Effects of spherical aberration on visual acuity at different contrasts

Jing Li, MD, Ying Xiong, MD, PhD, Ningli Wang, MD, PhD, Shiming Li, MD, Yun Dai, PhD, Lixia Xue, PhD, Haoxin Zhao, PhD, Wenhan Jiang, PhD, Yudong Zhang, PhD

PURPOSE: To evaluate the effect of spherical aberration on visual acuity by correcting and inducing spherical aberration using an adaptive optics vision simulator.

SETTING: Laboratory of Vision Science, Capital Medical University, Beijing, and Institute of Optics and Electronics, Chinese Academy of Sciences, Chengdu, China.

METHODS: An adaptive optics vision simulator comprising a wavefront sensor and a 37-segmented deformable mirror was used to correct and induce aberrations of the eye. The effective ocular wavefront aberration was manipulated with the deformable mirror, as the resulting visual performance was simultaneously measured. Subjective visual acuity measurements were performed with a 6.0 mm pupil. Visual acuity at different contrasts was measured when spherical aberration was fully corrected and the other natural aberrations in the eye were present and when spherical aberration values were induced with the other aberrations corrected.

RESULTS: The natural root-mean-square (RMS) value of spherical aberration in the 8 subjects examined was between −0.11 μm and 0.14 μm. There was no significant improvement in visual acuity with spherical aberration corrected and the subjects' natural aberrations present. When all aberrations were corrected, a decrease in visual acuity occurred when spherical aberration RMS was induced at 0.2 μm and 0.3 μm.

CONCLUSIONS: When fluctuation of other natural aberrations in the eye were present, there was a slight effect on visual acuity when the spherical aberration RMS was approximately 0.1 μm. Therefore, an RMS value of 0.1 μm could be an acceptable amount of spherical aberration when correcting spherical aberrations.

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The human eye is not a perfect optical system; therefore, the quality of the retinal image is degraded by scatter, diffraction, and wavefront aberrations. Clinical observations after intraocular lens (IOL) implantation or laser refractive surgery show that some patients report visual side effects (ghost images, glare, halos) and late-onset reduced visual acuity.[1,2]

Based on the recent development of wavefront technology and functional vision tests, some researchers have recognized the relationship between increased wavefront aberration and degradation in visual quality.[3,4] As age increases, the optical quality of the crystalline lens changes. This primarily results in a progressive increase in wavefront aberrations, in particular spherical aberration. The negative spherical aberration in a lens of a younger person can compensate for the positive spherical aberration of the cornea.[5,6] However, in older eyes, the spherical aberration in the crystalline lens progressively shifts to positive values, increasing the total aberration in the eye and resulting in decreased visual function. In addition, all current IOLs with spherical surfaces have positive spherical aberration, adding to the positive spherical aberration in the cornea and resulting in suboptimum visual function for the patient.

Clinical studies[7–9] also show that laser refractive surgery increases higher-order aberrations (HOAs), mainly spherical and coma. Several recent studies focused on the correction of wavefront aberrations. Guirao et al.[10] and Yoon and Williams[3] report that after correcting for HOAs, the optical quality and visual quality were improved to varying levels.

Furthermore, customized visual correction guided by measured wavefront aberrations is widely used in several clinical applications such as laser refractive surgery,[11,12] contact lenses,[13,14] and IOLs.[15,16]

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Adaptive optics technology is an effective tool that can be used in a controlled laboratory study of the visual benefit of correcting HOAs.[4]

In this study, an adaptive optics visual simulator was used to correct and induce spherical aberration to detect how spherical aberration affects visual acuity at high and low contrasts and how much spherical aberration can be tolerated with or without the presence of other natural aberrations in the eye.

SUBJECTS AND METHODS

This study included normal young subjects who were selected after passing a conventional ophthalmic examination that indicated their eyes were healthy. The study adhered to the tenets of the Declaration of Helsinki, and all subjects signed informed consent after receiving an explanation of the purpose and possible consequences of the study and of cycloplegia and mydriasis. An ethics committee approved the study.

Adaptive Optics Vision Simulator

In brief, the adaptive optics system consists of a 37-actuator piezo deformable mirror with a stroke of approximately 2 μm and a Hartmann-Shack wavefront sensor with 97 lenslets operating at 25 Hz. In this study, the wavefront aberrations were reconstructed or filtered using the first 20 Zernike polynomials. The bandwidth of adaptive optics system is approximately 1 Hz.

In the system, a laser diode with a 905 nm output wavelength is used as a beacon. The beacon is collimated as a parallel light after it passes through a spatial filter and the beam expander, is reflected by the mirror and the beam splitter, and then is directed into the subject's eye. The backward-scattered light from the subject's retina exits through the pupil, passes through a deformable mirror and pupil-matching system, and then projects onto a Hartmann-Shack wavefront sensor. The wavefront slope data measured by the wavefront sensor are acquired by a computer. By using the direct-slope algorithm and control algorithm, the slope data set is transformed into voltage data and used to drive the deformable mirror to correct the eye's aberration or construct a different aberration pattern. Therefore, eyes with different aberrations can be evaluated. Using measurement software, contrast sensitivity or visual acuity under different conditions can be measured. The power entering the human eye is approximately 2 μW, which is below the standard of the International Electrotechnical Commission.

Visual Acuity Testing

Visual stimulation was presented on a computer-controlled organic light-emitting diode micro display (EMA-100110, eMagin) that self-illuminates with a 550 nm monochromatic light source. A Freiburg Acuity Test[17] software package was used to measure the subject's monocular visual acuity through the adaptive optics system. The acuity software was run on a separate personal computer connected to the adaptive optics system's internal micro display monitor. The subject viewed the miniature monitor though the deformable mirror and pupil conjugation lenses of the simulator. These optical elements and the monitor were coaxially aligned in the system. The subject was presented with black Landolt C optotypes and responded by indicating the optotype orientation on a numeric keypad. After each response, the visual acuity software automatically modified the optotype size according to parameter estimation by a sequential testing method and then randomly selected a new optotype orientation from 4 directions. Each visual acuity test was terminated after 24 optotypes were presented. This staircase method provides a rapid psychophysical procedure to estimate visual acuity thresholds. Because the presentations depended only on the subject's response, the examiner's bias was minimized. To reduce the influence of learning effects, the subjects completed training acuity tests before the actual testing began.

Subjective visual acuity was measured under green light with a 6.0 mm (artificial) pupil. Two drops of tropicamide and phenylephrine ophthalmic solution (tropicamide 0.5% and phenylephrine 0.5%) were administered approximately 40 minutes before testing to initiate cycloplegia and mydriasis.

Testing comprised 4 procedures at 100% contrast and 10% contrast. All procedures were performed after defocus and astigmatism were corrected using trial lenses. Then, to compensate for the chromatic aberration in the system and the human eye, the position of visual target was adjusted along the optical axis until the subject clearly saw the target. The 4 procedures were as follows:

1. Visual acuity was measured after the aberrations in the adaptive optics system, called the systematic static aberrations (SSA), were corrected.
2. Spherical aberration in the subject's eye was corrected with the deformable mirror while other HOAs present in the subject's eyes remained uncorrected (SSA+SA).
3. All aberrations were corrected by a dynamic real-time closed-loop approach (CAA).
4. The levels and 2 orientations (0.1, 0.2, 0.3, −0.1, −0.2, and −0.3 μm) of spherical aberration were induced after all

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Jing Li, MD, and Ying Xiong, MD, PhD, contributed equally to this work.

From Beijing Tongren Eye Center (J. Li, Xiong, Wang, S. Li), Beijing Tongren Hospital, Capital Medical University, Beijing, and Institute of Optics and Electronics (Dai, Xue, Zhao, Jiang, Zhang), Chinese Academy of Sciences, Chengdu, China.

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Corresponding author: Ningli Wang, MD, PhD, Beijing Tongren Hospital, Capital Medical University, Beijing Tongren Eye Center, Dongjiaomin Lane 1, Dongcheng District, Beijing 100730, China. E-mail: wningli@vip.163.com.