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Spherical aberration yielding optimum visual performance: Evaluation of intraocular lenses using adaptive optics simulation

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Abstract

PURPOSE—To evaluate the influence of spherical aberration on contrast sensitivity using adaptive optics.

SETTING—Vision Science and Advanced Retinal Imaging Laboratory, Department of Ophthalmology & Vision Science, University of California, Davis Medical Center, Sacramento, California, USA.

METHODS—Contrast sensitivity at 8 cycles per degree was evaluated using an adaptive optics system that permitted aberrations to be measured with a Shack-Hartman wavefront sensor and controlled by a 109 actuator continuous-surface deformable mirror that was at a plane conjugate to the observer's pupil. Vertical Gabor patches were viewed through a 6.3 mm diameter pupil conjugate aperture. Contrast sensitivity was measured with the deformable mirror set to produce 1 of 5 spherical aberration profiles (-0.2 to $+0.2$ μm). Contrast sensitivity over the range of spherical aberration was fitted with a polynomial function.

RESULTS—Three observers (age 21 to 24 years) participated. The measured total mean spherical aberration resulting from the spherical aberration profiles produced by the deformable mirror was between -0.15 μm and $+0.25$ μm . The peak contrast sensitivity of this function for the 3 observers combined occurred at $+0.06$ μm of spherical aberration. The peak contrast sensitivity was also achieved with positive spherical aberration for observer (mean 0.09).

CONCLUSION—There was intersubject variability in the measurements; however, the average visual performance was best with the introduction of a small positive spherical aberration.

Relationships between optimum spatial vision and higher-order aberrations (HOAs) of the eye are complex. In individuals with “supernormal vision” having uncorrected distance visual acuity better than 20/15, the average spherical aberration of the eye is approximately $+0.1$ μm .¹ This amount of positive spherical aberration was also the average in youthful eyes in several other studies with large sample sizes.^{2–4}

To use these findings in the pursuit of optimum spatial vision after cataract surgery, several manufacturers have modified their intraocular lens (IOL) designs so that positive corneal aberration is not completely compensated for, with the intended consequence of leaving a small

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residual postoperative spherical aberration. Three commercially available aspheric IOLs have a different intended target for postoperative spherical aberration that ranges from +0.27 to 0.00 μm .^{5,6}

Several approaches to evaluating HOA correction have been used. These include computation of expected improvements given wide variation in the normal population,⁷ prospective clinical trials to compare IOLs,⁸ and simulation and control of aberrations using contact lenses,⁹ phase plates,¹⁰ and adaptive optics.¹¹ The latter has been used to show significant improvements in contrast sensitivity in younger¹² and elderly¹³ individuals when HOAs are corrected.¹³

In a recent study, Piers et al.¹¹ used an adaptive optics system to evaluate the benefit of customized correction of spherical aberration. A Hartmann-Shack wavefront sensor detected temporally varying aberrations over a 4.8 mm pupil and addressed a deformable mirror with 37 actuators to control HOAs (with static correction of defocus). To extend the dynamic range of the system, aspheric phase plates were introduced with varying amounts of spherical aberration. Visual performance was measured through this system when correcting only spherical aberration Z(4,0) or when introducing a 0.149 μm spherical aberration. The results showed significant improvements in contrast sensitivity with both conditions; however, improvement was greater with customized correction. In a subsequent study, Piers et al.¹⁴ varied spherical aberration over the range of approximately -0.1 to $+0.2$ μm to encompass the range of values found with current aspheric IOLs. The 5 subjects fell into 3 groups, with best contrast sensitivity for negative, zero, or positive spherical aberration. Here, we report results in a similar study using a larger pupil diameter (6.3 mm), which may be more sensitive to variations in spherical aberration.

SUBJECTS AND METHODS

Observers

All observers had a corrected Snellen acuity of 20/15. The presence of abnormal ocular media and retinal disease was ruled out by a comprehensive ophthalmologic examination including slitlamp evaluation and ophthalmoscopy. Written informed consent was obtained following the tenets of the Declaration of Helsinki and with approval of the Institutional Review Board, University of California, Davis, School of Medicine.

Measuring Technique

Figure 1 shows the adaptive optics system used in this study; the visual psychophysics path is shown, but not the retinal imaging arm.¹⁵ Observers were tested monocularly using the preferred eye. The eye chosen for testing was dilated with tropicamide 1% and phenylephrine 2.5%, and head movements were minimized with the use of a bite bar.

A superluminescent diode operating at 835 ± 20 nm was used to form a wavefront sensor beacon on the retina. Light was relayed by telescopes in the path of the deformable mirror, and the eye pupil plane was imaged onto a Shack-Hartmann wavefront sensor. The wavefront was sampled at 20 Hz using a Dalsa camera (model CA-D7) with a 20×20 lenslet array (24.0 mm focal length) over a 7.0 mm pupil. Trial lenses were placed at the spectacle plane to correct sphere and cylinder for all experimental conditions to reduce the 2nd-order Zernike terms (defocus and astigmatism) and optimize the focus of written text on the cathode ray tube (CRT) display. With trial lenses in place, wavefront errors were modified with a 68.0 mm diameter, 109 actuator, continuous-surface deformable mirror (Litton Itek). The deformable mirror was located at a plane conjugate to the observer's pupil, had an approximate mirror stroke of ± 2 μm , and was operated using direct slope control. Contrast sensitivity was measured with the deformable mirror set to produce 1 of 5 spherical aberration profiles (-0.2 μm , -0.1 μm , 0

μm , $+0.1 \mu\text{m}$, $+0.2 \mu\text{m}$), which produced additional spherical aberration on top of the observer's habitual HOAs. This was intended to be analogous to what happens with cataract surgery in which an aspheric IOL functions with the observer's existing HOAs.

Stimuli were viewed through an aperture in a plane conjugate with the eye's pupil to subtend 6.3 mm diameter of the pupil. The stimuli were presented on a gamma-corrected, purpose-built, 25 cm monochrome CRT display ($\lambda_{\text{max}} = 550 \text{ nm}$, Moraine Displays) driven by a Macintosh G4 computer (Apple Inc.) with 10-bit resolution. Before testing, each observer was allowed to adapt to a uniform field of 75 candelas[cd]/m² (luminance measured at the observer's pupil plane) for 5 minutes. After adaptation, a single spherical aberration profile was loaded onto the mirror and held in place throughout the trial period. Contrast sensitivity was measured using a Gabor patch (sinusoidally modulated grating windowed by a Gaussian envelope with a standard deviation of 0.375 degrees at a spatial frequency of 8 cycles per degree [cpd]). The stimuli subtended 1.5 degrees (60.67 pixels per degree), and the mean luminance was the same as the adaptation field. Stimuli were presented for 1 second with a sine-wave modulation at 1 Hz, providing a single temporal contrast cycle. The orientation of the Gabor patch was vertical. The effect of different levels of spherical aberration is not expected to be orientation dependent. Other aberrations (eg, trefoil) would require testing at a greater number of orientations because the change in the point-spread function would be expected to alter contrast sensitivity in an orientation-dependent manner.

Contrast thresholds were determined using the method of adjustment. Five threshold measurements were obtained at each level of spherical aberration for 25 trials. The test data for a fixed level of spherical aberration were collected consecutively, while the order of the different levels of spherical aberration was random. Experimental software was written in MatLab (version 5.2.1, The MathWorks, Inc.) using the psychophysics toolbox extensions.^{16,17}

RESULTS

Three observers (1 woman) aged 21 to 24 years participated in the study. Two observers were emmetropic. The other observer had a refractive error of -3.75 diopters (D) sphere and $+1.00$ D cylinder in the tested eye.

Figure 2 shows the habitual HOAs (3rd through 6th order) in the eyes of the 3 observers after correction of cylinder and sphere with trial lenses. With trial lenses in place, observers had a mean defocus of $0.048 \text{ D} \pm 0.004 \text{ (SD)}$ and mean residual astigmatism $0.10 \pm 0.03 \text{ D}$ before the introduction of additional spherical aberration. In some cases, the addition of spherical aberration increased or decreased the amplitude of the 2nd-order aberrations, with a mean difference of $0.108 \pm 0.03 \text{ D}$ of defocus ($0.2 \pm 0.03 \text{ Z}[0,2]$) and $0.05 \pm 0.01 \text{ D}$ of astigmatism ($0.06 \pm 0.01 \text{ Z}[-2,2]$ and $0.10 \pm 0.02 \text{ Z}[2,2]$). Table 1 shows the spherical aberration $\text{Z}(0,4)$ written to the mirror, the measured spherical aberration for the individual observers, the mean spherical aberration, and the change in spherical aberration. These results show that the deformable mirror had sufficient stroke to produce the desired change in spherical aberration. Figure 3 shows how differing HOAs (3rd and 4th order) for 1 observer were altered by the introduction of additional spherical aberration; HOAs other than spherical aberration were little changed.

Contrast sensitivity at 8 cpd is plotted in Figure 4 as a function of total spherical aberration (each observer's natural spherical aberration combined with that induced on the deformable mirror). Data for all observers fitted with a 2nd-order polynomial showed an r value of 0.65. The peak of the fitted function implies maximum contrast sensitivity at $+0.06 \mu\text{m}$ spherical aberration. The peak is still positive if the point with contrast sensitivity greater than 21 is

omitted. The contrast sensitivity data of each observer were also fitted with a 2nd-order polynomial; in each case, the peak occurred with positive spherical aberrations (mean 0.09 μm).

DISCUSSION

The purpose of this study was to identify the postoperative spherical aberration that optimizes visual performance assessed by contrast sensitivity. Using a state-of-the-art adaptive optics system, the HOAs could be measured and spherical aberration varied systematically. Although we did not measure depth of focus, it has been noted that spherical aberration may improve vision by increasing depth of focus.^{11,18,19}

To simulate natural conditions in which IOLs are implanted (ie, an implanted IOL has a fixed spherical aberration incorporated), we introduced spherical aberration over a 7.0 mm pupil. As a practical matter, however, psychophysical testing was done over a 6.3 mm pupil to avoid edge effects due to limits of the deformable mirror. Changing between 7.0 mm and 6.3 mm pupil diameters will produce a small change in aberrations. To evaluate this effect, we recalculated the Zernike coefficients over a 6.3 mm pupil. This resulted in modest changes in quantitative results and did not affect our conclusions. The mean contrast sensitivity reached a peak with a spherical aberration of 0.09 μm with a 7.0 mm pupil and 0.06 μm with a 6.3 mm pupil. In all cases, the best contrast sensitivity with both pupil diameters was achieved with a positive spherical aberration.

Variability in contrast sensitivity and fitting with a polynomial preclude an exact determination of the optimum spherical aberration; however, our results are consistent with those in a clinical study by Beiko,⁸ who found that targeting a residual spherical aberration of +0.1 μm after cataract surgery resulted in better vision than targeting 0.0 μm . Eyes targeted for +0.1 μm spherical aberration had significantly better contrast sensitivity at 6 cpd and 12 cpd under photopic (85 cd/m^2) and mesopic (3 cd/m^2) conditions. In another study, eyes that had implantation of an AcrySof IQ IOL (Alcon Laboratories) had significantly higher contrast sensitivity than eyes with a Tecnis IOL (Abbott Medical Optics, formerly Advanced Medical Optics) or a spherical IOL (G. Beiko, MD, "Customizing the Correction of Spherical Aberration," *Cataract and Refract Surgery Today* November/December 2006; pages 92–94. Available at: http://www.crstoday.com/PDF%20Articles/1106/CRST1106_17.php. Assessed March 17, 2009).

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References

1. Levy Y, Segal O, Avni I, Zadok D. Ocular higher-order aberrations in eyes with supernormal vision. *Am J Ophthalmol* 2005;139:225–228. [PubMed: 15733980]
2. Wang L, Koch DD. Ocular higher-order aberrations in individuals screened for refractive surgery. *J Cataract Refract Surg* 2003;29:1896–1903. [PubMed: 14604708]
3. Thibos LN, Hong X, Bradley A, Cheng X. Statistical variation of aberration structure and image quality in a normal population of healthy eyes. *J Opt Soc Am A Opt Image Sci Vis* 2002;19:2329–2348. [PubMed: 12469728]
4. Porter J, Guirao A, Cox IG, Williams DR. Monochromatic aberrations of the human eye in a large population. *J Opt Soc Am A Opt Image Sci Vis* 2001;18:1793–1803. [PubMed: 11488483]

5. Beiko GHH, Haigis W, Steinmueller A. Distribution of corneal spherical aberration in a comprehensive ophthalmology practice and whether keratometry can predict aberration values. *J Cataract Refract Surg* 2007;33:848–858. [PubMed: 17466860]
6. Altmann GE, Nichamin LD, Lane SS, Pepose JS. Optical performance of 3 intraocular lens designs in the presence of decentration. *J Cataract Refract Surg* 2005;31:574–585. [PubMed: 15811748]
7. Guirao A, Porter J, Williams DR, Cox IG. Calculated impact of higher-order monochromatic aberrations on retinal image quality in a population of healthy eyes: erratum. *J Opt Soc Am A Opt Image Sci Vis* 2002;19:620–628. [PubMed: 11876329]
8. Beiko GHH. Personalized correction of spherical aberration in cataract surgery. *J Cataract Refract Surg* 2007;33:1455–1460. [PubMed: 17662441]
9. López-Gil N, Castejón-Mochón JF, Benito A, Marín JM, Lo-a-Foe G, Marin G, Fermigier B, Renard D, Joyeux D, Château N, Artal P. Aberration generated by contact lenses with aspheric and asymmetric surfaces. *J Refract Surg* 2002;18:S603–S609. [PubMed: 12361166]
10. Navarro R, Moreno-Barriuso E, Bará S, Mancebo T. Phase plates for wave-aberration compensation in the human eye. *Opt Lett* 2000;25:236–238. [PubMed: 18059840]
11. Piers, PA.; Fernandez, EJ.; Manzanera, S.; Norrby, S.; Artal, P. Adaptive optics simulation of intraocular lenses with modified spherical aberration; *Invest Ophthalmol Vis Sci*. 2004 [Accessed March 17, 2009]. p. 4601-4610. Available at: <http://www.iovs.org/cgi/reprint/45/12/4601>
12. Liang J, Williams DR, Miller DT. Supernormal vision and high-resolution retinal imaging through adaptive optics. *J Opt Soc Am A* 1997;14:2884–2892.
13. Elliott, SL.; Choi, SS.; Doble, N.; Hardy, JL.; Evans, JW.; Werner, JS. Role of high-order aberrations in senescent changes in spatial vision; *J Vision*. 2009 [Accessed March 17, 2009]. p. 24p. 1-16. Available at: <http://www.journalofvision.org/9/2/24/Elliott-2009-jov-9-2-24.pdf>
14. Piers, PA.; Manzanera, S.; Prieto, PM.; Gorceix, N.; Artal, P. Use of adaptive optics to determine the optimal spherical aberration; *J Cataract Refract Surg*. 2007 [Accessed March 17, 2009]. p. 1721-1726. Available at: http://io.um.es/publications/PDFs_main/2007_JCRS_Optica_Adaptativa.pdf
15. Choi, SS.; Doble, N.; Hardy, JL.; Jones, SM.; Keltner, JL.; Olivier, SS.; Werner, JS. In vivo imaging of the photoreceptor mosaic in retinal dystrophies and correlations with visual function; *Invest Ophthalmol Vis Sci*. 2006 [Accessed March 17, 2009]. p. 2080-2092. Available at: <http://www.iovs.org/cgi/reprint/47/5/2080?ck=nck>
16. Brainard, DH. The psychophysics toolbox; *Spatial Vis*. 1997 [Accessed March 17, 2009]. p. 433-436. Available at: <http://color.psych.upenn.edu/brainard/PsychToolbox.pdf>
17. Pelli, DG. The Video Toolbox software for visual psychophysics: transforming numbers in movies; *Spatial Vis*. 1997 [Accessed March 17, 2009]. p. 437-442. Available at: <http://www.psych.nyu.edu/pelli/pubs/pelli1997videotoolbox.pdf>
18. Campbell FW. The depth of field of the human eye. *J Mod Opt* 1957;4:157–164.
19. Nio YK, Jansonius NM, Fidler V, Geraghty E, Norrby S, Kooijman AC. Spherical and irregular aberrations are important for the optimal performance of the human eye. *Ophthalmic Physiol Opt* 2002;22:103–112. [PubMed: 12014483]

Biography

Figure 1.

Psychophysics arm of the adaptive optics system. Dark gray area represents the adaptive optics control loop and the light gray, the noncommon CRT light path (CRT = cathode ray tube display; DM = deformable mirror; SLD = superluminescent diode; WFS = wavefront sensor)

Figure 2.
Total HOAs for 3 observers over a 7.0 mm pupil. Second-order aberrations (defocus and astigmatism) are not included.

Figure 3.
Change in 3rd- and 4th-order wave aberrations for observer 2 with differing amounts of spherical aberration introduced with the deformable mirror (HOAs = higher-order aberrations).

Figure 4.

Mean contrast sensitivity measured at 8 cpd for 3 observers as a function of total spherical aberration RMS error. The error bars denote ± 1 SEM. The data were fitted using a 2nd-order polynomial ($y = 108.27x^2 + 10.66x + 14.41$; $r = 0.65$) (c/deg = cycles per degree; SA RMS = spherical aberration root mean square).

Table 1
Measured spherical aberration for different values induced by the deformable mirror

Parameter	Measured Spherical Aberration (μm)				
	-0.2	-0.1	0.0	+0.1	+0.2
Observer 1	-0.151	-0.057	0.111	0.234	0.322
Observer 2	-0.180	-0.029	0.043	0.104	0.176
Observer 3	-0.129	-0.026	0.071	0.156	0.252
Mean	-0.154	-0.037	0.075	0.165	0.250
Change	-0.229	-0.112	0.000	0.090	0.175