Vision Improvement by Correcting Higher-order Aberrations With Phase Plates in Normal Eyes

Geunyoung Yoon, PhD; Tae Moon Jeong, PhD; Ian G. Cox, PhD; David R. Williams, PhD

ABSTRACT

PURPOSE: To psychophysically demonstrate vision improvement when correcting higher-order aberrations with phase plates in normal eyes.

METHODS: The wavefront aberrations of three nonsurgical normal eyes were measured with a Shack-Hartmann wavefront sensor. With these measured aberrations, phase plates were fabricated using a lathing technique. Theoretical improvement in retinal image quality was estimated by calculating the optical modulation transfer functions under the white light condition. Visual acuity measurements were also conducted to demonstrate improvement in visual performance after correcting higher-order aberrations with the phase plate. In this visual acuity measurement, a tumbling "E" with high (100%) and low (10%) contrast was used.

RESULTS: The phase plate reduced the higher-order root mean square (RMS) wavefront error from 0.39 ± 0.09 to 0.15 ± 0.02 µm (mean ± standard deviation from three eyes) for a 6-mm pupil. With the phase plate, retinal image quality based on the volume of modulation transfer function under 60 cycles per degree (c/deg) was improved by a factor of 1.8 ± 0.4 over that of the eyes with spherocylindrical correction only. Average improvement in visual acuity achieved by correcting the higher-order aberration was 0.23 lines with high-contrast letters and 1.12 lines with low-contrast letters. All subjects reported subjective improvement in image quality of the letter with the phase plate.

CONCLUSION: The phase plate effectively corrected the higher-order aberrations in normal eyes.

As a result, both retinal image quality and visual acuity especially with the low-contrast letters were improved. This study demonstrated the feasibility of correcting higher-order aberrations and improving vision with customized optics. [*J Refract Surg* 2004;20:S523-S527]

Since wavefront-sensing techniques were developed for vision research[1,2], studies on the ocular wavefront aberrations and their correction in human eyes have drastically evolved.[3,4] By measuring the eye's wave aberration in a normal population, Porter[5] found significant amounts of higher-order aberration that may degrade visual performance. In contrast to the second-order aberrations such as defocus and astigmatism, these aberrations cannot be corrected with conventional spectacles and contact lenses. The remaining higher-order aberrations can still significantly deteriorate the visual performance of human eyes. Guirao et al[6] and Yoon and Williams[7] calculated the theoretical visual benefit under the condition that these higher-order aberrations were perfectly corrected. They concluded that correcting higher-order aberrations provides visual benefit even in normal eyes. This benefit can be significantly increased in eyes with abnormal corneal conditions such as keratoconus and corneal transplant simply because they have much larger amounts of the higher-order aberration than normal eyes.

To compensate for higher-order aberrations, optical and clinical methods, such as an adaptive optics (AO) system[7,8], phase plates[9], customized contact lenses[10], and customized refractive surgery[11], have been proposed and proven to be effective. The first vision improvement under monochromatic light by correcting higher-order aberrations was obtained with the AO system by Liang.[4] Yoon[7] also demonstrated vision improvement in contrast sensitivity

and visual acuity under white light condition with the AO system. Even though the AO system is a powerful and noninvasive tool to correct the higher-order aberrations, it is an impractical correction method because of the size of the entire system. Laser refractive surgery is also available for customized vision correction. It is, however, a nonreversible surgical method and its availability is restricted by factors such as corneal thickness and the amount of higher-order aberration. The phase plate, as one of these customized optical corrections, is another practical candidate for higher-order correction. With phase plates, Navarro[9] observed considerable reduction of higher-order aberrations in human eyes and Burns[12] obtained superior retinal images by correcting higher-order aberrations.

Psychophysical vision improvement using phase plates has not yet been experimentally demonstrated. The purpose of our study is to demonstrate the feasibility of using a phase plate to improve visual performance by correcting higher-order aberrations in normal eyes. This paper presents correction of the higher-order aberration with a phase plate and demonstration of theoretical improvement in retinal image quality using the optical modulation transfer function. We then demonstrate psychophysical vision improvement by measuring visual acuity with low and high contrast letters.

SUBJECTS AND METHODS

This research was approved by the University of Rochester Research Subject Review Board and all subjects signed an informed consent before their participation in this study.

Three normal, nonsurgical eyes (GY, JP, and IC) were used in our experiments. The mean ± standard deviation of spherical and cylindrical refractive errors was -0.40 ± 0.70 diopters (D) and -0.60 ± 0.20 D, respectively. Subject GY had a higher-order RMS of 0.38 μm and spherical aberration amounting to 0.32 μm for a 6-mm pupil. For the same pupil size, major higher-order aberrations (higher order RMS error = 0.32 μm) of subject JP were coma (0.26 μm) and spherical aberration (0.15 μm). Subject IC had relatively large amounts of higher-order aberrations compared to other normal subjects: coma (0.34 μm), trefoil (0.21 μm), and spherical aberration (-0.23 μm). The higher-order RMS for subject IC was 0.49 μm for a 6-mm pupil. With these measured aberrations, phase plates were fabricated with plastic (PMMA) pieces using a lathing technique.

A Helium-Neon laser was used as a light source to form a laser beacon on the retina. A 400-μm incident beam diameter was used to reduce variability of the laser beacon size on the retina that may occur due to local refractive error of the eye where the beam passes through. The corneal reflection was avoided by shifting the incident beam from the apex of the cornea.[13] Input laser power on the cornea was approximately 10 μW.

The experimental setup consisted of two parts: a wavefront sensor and an auxiliary system to aid in visual acuity measurement. In the wavefront sensing path, two-image relay optic systems were used to create multiple conjugate planes with the eye's pupil. The first conjugate plane was used for the placement of phase plates. Although the phase plate is physically separated from the eye, it is optically on the cornea. This makes it possible to correct the higher-order aberrations on the plane of the corneal apex, not the spectacle plane. The microlens array for the Shack-Hartmann wavefront sensor was located in another conjugate pupil plane. With this setup, we measured the wave aberration of the eye before and after correcting higher-order aberration, namely without and with phase plate. The microlens array had a spacing of 400 μm and a focal length of 5.2 mm. Each spot formed by the microlens was imaged on a CCD camera. The wave aberration expressed in terms of Zernike coefficients was calculated from this spot array pattern. We measured the wave aberration for a 7.09-mm pupil and computed 63 Zernike coefficients corresponding to up to 10th order Zernike polynomials. The measured Zernike coefficients were theoretically renormalized for a 6-mm pupil. The measured wave aberration was used to calculate the white light modulation transfer function to estimate theoretical visual benefit of correcting higher-order aberrations under different experimental conditions. For the white light modulation transfer functions, the equal energy spectrum, namely, perfect white light source was assumed and the photopic luminosity function (V-lambda) was used to weigh the monochromatic modulation transfer functions at each wavelength. Other detailed methods used in this calculation were described elsewhere.[7]

In the visual acuity test branch, we used a computer projector (Sharp, Notevision PMG-20X) as a display device that used a digital micromirror device (DMD) that is small and bright compared to conventional CRT monitors. This projector was located at the focus of the achromatic imaging lens, which is a conjugate plane with the retina. The magnification between the retinal and projector planes was 23, assuming the eye's focal length is 17.6 mm. The

projector was controlled by a computer. The computer sent a calibrated video signal of the capitalized letter "E" to the projector as an acuity testing target. The letter "E" was programmed to have four orientations—0°, 90°, 180°, and 270°. This orientation was randomly changed and the subject's task was to respond to the orientation of the letter "E". We used the same psychophysical procedure to determine visual acuity, described elsewhere.[7] An aperture in the psychophysical path was put on the conjugate pupil plane and used to control pupil size for visual acuity measurement. High (100%) and low (10%) contrast visual acuities were measured with the spherocylindrical correction only and both lower- and higher-order corrections. The refractions of sphere and cylinder were subjectively optimized with a conventional trial lens. The result under this condition, the best conventional correction, was used as a baseline to compare visual benefit of correcting higher-order aberrations. All visual acuities under each condition were measured at least four times. Two-tailed Student's *t*-tests were conducted to test statistical significance when comparing visual acuity with and without higher-order aberration correction.

RESULTS

Correction of Wavefront Aberrations

Figure 1A shows a plot of Zernike coefficients with and without the phase plate for subject IC. Coma, trefoil, and spherical aberrations were significantly reduced with phase plates. Mean ± standard deviation of the higher-order RMS across three subjects was reduced from 0.39 ± 0.09 to 0.15 ± 0.02 μm for a 6-mm pupil. Figure 1B shows the wavefront map of higher-order aberrations for a 6-mm pupil before and after correcting monochromatic aberrations with phase plates. The small amount of residual higher-order aberration is due to manufacturing error of the phase plates and slight misalignment between the pupil and the phase plate due to eye movement.

Theoretical improvement in retinal image quality was evaluated by calculating the modulation transfer functions based on the measured wave aberration with and without phase plate. Figure 2A shows three different white light modulation transfer functions for a 6-mm pupil averaged from three eyes used in visual acuity experiments. Each modulation transfer function from the bottom corresponds to the naked eye, the eye with spherocylindrical correction, the lower-order and higher-order corrected eye with the phase plate, and diffraction-limited eye,
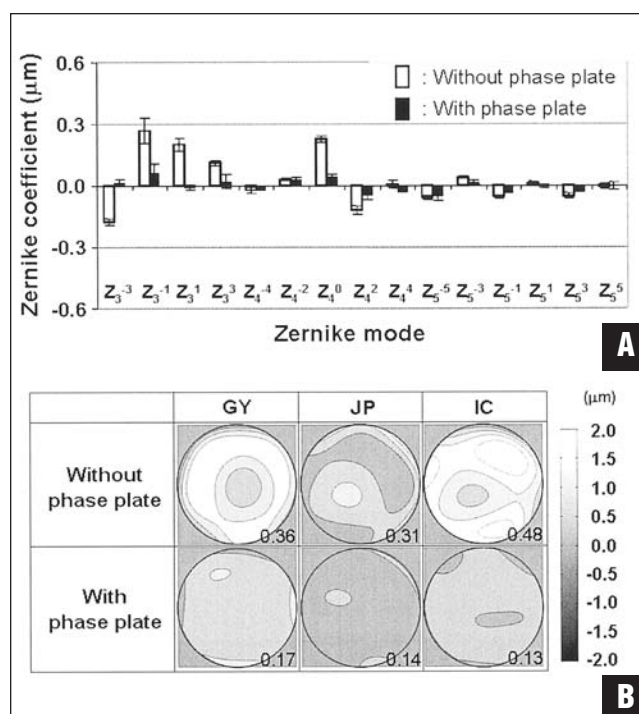

Figure 1. A) Plot of Zernike coefficients with and without the phase plate for subject IC. Major higher-order aberrations, coma, trefoil, and spherical aberration were substantially reduced with the phase plates. Error bars represent ± standard deviation. **B)** Higher-order wavefront aberration map for each subject with and without higher-order correction. Numbers in each map represent higher-order RMS values. The difference in wavefront height between contour lines is 0.75 μm. Phase plates effectively reduced the higher-order aberration in all subjects.

namely perfect correction of all aberrations. Under each condition, the volume modulation transfer functions up to 60 cycles per degree (c/deg) were 35%, 42%, and 73% of the polychromatic diffraction-limited modulation transfer function, respectively. Visual benefit of correcting higher-order aberrations, which is defined by the ratio of the volume modulation transfer function between the eye with spherocylindrical correction and the lower-order and higher-order corrected eye, was 1.8 on average.

Convolved images of the letter "E" based on the measured aberration were also calculated for each subject under the normal viewing condition to simulate retinal image quality. Figure 2B shows convolved images of letter "E" with no correction, spherocylindrical correction, and second- and higher-order correction. As shown in Figure 2B, although the spherocylindrical correction greatly improved retinal image quality, the best image quality was obtained from correction of higher-order aberrations. Especially for subject IC, the horizontally
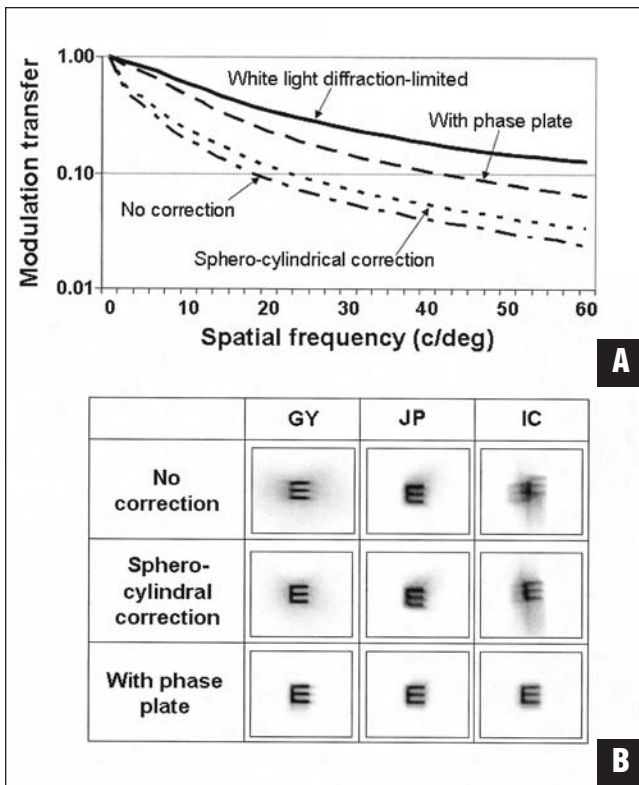
Figure 2. A) Average white light modulation transfer functions calculated with the three subjects' aberrations with no correction (dashed dot line), the spherocylindrical correction (dotted line), the second- and higher-order correction (dashed line), and perfect correction (solid line). Error bars were not included to avoid complexity. **B)** Simulated retinal images for each subject under the white light condition. Higher-order corrections further improve retinal image quality compared to the spherocylindrical correction. The letter size of the E used in this simulation corresponds to a 20/40 Snellen letter.

flipped secondary image was observed from the naked eye's aberration and could not be removed by the spherocylindrical refractive correction. This horizontally flipped secondary image was removed only through the correction of higher-order aberrations. Subject IC reported the same retinal images with the spherocylindrical correction and higher-order aberration correction, indicating that theoretically convolved retinal images can be a useful tool to qualitatively explain the improvement in visual performance.

Visual Performance Measurement

Figure 3 shows the high (100%) and low (10%) contrast visual acuities with and without phase plate. The lower-order aberrations, defocus and astigmatism, were first refracted in both cases. The visual acuity was expressed in terms of log minimum angle of resolution (logMAR) units. For the high-
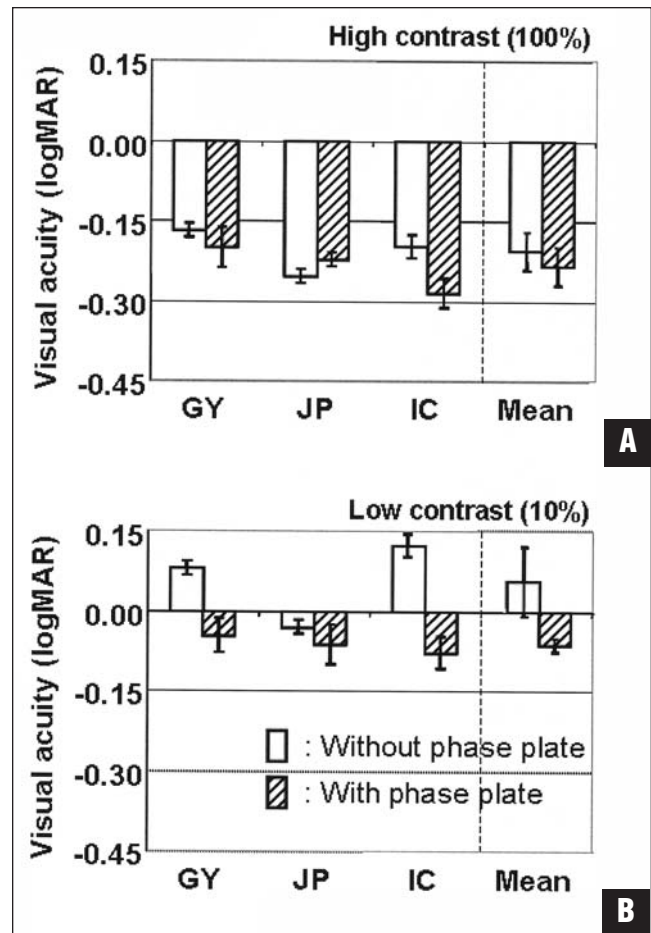

Figure 3. A) High (100%) and **B)** low (10%) contrast visual acuities for the eyes with spherocylindrical correction and the second- and higher-order corrected eyes. The open bar represents the visual acuity for the eye with spherocylindrical correction and hatched bar for the second-order and higher-order corrected eye.

contrast visual acuity experiment, although visual acuity was improved by 0.02 logMAR units on average, this average improvement was not statistically significant (P=.46). Vision improvement with the low-contrast letter target was significantly larger than that in the high-contrast letter target. In the low-contrast visual acuity experiments, the average vision improvements of 0.11 logMAR units (P=.06) were observed. Although the small sample (n=3) only gave P=.06 for a relatively large change in visual acuity, two subjects (GY and IC) showed statistically significant improvement. This result indicates that nonsurgical normal eyes experienced approximately 1 line of improvement in low-contrast visual acuity.

DISCUSSION

Our study showed the feasibility of using customized optics to correct higher-order aberrations

and to improve visual performance. It is expected that larger visual benefit can possibly be achieved by correcting the higher-order aberrations in eyes with abnormal corneal conditions such as keratoconus and corneal transplant. Factors such as pupil size, peripheral visual performance, and movement of corrective optics reduce visual benefit of correcting higher-order aberrations. The visual benefit for a smaller pupil is reduced simply because the magnitude of the higher-order aberration contained becomes smaller as the pupil size is decreased. The maximum visual benefit from the modulation transfer functions for a 4.4-mm pupil calculated with the population data is approximately 1.7 at 16 c/deg compared to 2.5 for a 5.7-mm pupil at the same spatial frequency.[6] Although within relatively small visual fields, retinal image quality stays similar to that at the fovea, it is important to note that correcting the higher-order aberration to improve foveal vision may not be optimal for peripheral vision affected by the off-axis aberration. However, it is also possible to optimize retinal image quality for both foveal and peripheral vision using the measured aberration at different eccentricities if required.[14] In our experiment, any misalignment of the phase plate to the eye's pupil was minimized by using a pupil camera that can simultaneously monitor the position of both the eye's pupil and phase plate. However, during visual acuity measurement, dynamic eye movement may reduce the visual benefit. The high-contrast visual acuity data for the subject JP is a good example, showing that visual acuity became worse after higher-order aberration correction, although this subject reported subjective improvement in image quality of the letter with the phase plate. Also, any unexpected movement of customized optics that may occur in the practical use of these optics is a major factor, reducing the visual benefit of correcting higher-order aberrations. In some eyes, the movement could make visual performance worse than without higher-order correction unless a special algorithm[15] is used to optimize how many higher-order aberrations should be attempted to correct to minimize this reduction in visual bene-

fit due to lens movement. It would be a challenge to achieve similar vision improvement using more practical optical components such as customized contact lenses and intraocular lenses when decentration and rotation of the lens exist.

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