Order Correction

The benefit obtained when correcting higher order aberrations with an adaptive optics system are subjectively obvious. Is this benefit great enough, to warrant the development of customized correcting methods? There are some important caveats about the visual benefit that could be realized by customized correction procedures in ordinary vision. Factors such as chromatic aberration, pupil size, accommodation, temporal instability of the wave aberration, and centration errors during corneal or contact lens ablation will all play a part in reducing the maximum visual benefit attainable with any corrective procedure. In this section, we will briefly discuss these factors that could potentially reduce the maximum visual benefit attainable from a customized procedure.

5.1. Chromatic aberration

The eye's chromatic aberration poses one of the strongest limitations on the visual benefit that could be obtained with a customized correction of the eye's aberrations. Chromatic aberration is not particularly deleterious under normal viewing conditions because its effect is overwhelmed by the combined effect of the numerous monochromatic aberrations. The residual higher order aberrations remaining after a conventional refraction with spectacles or contact lenses help to dilute the impact of axial chromatic aberration (Yoon *et al.*, 1999). It is not until the higher order monochromatic aberrations are corrected that the full impact of chromatic aberration is revealed. Fig. 12 illustrates the effect of chromatic aberrations on the visual benefit of correcting higher order monochro-

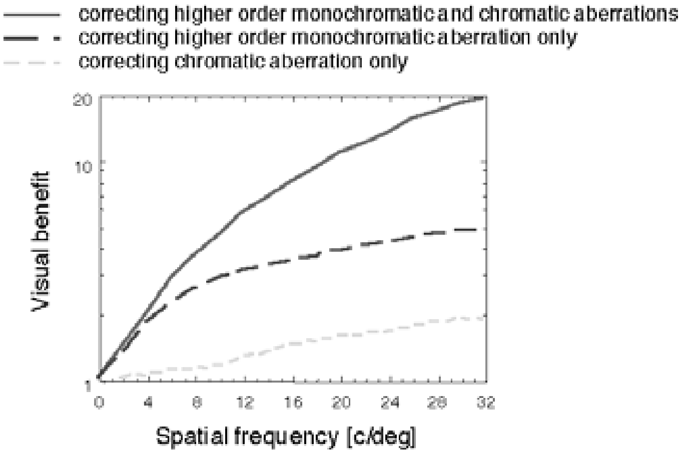

Figure 12. Visual benefit of correcting higher order monochromatic aberrations and/or chromatic aberration for a 6 mm pupil in white light.

matic aberrations. Although the effects of chromatic aberration are substantial, it reduces the theoretical visual benefit by as much as a factor of 5, and the experimentally measured visual benefit by about a factor of 2.

5.2. Pupil size

Pupil size affects the visual benefit that can be expected from the correction of higher order aberrations. Fig. 13 shows PSFs for two different pupil sizes. Image quality for a small pupil size (2-3 mm) is limited mainly by diffraction. For large pupil sizes, the dominant sources of image degradation are the eye's aberrations. Average MTFs for two pupil sizes in monochromatic light are shown in Fig. 14 (Liang & Williams, 1997).

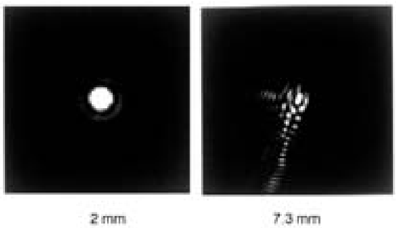

Figure 13. PSFs of two different pupil sizes. Diffraction dominates the PSF (and hence the quality of the retinal image) for small pupil sizes, while aberrations are the major source of degradation in the PSF (and retinal image) for large pupils.

In each panel, the bold solid line represents the diffraction limited MTF in which all of the eye's monochromatic aberrations are corrected. The solid curve with square symbols denotes the average MTF when defocus and astigmatism have been corrected. These figures indicate that correcting defocus and astigmatism has a larger impact on improving visual performance when the pupil is small. The MTF when defocus and astigmatism are corrected lies very close to the diffraction-limited MTF for the 3 mm pupil size since higher order aberrations are generally small for a small pupil size. On the other hand, merely correcting defocus and astigmatism is not enough for a large pupil, as subjects are left with an MTF that is considerably lower than the diffraction-limited case. The top panels show the visual benefit of correcting higher order aberrations, which can be calculated by the ratio of improvement achieved by the correction of all monochromatic aberrations to that achieved by the correction of defocus and astigmatism. It is clear that the largest visual benefit of a customized correction of the eye's higher order aberrations is achieved for large pupils.

5.3. The effect of accommodation

Any attempt to improve the eye's optics with a customized correction will only be beneficial if the values of the eye's aberrations are relatively stable. If the eye's aberrations fluctuate, any efforts made to improve vision may have limited value. It is therefore important to note that the eye's higher order aberrations

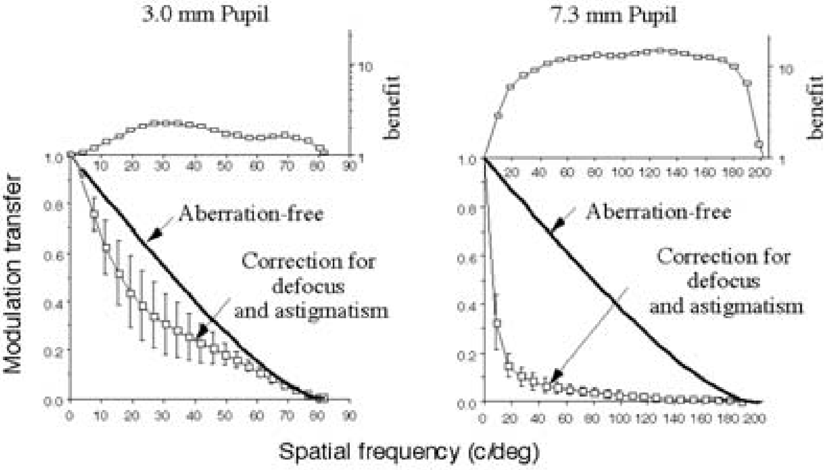

Figure 14. Calculated maximum visual benefit in monochromatic light for two different pupil sizes is shown in the upper parts of both figures. The lower half of each figure shows the mean of the radially averaged MTF from 12 (3 mm) and 14 (7.3 mm) subjects when only defocus and astigmatism have been corrected (squares) and when all of the eye's monochromatic aberrations have been corrected (bold line) (Liang & Williams, 1997).

can change substantially with accommodation. How will the visual benefit that could be obtained with a customized correction be affected by these fluctuations in the eye's optical quality. Fig. 15 shows how three of the eye's aberrations; coma, astigmatism, and spherical aberration; varied for a 4.7 mm pupil in three subjects as they smoothly changed their accommodation from distant (far point) to near accommodation (about 2 diopters) (Artal *et al.*, 1999b). Although the nature of the change in the eye's higher order aberrations is generally different in different subjects, it is clear that for each subject there are substantial, systematic changes in the aberrations that depend on accommodative state. This means that a higher order correction tailored for distance vision would not be appropriate for near viewing and vice versa.

5.4. Temporal instability

If the aberrations of the eye are temporally stable, then the methods that correct static aberrations, such as contact lenses and refractive surgery, are very useful. However, if the aberrations vary in time, the benefit resulting from these correcting methods will not be sufficient, and a dynamic correcting method will be required to deal with the temporal characteristics of the eye's aberrations.

The dynamics of the eye's wave aberrations have been measured (Hofer *et al.*, in press). Fig. 16 shows the temporal power spectrum of the rms wavefront error obtained from two subjects. This plot is the mean data of two subjects, whose accommodation was kept at infinity for a pupil size of 4.7 mm. This graph illustrates the trend that the low temporal frequency components are larger in

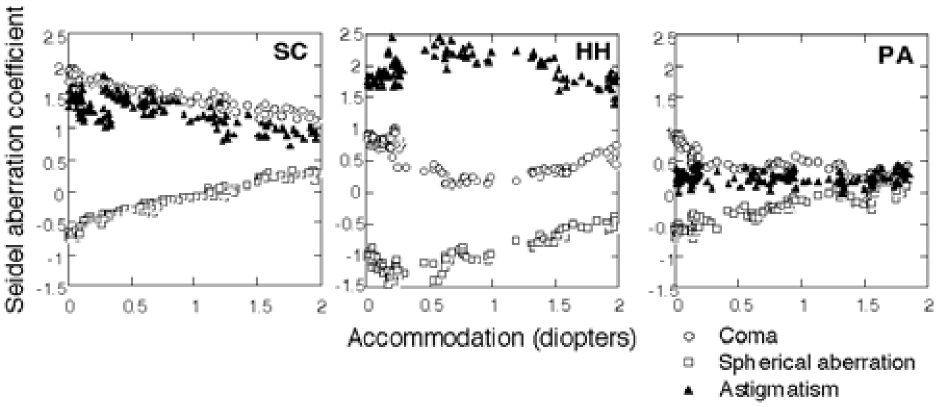

Figure 15. Changes of three higher order aberrations; coma (circles), astigmatism (triangles) and spherical aberration (squares); over a 2 diopter change in focus for a 4.7 mm pupil. These three aberrations were calculated from wave aberration data using a real-time Hartmann-Shack wavefront sensor operating at a rate of 25 Hz.

magnitude than the high temporal frequency components. From the previous section with the open and closed loop rms, one see that these dynamics can reduce the performance of the system by about a factor of 2.

For a fixed accommodative state, the wave aberration of the eye is stable both within a day and probably over a period of many months as well. Although similar data for more subjects would be required to make a definitive statement about longer periods, the evidence that is available indicates that a custom surgical procedure to correct higher order aberrations would be of value to the patient for an extended period of time.

Although we believe the wave aberration to be fairly stable over relatively long time periods, it is known that spatial vision does deteriorate with age (Owsley *et al.*, 1983). In addition to neural factors, a significant steady increment in ocular aberrations with age has been found (Artal *et al.*, 1993; Guirao *et al.*, 1999), which produces a degraded retinal image in the older eye. Both changes in the crystalline lens (Cook *et al.*, 1994; Glasser and Campbell, 1998) and changes in the cornea (Oshika *et al.*, 1999; Guirao *et al.*, 2000b) are responsible. However, the cause of the degradation of the eye's optical quality is the loss of the aberration balance between cornea and lens that seems to be present in the younger eye (Artal & Guirao, 1998; Artal *et al.*, 1999a, Berrio *et al.*, 2000). These factors ultimately limit the longevity of an effective customized correction.

5.5. Accuracy of the correcting method

The visual benefit that could be achieved by correcting the eye's higher order aberrations will be limited by any decentrations or rotations of the correcting method. In this section, we will describe the accuracy and the limit of the methods.

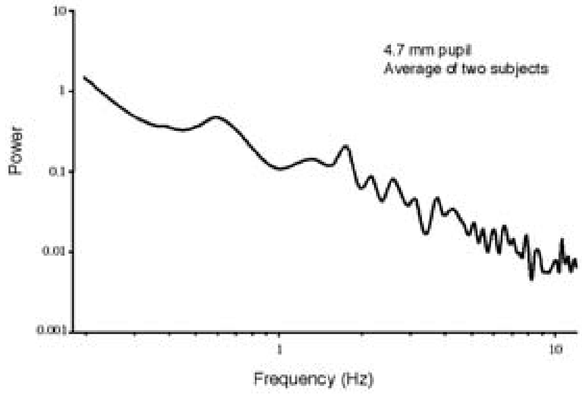

Figure 16. Temporal fluctuations of higher order aberrations across a 4.7 mm pupil. The plot shows the average result for two subjects who were accommodating at infinity.

Customized contact lenses will work best when they are exactly centered on the eye to compensate for all of the higher order aberrations. However, a customized contact lens will still translate and rotate with respect to the eye's pupil, slightly decreasing their effectiveness since some higher order aberrations depend on position and direction. Calculations suggest that reasonable decentrations and rotations do not greatly detract from the potential benefit (Guirao *et al.*, 2000a, 2001).

Fig. 17 shows the effects of (a) the fixed rotations and (b) the fixed translations on the ocular MTF in monochromatic light for a 7 mm pupil, averaged across 10 subjects, after correcting higher order aberrations. The solid line shows the ideal correction corresponding to a complete compensation of the eye's aberrations. The finely dotted line shows the MTF for a conventional correction that only removes defocus and astigmatism. Maximum translations and rotations reported for soft contact lenses allow us to estimate their typical decentration to be within a range of 0.2-0.3 mm of standard deviation for translation, and 2-3 degree for rotation (Tomlinson *et al.*, 1994; Schwiegerling & Snyder, 2000). The remaining curves shown in Fig. 17 illustrate the impact of movements within this reasonable interval on the MTF. These typical decentrations and rotations will slightly reduce the optical benefits expected from the ideal correction. Even with fixed translations or rotations of up to 0.6 mm and 30 degrees, a correction of the higher order aberrations would still yield an improvement over a typical sphero-cylindrical refraction.

5.6. Current refractive surgical procedures

As described in the preceding chapter, the refractive surgery such as LASIK changes the curvature of the cornea so that it changes the optical quality of the eye to correct defocus. Figure 18 shows the wave aberration, PSF and the retinal images of a patient and a typical subject. It is clearly shown that the patient has a large amount of s pherical aberration at the pupil margin.

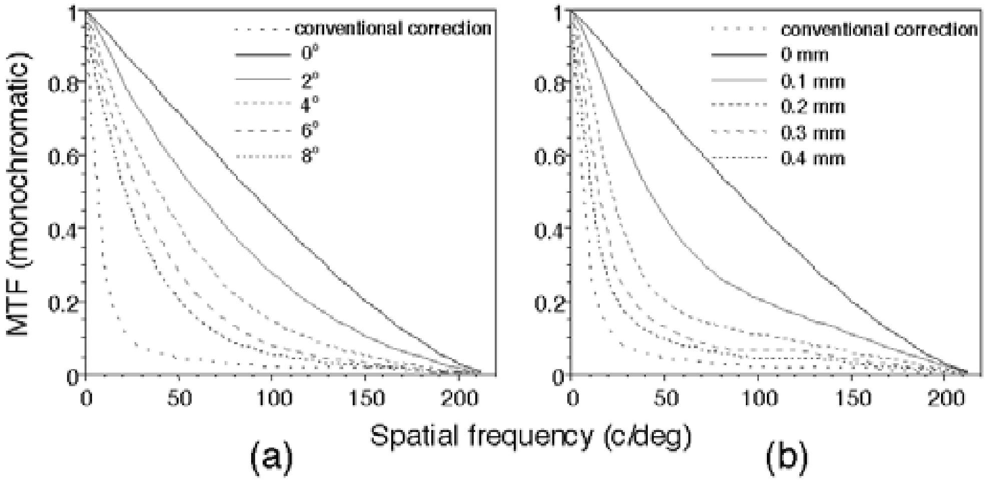

Figure 17. The effect of (a) rotation and (b) translation of an ideal contact lens on the eye's monochromatic MTF for a 7 mm pupil.

This implies that with a large size pupil, the subject may suffer from higher aberrations which were introduced by the operation. Correcting higher order aberrations with a surgical method has a possibility that it will induce some new aberration, although the residual total aberrations might be reduced. The surgery combined with a wavefront sensing may reduce the total amount of aberrations, and it will be useful in correcting them.

6. Summary

In this chapter, we have described several methods used to correct higher order aberrations in the human eye. Spectacles, which correct only defocus and astigmatism, have made it possible for most of the population to have a clear view of the world. New corrective technologies that can eliminate higher order aberrations might raise visual performance standards to a higher level. As presented in the previous section, there are several factors that need to be considered when trying to perfect these customized techniques, such as adaptive optics, customized contact lenses and laser refractive surgery. However, the results shown here indicate that many normal and pathological subjects can reap the benefits of a customized correction of their higher order aberrations, encouraging the continued development and implementation of these corrective methods for everyday vision.

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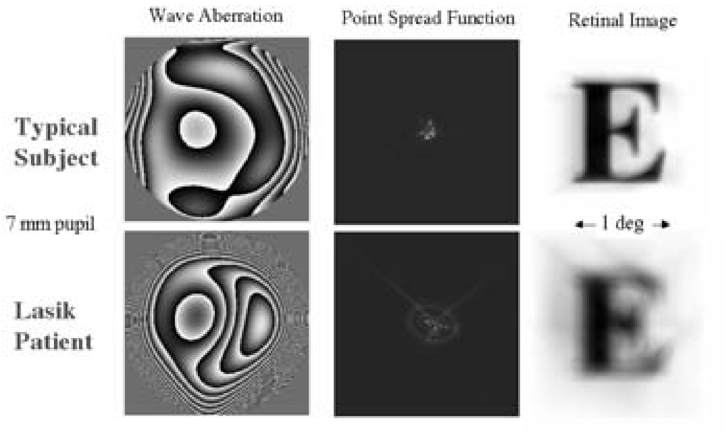

Figure 18. The wave aberration, PSF and retinal image of a typical subject and a LASIK patient for a 7 mm pupil size.

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