Use of adaptive optics to determine the optimal ocular spherical aberration

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PURPOSE: To explore the impact of spherical aberration (SA) on contrast sensitivity using an adaptive optics vision simulator to determine the optimal amount of SA to include in customized corrections of wavefront aberrations.

SETTING: Laboratorio de Optica, Universidad de Murcia, Murcia, Spain, and AMO Groningen BV, Groningen, The Netherlands.

METHODS: An adaptive optics vision simulator consisting of a wavefront sensor, a 97-segmented deformable mirror to induce and correct aberrations of the eye, and a visual testing path was constructed for this study. The deformable mirror allows the effective ocular wavefront aberration to be manipulated and the resulting visual performance to be measured simultaneously. Subjective measurements of contrast sensitivity at 15 cycles per degree were performed with a 4.8 mm pupil in 5 subjects with different levels of naturally occurring SA. Contrast sensitivity was measured when SA values of -0.09 μm, 0.0 μm, 0.09 μm, and 0.182 μm were induced when the other natural aberrations of the eye were present, when the aberrations were corrected, and at defocus values of ±0.25 diopter (D) and ±0.50 D.

RESULTS: Subjects experienced peak contrast sensitivity performance with varying levels of SA when their natural aberrations were present; however, average contrast performance peaked at 0 μm of SA. When all higher-order aberrations were corrected, all 5 subjects' peak performance occurred at 0 μm of SA.

CONCLUSIONS: The adaptive optics vision simulator reduced the root-mean-square wavefront aberration of the eye by up to a factor of 4 and allowed noninvasive testing of the visual performance resulting from any ocular wavefront aberration introduced by customized correction procedures. This study showed that, on average, contrast performance peaked when SA was completely corrected.

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An individual eye has a distinct wavefront aberration pattern[1–5] that plays a defining role in determining its potential for visual performance. In general, reducing higher-order aberrations (HOAs) improves ocular optical quality, retinal image contrast, and spatial vision.[6,7]

Two topics currently under study by researchers in visual optics and clinical ophthalmology are the relationship between ocular aberrations and spatial vision[8–11] as well as surgeries and devices that reduce higher-order ocular aberrations (those beyond defocus and astigmatism) and improve visual performance and patient satisfaction.[12–20] Customized vision correction targets aberrations on an individual basis and can consist of complete or partial correction of an individual's wavefront aberrations by modifying the optics of the eye. Customization is now available in corneal refractive surgery, contact lenses, and to some extent intraocular lenses (IOLs).

In recent years, the use of adaptive optics in research has significantly increased the understanding of the relationship between wavefront aberrations and visual performance. An adaptive optics visual simulator allows the researcher to simultaneously measure visual performance and manipulate the effective ocular wavefront aberration.[21–23]

In effect, the adaptive optics vision simulator is a noninvasive tool for assessing the effects on visual performance of any theoretical ocular wavefront profile that would be the product of customized aberration-correction procedures. The simulator includes a wavefront sensor to measure the aberration of the eye, an active element to manipulate this wavefront

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aberration, and a visual testing path to determine the resulting spatial vision. We describe the use of the Murcia adaptive optics vision simulator to measure the contrast sensitivity in a small group of young subjects with different controlled levels of induced spherical aberration (SA) to determine whether there is an optimal amount of SA to aim for when performing customized vision correction to provide improved spatial vision. We also investigated the correction's effect on subjective tolerance to small amounts of defocus.

SUBJECTS AND METHODS

The adaptive optics setup used in this experimental study is similar to the adaptive optics vision simulator previously described in the literature[21,22]; however, this setup uses a 97-actuator Xinetics deformable mirror (Xinetics Inc.), which provides improved closed-loop correction for a larger aberration production range and an improved chromatic performance compared with that of low-cost mirrors and liquid-crystal modulators.[24]

Figure 1 is a schematic of the adaptive optics vision simulator used in this study. A near-infrared diode laser illuminates the eye. The light reflected at the retina is relayed to the micro-deformable mirror by lenses L1 to L4 that conjugate the eye pupil with the micro-deformable mirror planes. The combined wavefront aberrations of the eye and the optical system, including the micro-deformable mirror, is measured by the Hartmann-Shack (H-S) wavefront sensor,[25] which is optically conjugated with the mirror plane by lenses L5 to L8. The target wavefront, including partial or total correction of the eye's aberrations and induction of known amounts of SA, is achieved by operating the H-S sensor and the micro-deformable mirror in closed-loop mode. A computer-controlled Badal optometer located between lenses L1 and L2 is used to correct or induce defocus, and a cold mirror placed in front of the H-S sensor allows the subject to participate in visual tests through the modified ocular aberrations. These tests, which are shown on a distant monitor, were developed using the standard Cambridge Research System libraries.

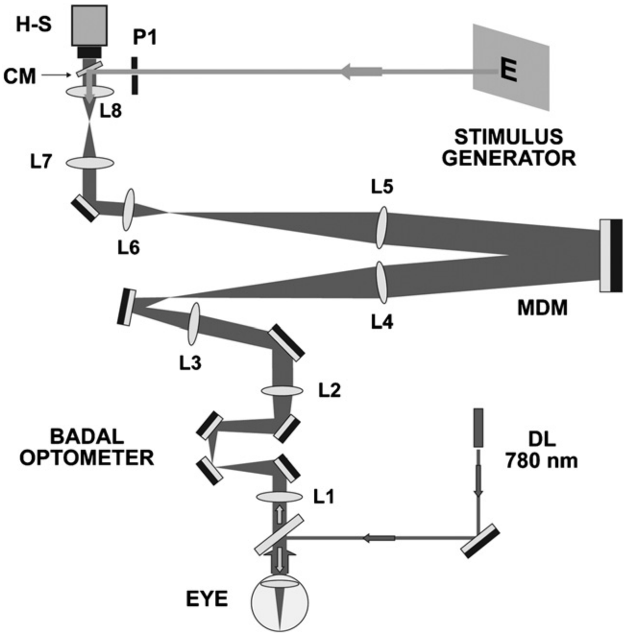

Figure 1. A schematic drawing of the adaptive optics vision simulator (CM = cold mirror; DL = near-infrared diode laser; E = visual testing target; H-S = Hartmann-Shack; MDM = micro-deformable mirror; P = artificial pupil).

Subjects

All procedures conformed to the Declaration of Helsinki requirements for research involving human subjects. Subjective measurements of contrast sensitivity at 15 cycles per degree (cpd) with a 4.8 mm artificial pupil were performed in 5 eyes of 5 subjects (ages 28 to 40 years) for 4 cases of induced ocular SA (−0.09 μm, 0.00 μm, +0.09 μm, and 0.182 μm). These SA testing values were chosen to span the range of values of the average pseudophakic SA found with the aspherical IOLs available today. The subjects had different levels of preexisting ocular wavefront aberration.

The undilated pupil of each subject was aligned with the center of the wavefront sensor and thus with the deformable mirror and the center of the visual testing target. After alignment, 2 drops of tropicamide 1% were instilled approximately 30 minutes before the experiments to initiate cycloplegia and mydriasis.

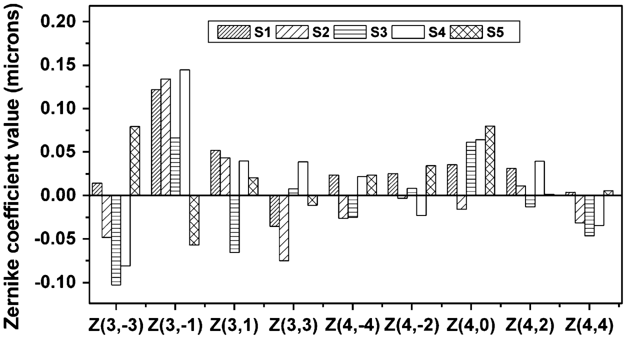

Figure 2. The natural 3rd- and 4th-order wavefront aberrations of the 5 subjects with a 4.8 mm pupil.

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Initially, the HOAs in the subjects' eyes were left uncorrected and visual testing was performed with the subjects' natural aberrations, except SA, present. Figure 2 shows the 3rd- and 4th-order wavefront aberration terms before correction of each subject.

For all 4 SA cases, astigmatism was corrected using the deformable mirror. The subjective best-focus position was determined by allowing the subject to move the Badal optometer (in 0.1 diopter [D] steps) until a target letter E (with stroke separation equivalent to 15 cpd) was judged to be in focus. This location is referred to as the 0 D position in Figures 3 and 4. All defocused measurements were performed by moving the Badal optometer system by the desired amount relative to this best-focus position. Negative values of defocus mean there is a need for negatively powered spherical correction (myopia). Positive values mean there is a need for positively powered spherical correction (hyperopia). Contrast sensitivity was measured at best focus, 4 defocus positions, and ±0.25 D and ±0.5 D, using polychromatic (white) vertical sine-wave targets. Subjects were shown targets that decreased in contrast until the subject could no longer see the grating pattern. This process was repeated 3 times to determine each subject's contrast threshold for each SA and defocus condition. This allowed the SA-defocus space to be partially mapped while identifying the true optimum performance. To avoid learning effects, the different levels of SA were presented in random order. Finally, to at least partially characterize the effect of other aberrations on the optimum SA value, the above tests were repeated with the deformable mirror correcting all higher-order wavefront aberrations (except SA) at once.

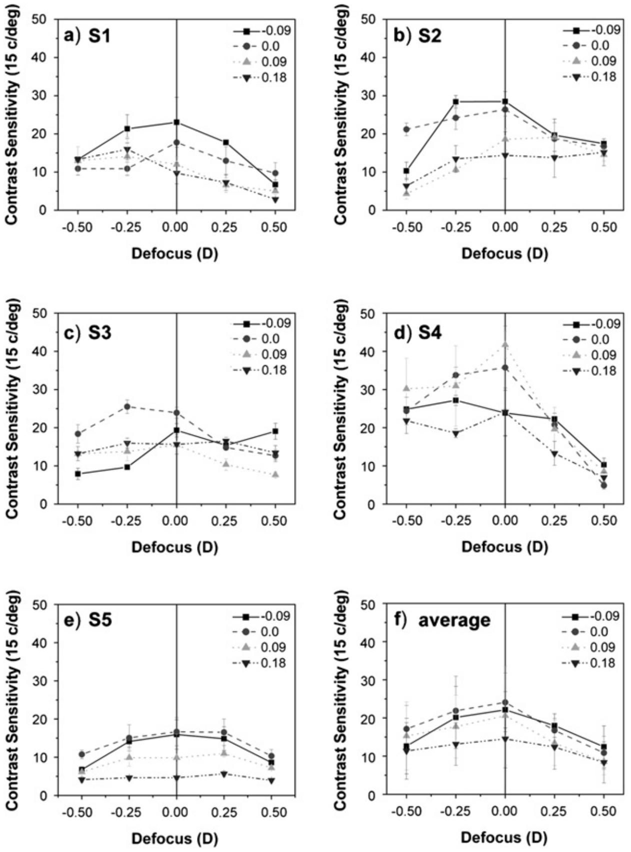

Figure 3. The through-focus contrast sensitivity for each test subject *a*: Subject 1. *b*: Subject 2. *c*: Subject 3. *d*: Subject 4. *e*: Subject 5. *f*: Mean through-focus contrast sensitivity for all subjects measured for 15 cpd with a 4.8 mm pupil and different levels of induced ocular SA with only lower-order astigmatism corrected.

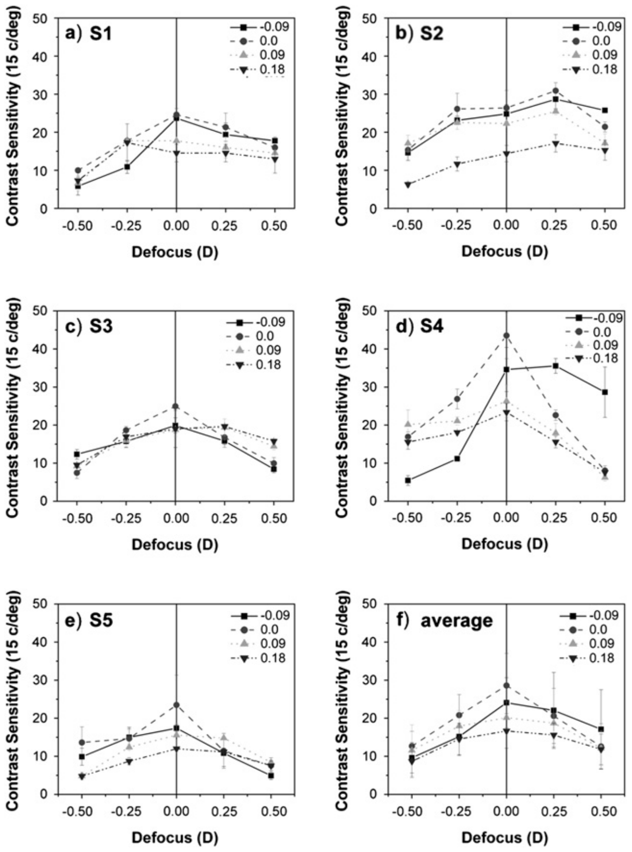

Figure 4. The through-focus contrast sensitivity for each test subject. *a*: Subject 1. *b*: Subject 2. *c*: Subject 3. *d*: Subject 4. *e*: Subject 5. *f*: Mean through-focus contrast sensitivity for all subjects measured for 15 cpd with a 4.8 mm pupil and different levels of induced ocular SA with all higher-order wavefront aberrations corrected.

RESULTS

The through-focus contrast sensitivity for all levels of SA when the HOA remain uncorrected are shown for each subject in Figure 3, *a* to *e*, and the mean for all 5 subjects is shown in Figure 3, *f*. The error bars indicate the standard deviation of the contrast sensitivity measured at each point. Two of the 5 subjects experienced peak contrast sensitivity with negative SA values, 1 experienced peak performance with positive SA, and 2 experienced peak performance with no SA. In terms of mean performance, peak contrast sensitivity was experienced with 0 μm of SA (mean 0.02 μm ± 0.075 [SD]).

The deformable mirror is effective in correcting the monochromatic aberrations of the eye. Figure 5 shows

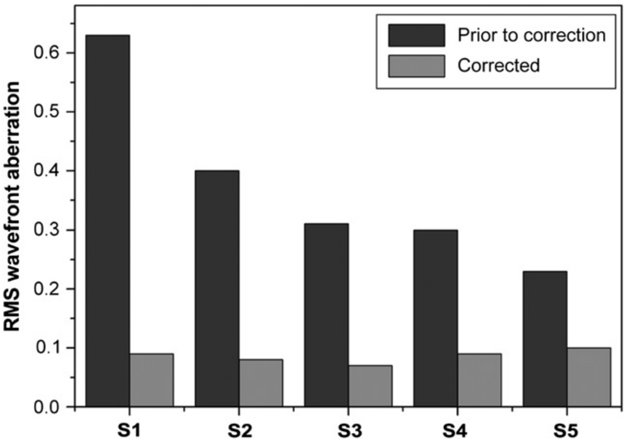

Figure 5. The RMS wavefront aberration of the 5 subjects before and afetre closed-loop correction with a 5.5 mm pupil and the deformable mirror.

the RMS wavefront aberration (in microns) for a 5.5 mm pupil before and after closed-loop correction. Figure 4, *a* to *e*, shows the through-focus contrast sensitivity with a 4.8 mm pupil and the 4 levels of SA when HOAs were corrected for each subject. Figure 4, *f*, shows the mean contrast performance. All 5 subjects had peak performance with 0 μm of SA. The mean contrast performance also peaked at 0 μm of SA.

DISCUSSION

Different lens designs cause pseudophakic eyes with IOLs to have different ocular wavefront aberration patterns.[26,27] Spherical IOLs have positive SA, which results in increased total ocular SA for the average pseudophakic patient.[26,27] All existing aspherical IOLs offer some reduction in SA; however, none addresses corneal SA on an individual level (G. Beiko, MD, "Personalized Correction of Spherical Aberration in Cataract Surgery," presented at the ASCRS Symposium on Cataract, IOL and Refractive Surgery, Washington, DC, USA, April 2005). The spread in corneal SA values in the cataract population contributes to a spread in ocular SA values in pseudophakic eyes. Addressing this variability for various wavefront aberrations, both lower and higher order, is the primary goal of customized IOLs.

An interesting related issue is the amount of SA typically present in subjects with excellent spatial vision. Levy et al.[28] determined that the mean value of root-mean-square (RMS) SA in subjects between the ages of 18 years and 51 years with "supernormal" vision (visual acuity 20/15 or better) was 0.1 μm for pupils larger than 6.0 mm. However, RMS values do not reveal whether the SA is positive or negative.

In a similar study, Schallhorn measured the wavefront aberration in pilots with supernormal vision and found these pilots (mean age 31.6 ± 4.9 years; personal communication, Steven Schallhorn, MD, December 2006) had an average SA component of approximately 0.1 μm for a 6.0 mm pupil (S. Schallhorn, MD, "Deciphering Wavefront Higher-Order Aberrations," Cataract & Refractive Surgery Today, January 2002, pages 47–48. Available at: http://www.crstodayarchive.com/03_archive/0102/crst0102_1_161.html). Alcon et al. found the average SA value in young subjects (younger than 25 years) with excellent visual acuity (better than 20/15) was not significantly different from zero (Alcon E, et al. IOVS 2006; 47:ARVO E-Abstract 1196). The differing results in these 2 studies may be due to the age of the subjects as it is well known that higher-order ocular aberrations, in particular SA, increase with age.[29] Nevertheless, the inconsistency in these study results prompted us to scrutinize the optimal value of SA correction in customized vision techniques.

In a clinical setting in which standard contrast sensitivity testing is performed , 1.5, 3, 6, 12, and 18 cpd are the levels tested. In a study, performed by some authors of the present study, 3, 6, and 15 cpd were used in an adaptive optics vision simulator to determine the improvement that would be provided by IOLs that correct pseudophakic SA. This study was performed using 15 cpd as it is well established from optical modeling that higher spatial frequencies are more sensitive to changes in wavefront aberration. Because this study was intended to determine the optimal value of SA correction and because of the testing times associated with the procedure, it was deemed appropriate to use a higher spatial frequency.

It has been suggested that ocular SA increases depth of focus.[30] Marcos et al.[31] determined theoretically (using the Strehl ratio calculated from wavefront aberrations for varying degrees of defocus) that aspherical IOLs that correct ocular SA showed a decreased tolerance to defocus. Piers et al.[22] also used adaptive optics to study the impact of SA on pseudoaccommodation. That study found that with SA corrected, subjects' visual acuity and contrast sensitivity at 6 cpd was as good as or better than it was when the same subjects had significant amounts of SA (SA similar to that displayed by patients with spherical lenses; ie, 0.15 μm for a 4.8 mm pupil) for defocus values as large as ±1.0 D. Biometric data from pseudophakic eyes and computational modeling were used to predict similar behavior for the through-focus image quality.[32] This study reports similar results for contrast sensitivity at 15 cpd and a larger range of SA values in the cases in which HOAs other than SA were not corrected. In this study, we evaluated a reduced range of defocus (−0.5 to +0.5 D). Each subject had a different degree of tolerance to defocus, which was not symmetrical

Table 1. Each subject's natural SA, SA with the peak value of contrast sensitivity when only astigmatism was corrected, and SA with the peak value of contrast sensitivity when all HOAs were corrected.

		SA Value for CS Peak	
Subject	Natural SA	With Uncorrected HOAs	With Complete Correction of HOAs
1	0.04	−0.09	0
2	−0.02	−0.09	0
3	0.06	0	0
4	0.06	0.09	0
5	0.08	0	0

CS = contrast sensitivity; HOAs = higher-order aberrations; SA = spherical aberration

for positive and negative values of defocus. Our study was not meant to examine depth of focus but rather to scan the SA-defocus space to find the true peak of contrast performance for each individual.

This study included subjects with different preexisting levels of ocular SA so that we could determine whether neural adaptation to aberrations influenced their preference for SA value. It has been shown that subjects prefer their own natural aberration pattern to manipulated patterns.[23] Table 1 shows each subject's natural SA and the SA value that gave each of them the best contrast sensitivity with other HOAs, corrected and uncorrected. Subject 1, whose natural SA was positive, experienced peak contrast performance with a negative SA value. Two subjects (3 and 5) had significantly positive natural SA and experienced peak contrast sensitivity with 0 SA. These 3 cases suggest that in the case of SA, contrast performance is not always the best when values are similar to natural aberration patterns. Spherical aberration and changing defocus are typically balanced, which could prevent significant adaptation.

Spherical aberration and defocus cannot be separated; therefore, customized correction of SA with an IOL must simultaneously lower refractive error to achieve the optimal result. For correction methods such as contact lenses or corneal refractive surgery, if natural accommodation is still present, the coupling of SA and defocus is more complex because SA changes as the eye accommodates[33]; therefore, a single fixed value of SA cannot provide the best correction for all conditions.

CONCLUSION

On first consideration, one might suppose that the large range of and many differences in ocular wavefront aberrations that occur in the general population[2,3] would warrant a larger sample than that chosen for this study. Because the adaptive optics vision simulator allows each subject to be used as his or her own control, we reason that the sample is large enough to draw several conclusions about the optimal ocular SA correction. When HOAs remain uncorrected, the SA value at contrast performance peaks varies from individual to individual. The variation can be attributed to the complex interaction among the different aberration terms.[34] However, on average, in-focus contrast performance peaks when all SA is corrected. When all HOAs are corrected, even accounting for varying patterns in natural aberrations, all subjects achieved peak performance with 0 SA. For the spatial frequency tested in this study, the results suggest that the goal for customized correction of SA should be as close as possible to zero.

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