Correcting Highly Aberrated Eyes Using Large-stroke Adaptive Optics

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ABSTRACT

PURPOSE: To investigate the optical performance of a large-stroke deformable mirror in correcting large aberrations in highly aberrated eyes.

METHODS: A large-stroke deformable mirror (Mirao 52D; Imagine Eyes) and a Shack-Hartmann wavefront sensor were used in an adaptive optics system. Closed-loop correction of the static aberrations of a phase plate designed for an advanced keratoconic eye was performed for a 6-mm pupil. The same adaptive optics system was also used to correct the aberrations in one eye each of two moderate keratoconic and three normal human eyes for a 6-mm pupil.

RESULTS: With closed-loop correction of the phase plate, the total root-mean-square (RMS) over a 6-mm pupil was reduced from 3.54 to 0.04 μm in 30 to 40 iterations, corresponding to 3 to 4 seconds. Adaptive optics closed-loop correction reduced an average total RMS of 1.73±0.998 to 0.10±0.017 μm (higher order RMS of 0.39±0.124 to 0.06±0.004 μm) in the three normal eyes and 2.73±1.754 to 0.10±0.001 μm (higher order RMS of 1.82±1.058 to 0.05±0.017 μm) in the two keratoconic eyes.

CONCLUSIONS: Aberrations in both normal and highly aberrated eyes were successfully corrected using the large-stroke deformable mirror to provide almost perfect optical quality. This mirror can be a powerful tool to assess the limit of visual performance achievable after correcting the aberrations, especially in eyes with abnormal corneal profiles. [*J Refract Surg.* 2007;23:947-952.]

The growth of wavefront-sensing techniques in vision science has contributed significantly to the measurement and correction of ocular aberrations in many eyes.[1-3] Studies of the eye's wave aberrations in a normal population showed significant amounts of higher order aberrations apart from defocus and astigmatism.[4-6] Higher order aberrations have a significant impact on vision in normal and abnormal eyes.[7] Eyes with abnormal corneal conditions such as keratoconus and corneal transplant have larger amplitudes of higher order aberrations than normal eyes,[8] which implies that the visual benefit of higher order aberration correction will be correspondingly larger.[7,9] Optical and surgical methods such as adaptive optics,[9,10] phase plates,[11] customized contact lenses,[12,13] and customized laser refractive surgery[14,15] have been proposed to compensate for higher order aberrations in such eyes to provide improvement in vision.

One specific advantage of adaptive optics over other methods is the ability to assess the visual benefit of correcting aberrations noninvasively in real-time. Liang et al[3] were the first to successfully use adaptive optics to measure and correct the higher order monochromatic wave aberrations in normal eyes. Yoon and Williams[9] evaluated the visual benefit of correcting higher order aberrations in normal eyes using adaptive optics in white light to account for ocular chromatic aberration. A similar study demonstrating the correction of aberrations in abnormal eyes has been limited by the insufficient stroke (magnitude of deformation) of conventional wavefront correctors in adaptive optics systems.[16]

Effective adaptive optics compensation of aberrations requires the maximum correctable magnitude of error (dynamic

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range) of the wavefront corrector to be at least equal to the peak-to-valley error of the aberrations.[16] When examining higher order aberrations alone, Doble et al[16] showed that the average peak-to-valley error that encompassed 95% of the two normal populations analyzed in their study was approximately 5 µm for a 6-mm pupil. Eyes with abnormal corneal conditions are affected by higher magnitudes of higher order aberrations, approximately 5 to 6 times more than what is typically observed in normal eyes for a 6-mm pupil.[8,17] In 19 keratoconic eyes, Pantanelli et al[17] measured a mean±standard deviation peak-to-valley error of 14.67±10.616 µm (6-mm pupil). These eyes, in particular, are dominated by negative vertical coma.[8,17]

Most conventional wavefront correctors have sufficient stroke to correct higher order aberrations in normal eyes with second order aberrations pre-corrected by other means (eg, trial lenses), but they are limited by their inadequate dynamic range to correct the higher order aberrations in keratoconic eyes. The purpose of this study was to investigate the optical performance of a large-stroke deformable mirror in correcting large aberrations in highly aberrated eyes. This article presents static (phase plate) and dynamic (normal and keratoconic eyes) aberration correction performance using large-stroke adaptive optics.

PATIENTS AND METHODS

The University of Rochester Research Review Board approved this research and all patients signed an informed consent before their participation in this study.

A super-luminescent diode laser (Volga Technology Ltd, Bridgend, United Kingdom) set at 830 nm with a bandwidth of 30 nm was used as a light source to form a laser beacon on the retina. Such a light source with a large spectral bandwidth reduces speckle in the final Shack-Hartmann spot array pattern introduced from back reflections from the retina. Input laser power on the cornea was approximately 10 µW. The adaptive optics experimental set-up consisted of a large-stroke deformable mirror (Mirao 52D; Imagine Eyes, Orsay, France)[18] and a custom-made in-house Shack-Hartmann wavefront sensor. The Shack-Hartmann microlens array had a spacing of 300 µm and a focal length of 7.6 mm. Each spot formed by the microlens array was imaged on a charge coupled device camera having a pixel size of 7.4 µm. The wave aberrations expressed in terms of Zernike coefficients were calculated from this spot array pattern. We measured the wave aberrations for a 6-mm pupil and computed 63 Zernike coefficients corresponding to 10th order Zernike polynomials. The Zernike coefficients are expressed according to ANSI Z80.28-2004 standard.[19]

The deformable mirror consisted of a magnetic membrane whose movement could be controlled by applying voltages to 52 independent actuators. The eye's pupil, the deformable mirror, and the microlens array were conjugated using image relay optics. A 6-mm pupil of the eye was magnified optically to cover 14 mm of the deformable mirror aperture and then was demagnified from the deformable mirror to cover a 6-mm pupil on the microlens array. Although a 14-mm aperture of the mirror encompassed 36 mirror actuators completely, all 52 actuators were used to control the mirror to reduce errors introduced by edge effects. The closed-loop control of the deformable mirror was obtained using the direct-slope algorithm.[20]

Influence functions composed of slopes corresponding to the spot displacements in x and y directions generated by the mirror surface deformation on applying unit voltages to each actuator were combined to form an influence function matrix (M). The slopes in x and y directions as computed from the horizontal and vertical Shack-Hartmann spot displacements, corresponding to the aberrations of an eye, are combined to form a slope vector ($\vec{S}$). Vector $\vec{V}$ containing the set of voltages to be applied to each mirror actuator is calculated by multiplying the inverse influence matrix with the slope vector as follows:

$$\vec{V} = gM^{-1}\,\vec{S}.$$

The gain factor g denotes the proportional magnitude of the wavefront corrected in each iteration and ranges between 0 and 1. This process is repeated recursively in a closed loop until the ocular aberrations are optimally corrected. Such an adaptive optics control is more reliable than a conventional algorithm that might be affected by wavefront reconstruction error. In addition, this method is faster than a conventional wavefront-based algorithm[21] because it does not necessitate the reconstruction of the wavefront shape.

The adaptive optics system can measure and correct the eye's aberrations in real time at rates up to 30 Hz (a rate ultimately limited by the speed of the wavefront sensor charge coupled device camera). For this study, it was operated at a rate of 10 Hz with Shack-Hartmann image exposures of 100 ms. These parameters were determined empirically to give the best trade-off between speed and noise, resulting in optimal correction. The mirror was evaluated first for linearity by measuring the magnitude of the peak deformation of the surface with applied voltages to single actuators. Hysteresis characteristics were subsequently assessed. Individual Zernike modes up to the 6th order were constructed using the mirror to estimate the maximum magnitudes of modes that can be generated reliably without introducing other undesirable modes.

TABLE

Maximum Magnitudes (μm) of Each Zernike Mode (Z_n^m)* Generated With the Deformable Mirror Over a 6-mm Pupil

n \ m	−6	−5	−4	−3	−2	−1	0	1	2	3	4	5	6
2					7		10		7				
3				5		5		5		5			
4			2		2		2		2		2		
5		2		1		1		1		1		2	
6	1		0.5		0.2		0.2		0.2		0.5		1

n = radial order, m = azimuthal frequency
**Expressed according to ANSI Z80.28-2004 standard.[19]*

Closed-loop correction of static aberrations from a phase plate designed for an advanced keratoconic eye was performed for a 6-mm pupil. The keratometric readings from corneal topography maps were used to classify the keratoconic patients as moderate or advanced, as suggested in the Collaborative Longitudinal Evaluation of Keratoconus study.[22] The same adaptive optics system was then used to correct the aberrations in two moderate keratoconic (K1 and K2) and three normal (N1, N2, and N3) eyes for a 6-mm pupil. K1 and K2 had uncorrected spherical/cylindrical refractive errors of −5.10 diopters (D)/2.60 D and 6.00 D/1.00 D, respectively. N1, N2, and N3 had uncorrected spherical/cylindrical refractive errors of −6.50 D/0 D, −2.10 D/0.90 D, and 0.90 D/0.90 D, respectively.

Paralysis of accommodation and dilation of the pupil in all patients were achieved with 1% tropicamide ophthalmic solution. We partially compensated for defocus and astigmatism prior to closed-loop correction in the highly aberrated eyes and one normal eye (N1) using a Badal system and a phoropter to conserve the dynamic range of the deformable mirror. Head movements were stabilized in all patients using a bite bar mount. The residual aberrations were averaged from 5 to 15 seconds after correction to determine the overall corrective performance. Root-mean-square (RMS) wavefront error and higher order RMS were used as metrics to quantify the correction of aberrations.

RESULTS

DEFORMABLE MIRROR CHARACTERISTICS

The magnitudes of the mirror surface deformation as a function of the applied voltage showed 99.99% linearity. The maximum strokes measured for one of the central and peripheral actuators were 38.43 and 27.36 μm in wavefront error, respectively. Individual Zernike modes were constructed using the mirror to estimate the maximum magnitudes of modes that can be generated reliably without inducing spurious modes. The large dynamic range of the mirror allowed individual 2nd order Zernike modes up to 7 to 10 μm RMS, 3rd order modes up to 5 μm RMS, 4th order modes up to 2 μm RMS, 5th order modes up to 1 to 2 μm RMS, and 6th order modes up to 0.2 to 1 μm RMS to be accurately produced with negligibly small residual aberrations of less than 0.15 μm RMS. The Table shows the maximum magnitude of each individual mode over a 6-mm pupil that can be fabricated reliably with the large-stroke adaptive optics.

ADAPTIVE OPTICS CORRECTION OF STATIC ABERRATION: PHASE PLATE

The phase plate designed for an advanced keratoconic eye served as a static aberration generator and had negative vertical coma (−2.21 μm) and positive horizontal coma (1.74 μm) as the most dominant higher order aberrations. The total RMS and higher order RMS for the wave aberrations of the phase plate were 3.54 and 3 μm, respectively, over a 6-mm pupil that corresponded to a peak-to-valley error of 19.72 μm. In closed-loop correction, the total RMS and higher order RMS of the phase plate over a 6-mm pupil were reduced to 0.038 and 0.037 μm, respectively, in 30 to 40 iterations corresponding to 3 to 4 seconds at 10 frames per second. The RMS obtained after correction was smaller than the diffraction-limited RMS, indicating an almost perfect optical quality with the correction of static aberrations. The gain used for this static correction was 0.2 (ie, 20% of the aberrations measured with the Shack-Hartmann wavefront sensor were corrected in each iteration). Figure 1 shows the time-course of the correction of the static aberrations of the phase plate and the wavefront height maps before and after adaptive optics correction.

ADAPTIVE OPTICS CORRECTION OF THE EYE'S ABERRATIONS

Mean±standard deviation of the total RMS and higher order RMS across the three normal eyes was 1.73±0.998

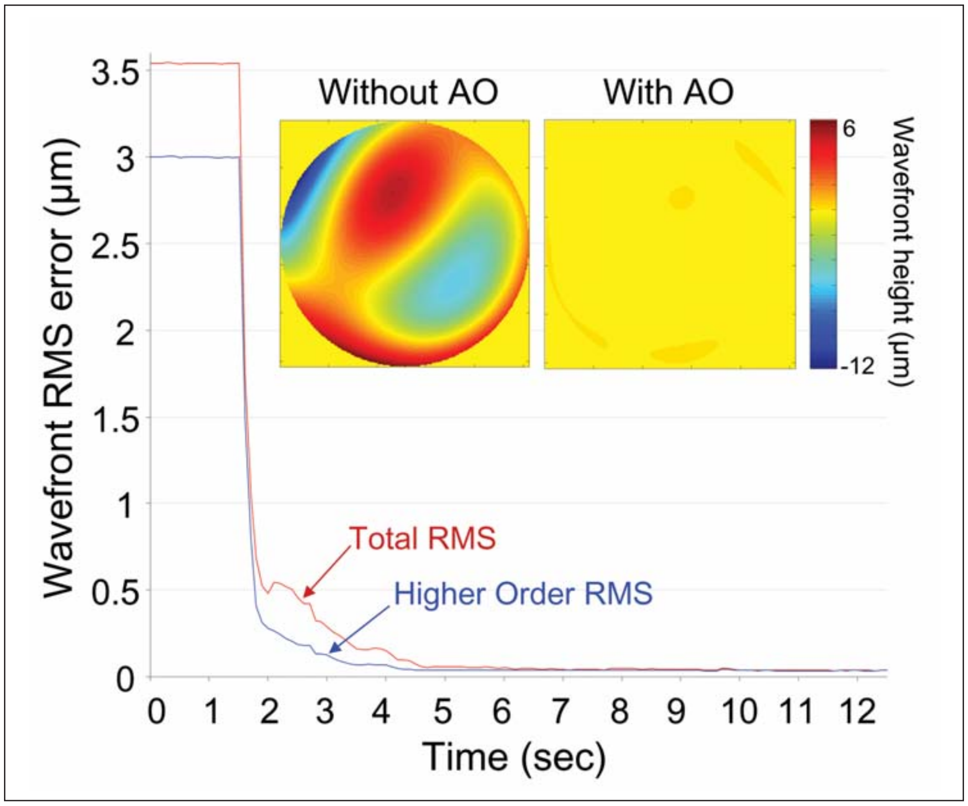

Figure 1. Time-course of the correction of the static aberrations of the phase plate. The two curves represent the evolution of total root-mean-square (RMS) (red) and higher order RMS (HORMS) (blue) after the adaptive optics (AO) was switched on. The wavefront height maps on the same color scale for the aberrations of the phase plate as measured without and with adaptive optics for a 6-mm pupil are also shown.

and 0.39±0.124 µm, respectively, over a 6-mm pupil and after refractive error compensation for N1. In the closed-loop correction, the mean±standard deviation of the total RMS and higher order RMS was reduced to 0.10±0.017 and 0.06±0.004 µm, respectively. The gain used for the correction of both normal and keratoconic eyes was 0.05.

For the two keratoconic eyes, adaptive optics closed-loop correction reduced the average pre-compensated total RMS from 2.73±1.754 to 0.10±0.001 µm and the average pre-compensated higher order RMS from 1.82±1.058 to 0.05±0.017 µm. The adaptive optics correction performance indicates the ability of large-stroke adaptive optics to provide almost perfect optical quality in both cases, irrespective of the different magnitudes of aberrations in the two sets of eyes.

Figure 2A shows the total RMS before and after correction for the three normal and two keratoconic eyes. Convolved images of the letter "E" based on the measured aberrations were also calculated under the normal viewing condition by including chromatic aberrations to simulate retinal image quality and are shown in Figure 2B for normal (N1) and keratoconic (K1) eyes. The letter size used in this simulation corresponded to a 20/40 Snellen letter. The polychromatic point spread functions together with their corresponding Strehl ratios, as computed from the measured aberrations, are also shown in Figure 2B.

As expected, the theoretical improvement in retinal image quality and Strehl ratio is more pronounced in the keratoconic eyes than in normal eyes given the relatively larger magnitudes of higher order aberrations in the keratoconic eyes. The absolute values of the polychromatic Strehl ratios for both groups of eyes are still relatively low due to the presence of chromatic aberrations that are not corrected by adaptive optics but are still close to the maximum achievable Strehl ratio of 0.2 under white light conditions. The monochromatic Strehl ratio for N1 without and with adaptive optics was 0.023 and 0.925, respectively, whereas that for K1 without and with adaptive optics was 0.007 and 0.877, respectively.

DISCUSSION

Our study showed the feasibility of correcting large aberrations in highly aberrated eyes using large-stroke adaptive optics. The large-stroke adaptive optics can provide almost perfect optical quality in both normal and keratoconic eyes as long as the peak-to-valley error of the aberrations to be corrected is within the dynamic range of the deformable mirror. For both normal and keratoconic eyes, we pre-compensated for defocus and astigmatism prior to adaptive optics correction when the peak-to-valley value of the total aberrations was larger than the maximum stroke of the mirror. For a 6-mm pupil, Doble et al[16] reported a peak-to-valley error of nearly 30 µm in wavefront, accounting for 95% of the normal population.

In the current study, we evaluated adaptive optics cor-

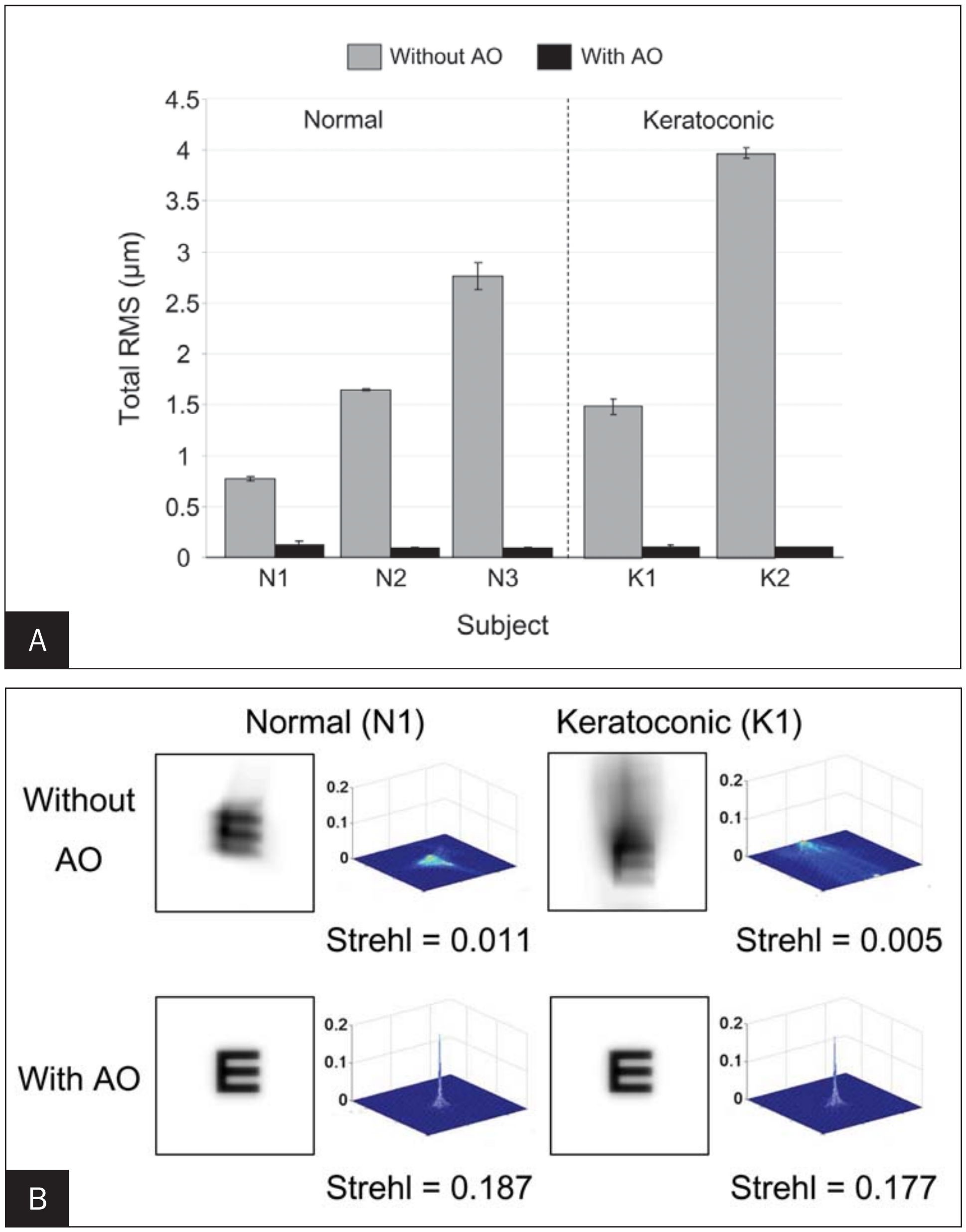

Figure 2. A) Total root-mean-square (RMS) before and after adaptive optics (AO) correction for the three normal and two keratoconic eyes over a 6-mm pupil. The RMS values shown for a normal eye (N1) and both keratoconic eyes were measured after the pre-compensation of second order aberrations. **B)** Convolved images of the letter "E" based on the measured aberrations calculated under the normal viewing condition including chromatic aberrations to simulate retinal image quality for normal (N1) and keratoconic (K1) eyes. The letter size used in this simulation corresponds to a 20/40 Snellen letter. Polychromatic point spread functions together with Strehl ratios as computed from the measured aberrations are also shown.

rection performance based on the aberrations measured with the wavefront sensor. It is important to note that the point spread function should be measured for more complete evaluation of the large-stroke adaptive optics performance because other high frequency optical defects are not measurable with the wavefront sensor.

The 97-channel deformable mirror manufactured by Xinetics Inc (Devens, Mass) and the MEMS Boston Micromachines (Boston Micromachines Corp, Cambridge, Mass) mirror have maximum strokes of 8 and 4 µm, respectively, in wavefront.[23] This dynamic range can sufficiently correct normal eyes (with defocus and astigmatism pre-corrected) to the same level as the deformable mirror used in our study.[23] However, these mirrors have insufficient stroke to correct the aberrations in the keratoconic eyes, even after pre-correction of defocus and astigmatism. In addition, the relatively large aperture size of the Xinetics mirror requires a high pupil magnification that may be disadvantageous, especially for a future clinical adaptive optics system. However, these mirrors have the benefit of a greater number of actuators (Xinetics: 97, Boston Micromachines: 144), which makes them feasible to correct a wavefront with higher spatial frequencies.

A combination of a bimorph and a MEMS deformable mirror has been demonstrated in cascade to achieve a higher overall dynamic range of the adaptive optics with more degrees of freedom.[24] Using this system, Chen et al[24] also demonstrated the capability of axial sectioning in scanning laser ophthalmoscopy, providing an easier way to move the focus axially through the different layers of the retina. It would be ideal if a single deformable mirror had a sufficient dynamic range and number of actuators to achieve this high-resolution retinal imaging more rapidly. In abnormal eyes, a large-stroke deformable mirror can aid in obtaining adaptive optics corrected retinal images, helping to visualize retinal pathologies in these eyes.

Another application of the large-stroke adaptive optics system in vision science and ophthalmology is for vision testing in eyes with abnormal corneal conditions. An assessment of visual quality after correcting higher order aberrations in these eyes will be an effective screening process before customized contact lens fitting to provide optimal visual performance with a corrective option. Investigating interaction between optics of the eye and the human visual system is also interesting.

The neural adaptation to optical blur in normal eyes has been studied by Artal et al.[25] The results of that experiment supported the hypothesis that the visual system may be adapted to the eye's particular higher order aberrations, even in normal eyes. This effect could be even more significant in eyes with abnormal corneas because these eyes have experienced poor optical quality for many years. Although the large-stroke adaptive optics system can provide them with perfect optical quality with some pre-correction, whether they can immediately achieve perfect visual performance as predicted by optical theory remains an intriguing question. Addressing this question may provide both scientific and clinical insights for customized vision correction.

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