1040-5488/12/8909-0001/0 VOL. 89, NO. 9, PP. 1–●●●
OPTOMETRY AND VISION SCIENCE

CASE REPORT

Benefit of Adaptive Optics Aberration Correction at Preferred Retinal Locus

Karthikeyan Baskaran*, Robert Rosén†, Peter Lewis*, Peter Unsbo‡, and Jörgen Gustafsson‡§

ABSTRACT

Purpose. To investigate the effect of eccentric refractive correction and full aberration correction on both high- and low-contrast grating resolution at the preferred retinal locus (PRL) of a single low-vision subject with a long-standing central scotoma.

Methods. The subject was a 68-year-old women with bilateral absolute central scotoma due to Stargardt disease. She developed a single PRL located 25° nasally of the damaged macula in her left eye, this being the better of the two eyes. High- (100%) and low-contrast (25 and 10%) grating resolution acuity was evaluated using four different correction conditions. The first two corrections were solely refractive error corrections, namely, habitual spectacle correction and full spherocylindrical correction. The latter two corrections were two versions of adaptive optics corrections of all aberrations, namely, habitual spectacle correction with aberration correction and full spherocylindrical refractive correction with aberration correction.

Results. The mean high-contrast (100%) resolution acuity with her habitual correction was 1.06 logMAR, which improved to 1.00 logMAR with full spherocylindrical correction. Under the same conditions, low-contrast (25%) acuity improved from 1.30 to 1.14 logMAR. With adaptive optics aberration correction, the high-contrast resolution acuities improved to 0.89/0.92 logMAR and the low-contrast acuities improved to 1.04/1.06 logMAR under both correction modalities. The low-contrast (10%) resolution acuity was 1.34 logMAR with adaptive optics aberration correction; however, with purely refractive error corrections, she was unable to identify the orientation of the gratings.

Conclusions. Correction of all aberrations using adaptive optics improves both high- and low-contrast resolution acuity at the PRL of a single low-vision subject with long-standing absolute central scotoma.
(Optom Vis Sci 2012;89:1–●●●)

Key Words: eccentric viewing, preferred retinal locus, absolute central scotoma, adaptive optics, eccentric correction, aberrations

Patients with end-stage macular disorders, such as age-related macular degeneration and Stargardt disease, have absolute central scotomas, which result in the loss of their central vision. Consequently, they have difficulties in performing day to day visual tasks such as reading[1,2] and recognizing faces.[3,4] To compensate for the loss of central vision, patients often adopt an eccentric viewing strategy to realign the object of interest on an area away from the damaged macula. This area of peripheral retina used consistently for performing visual tasks is known as a preferred retinal locus (PRL). Cross-land et al.[5] defines a PRL as "one or more circumscribed regions of functioning retina, repeatedly aligned with a visual target for a specified task, that may also be used for attentional deployment and as the oculomotor reference." Fletcher and Schuchard reported that 84.4% of eyes with central scotomas demonstrated a PRL, generally located in proximity to the border of the scotoma.[6] In addition, the location of the PRL could vary from 5 to 35° in the peripheral retina, depending on the size of the scotoma.[7–9]

The ability to resolve fine detail at the PRL is reduced because of the neural limitations in the peripheral retina and the optical aberrations induced by the use of off-axis vision. Although the retinal sampling poses a fundamental limit, the reduced image quality due to optical imperfections may also influence the resolution acuity at the PRL. Optical imperfections consist of both eccentric refractive errors and higher-order aberrations at the PRL. A full eccentric correction should correct both refractive errors as well as higher-order aberrations at the PRL. Studies have shown that the magnitude of peripheral higher-order aberrations, primarily coma, increases with increasing eccentric-

*BSOptom
†MSc
‡PhD
§FAAO
Vision Enabling Laboratory, Section of Optometry and Vision Science, School of Natural Sciences, Linnaeus University, Kalmar, Sweden (KB, PL, JG), and Biomedical and X-Ray Physics, Royal Institute of Technology (KTH), Stockholm, Sweden (RR, PU).

ity.[10,11] Moreover, coma is the dominant higher-order aberration, constituting 70 to 90% of the total higher-order root mean square (HO RMS) at eccentricities >10° in the periphery.[10] Studies have also shown that the magnitude of coma is larger in older eyes than in young eyes, both centrally and peripherally.[12–14]

The potential benefit of peripheral refractive error correction has previously been investigated, both in healthy subjects and in patients using a PRL,[8] where an interesting difference between these two groups has been observed. Healthy subjects observe aliasing in the periphery[15–18] (manifest as a significant difference between high-contrast detection and resolution acuity), and as a result, they show no improvement in high-contrast resolution acuity when peripheral refractive errors are corrected. Conversely, peripheral refractive error corrections have been shown to improve high-contrast resolution acuity in patients using a PRL.[7,8] Additionally, peripheral refractive error corrections improve low-contrast resolution acuity in both healthy subjects and patients using a PRL.[8,15] However, the effect of aberrations on the peripheral vision is less well known. One previous study using adaptive optics (AO) on healthy subjects showed a negligible improvement in high-contrast resolution at 20° eccentricity.[19] Nevertheless, it is possible that correction of aberrations in patients using a PRL would improve their resolution acuity, as their high-contrast resolution has been shown to improve with solely refractive error correction.[7,8] In this study, we have corrected eccentric refractive errors as well as higher-order aberrations using AO and evaluated both high- and low-contrast grating resolution acuity at the PRL of a single subject with a long-standing central scotoma.

METHODS

Subject

The subject was a 68-year-old Caucasian woman diagnosed with bilateral juvenile macular degeneration at the age of 17 years; this diagnosis was confirmed as Stargardt disease, with flavimaculatas changes in both eyes at a later stage in her life. She had bilateral central scotomas, with unaided visual acuity of 1.5 and 1.4 logMAR in the right and left eye, respectively, as measured using an Early Treatment Diabetic Retinopathy Study letter acuity chart at 1-meter distance. In her left eye, she developed a single PRL located 25° nasally from the damaged macula. According to her, she has been using the PRL consistently for all visual tasks during the past 40 years. In a previous study by Lundström et al.,[8] the same subject was prescribed a refractive error correction of −3.25/−1.75 × 80° at her PRL (based on the optimum Strehl ratio metric), which the subject used as her habitual correction. Her distance visual acuity in the left eye with this habitual correction was 1.3 logMAR. In addition to this correction, which she was using for the past 5 years, she used an 11× spectacle-mounted magnifier for spot reading. With this magnifier, near visual acuity was 0.2 logMAR at a working distance of approximately 1 cm. Slit lamp findings of the anterior segment were unremarkable and showed only mild age-related changes in the lens. Color fundus photographs were taken, showing geographic atrophy of the macular region in both eyes (Fig. 1A, B). Fixation stability was evaluated using a Spectral OCT/SLO scanning laser ophthalmoscope (OPKO Health, Miami, FL), whereby a fixation cross was projected on to the PRL and the subject was instructed to fixate the cross for a duration of 20 s (Fig. 2). This specific subject was recruited because she had a relatively stable fixation (with a variation limited to approximately 2°) at the PRL and had a large central scotoma. She gave her informed consent after the nature and intent of the study had been explained. The local ethics committee approved the study, and the protocol was designed in accordance with the tenets of Declaration of Helsinki.

AO System

Fig. 3 shows the AO system combined with a system for visual psychophysics developed by the Visual Optics group at the Royal Institute of Technology in Stockholm. The principal components of the system are a Hartmann-Shack wavefront sensor, which uses

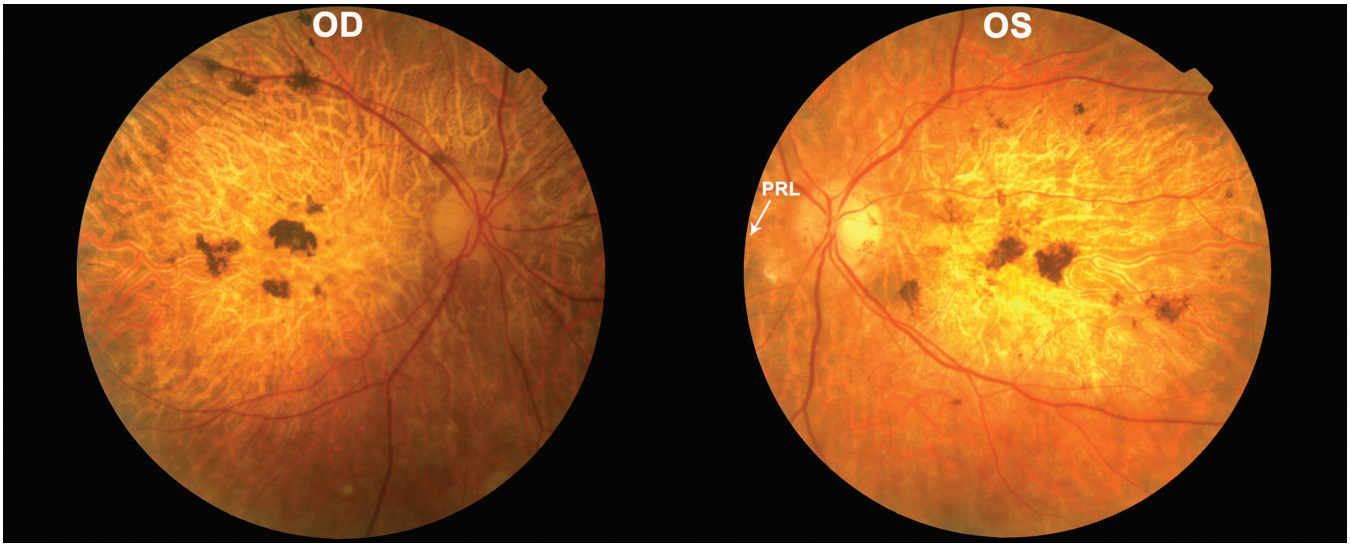

FIGURE 1.
(A, B) Fundus photographs of the right and left eye show the extent of geographical atrophy and the degenerative changes in the posterior pole. The approximate location of the preferred retinal locus (PRL) is denoted in (B). A color version of this figure is available online at www.optvissci.com.

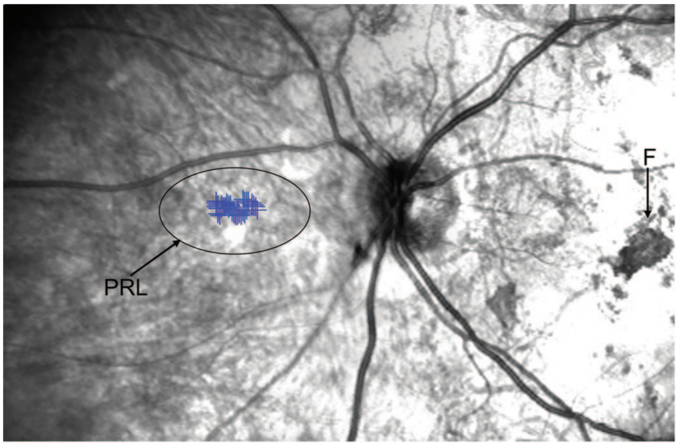

FIGURE 2.

Fixation stability at the PRL assessed using the fixation cross by the Spectral OCT/SLO instrument. The figure is a montage of two pictures, and the area of the PRL and the approximate location of the damaged fovea (F) are marked. The crosses represent fixational stability over the duration of 20 s. A color version of this figure is available online at www.optvissci.com.

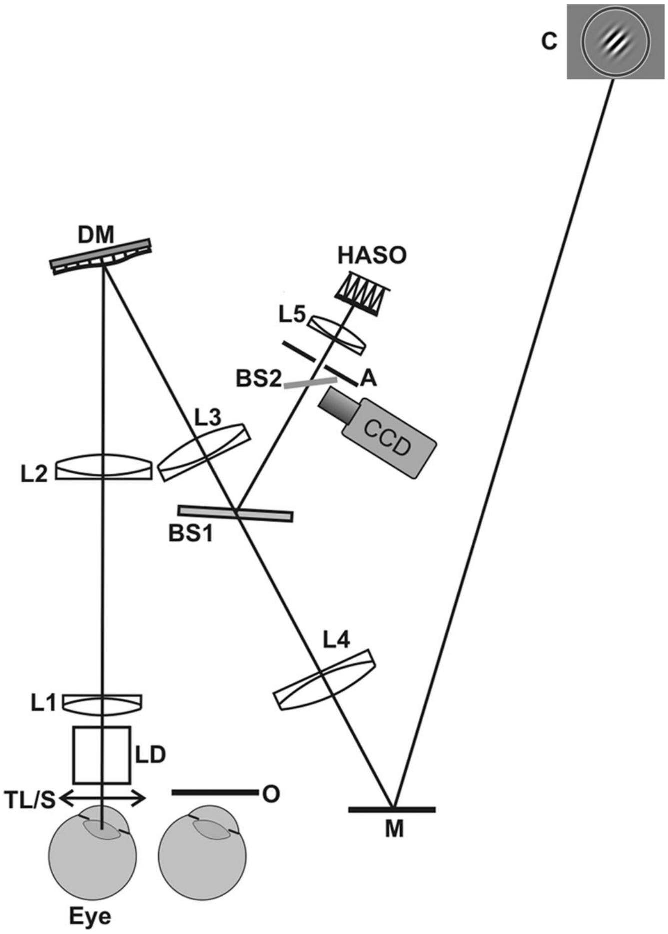

FIGURE 3.

Schematic representation of the adaptive optics system containing Hartmann-Shack sensor, deformable mirror, and CRT screen. For the ease of convenience, both the equiluminant circle and the grating are shown at the CRT screen, although during the procedure, the circle disappeared when the grating was presented and the vice versa. The explanation of all the abbreviations in the system is as follows: L1—achromat f′ = 120 mm, L2—achromat f′ = 200 mm, forms a telescope with L1, L3—achromat f′ = 200 mm, forms a telescope with L2, L4—achromat f′ = 120 mm, forms a telescope with L3, L5—achromat f′ = 50 mm, forms a telescope with L3, LD—laser diode tower, 4-μW intensity at 830 nm that is sent to the eye through a pellicle beam splitter, BS1—hot mirror reflects infrared and transmit visible light, BS2—pellicle beam splitter, DM—deformable mirror, CCD—pupil camera, A—5-mm aperture, HASO—wavefront sensor, C—visual stimulus computer screen, TL/S—trial lenses/spectacle, O—occluder.

a 32 × 32-microlenslet array (HASO 32, Imagine Eyes, France), an electromagnetic deformable mirror (MIRAO 52d, Imagine Eyes, France) with 52 actuators, and a CRT screen placed at the end of the system used for presenting visual stimuli. The pupil plane of the eye was conjugate to that of the deformable mirror using telescopes. The eye was aligned at the front focal plane of lens L1 with help of the pupil camera. The stimuli were imaged through the system by the telescopes formed by lens L4, L3, L2, and L1, with a total magnification of 1. The optimal defocus was −0.6 D after compensating for both wavelength (830–555 nm) and test distance (2.6 meter); this value was incorporated in the AO system before measurements. Aberrations were corrected by the AO system in a continuous closed loop throughout the visual testing. The subject was free to blink at any time, and a natural pupil size was used. Temporary lockups occurred occasionally when the subject moved her eye during AO correction. During those occurrences, the mirror would temporarily freeze, and the recorded aberrations would be identical for a given period. However, these periods were <1 s in duration, and the system was able to resume aberration correction automatically in all cases.

Visual Stimuli and Psychophysical Algorithm

The visual stimulus was a Gabor patch, a sine-wave grating multiplied with a Gaussian standard deviation of 0.6°, with an oblique orientation of ±45°. High- and low-contrast gratings corresponding to 100, 25, and 10% were used in this study. MATLAB (The MathWorks, Natick, MA) and the Psychophysics Toolbox[20,21] were used to draw the stimuli and implement the psychophysical algorithm. The frequency of seeing was defined as the probability $P(x)$ of answering correctly, given a stimulus of size x, and was assumed to vary as a cumulative logistic function:

$$P(x) = g + \frac{(g - \delta)}{1 + e^{\frac{-(x-\mu)}{s}}}$$

The guess rate g was 0.5, as the experiments were based on a two-alternative forced choice paradigm. The lapse rate δ was set to 0.02, the slope s was set to 0.04 logMAR, and threshold μ, measured in logMAR, was the estimated quantity. The stimulus size x could vary between 0.7 to 1.6 logMAR. The psychometric algorithm used in this study is based on the Bayesian adaptive estimation of the slope and threshold that is described in detail by Konstevich and Tyler.[22] This algorithm requires only 30 trials to estimate the probability density function of the threshold; the advantage and accuracy of this algorithm in evaluating visual function are discussed in detail by Rosen et al.[15]

Optical Correction Conditions

We evaluated grating resolution acuity under four different optical corrections. The first two were solely spherocylindrical corrections, and the latter two were full correction of all the Zernike coefficients up to sixth order (including the residual lower-order terms of sphere and cylinder) in a continuous closed loop at the PRL. The correction conditions were randomized, and the subject was unaware of the correction that could possibly benefit her. The correction conditions are as follows: Habitual spherocylindrical correction (Hab Spec): the subject used her habitual spectacle correction (−3.25/−1.75 × 80°) during vision evaluation. We recorded the residual aberrations over her habitual correction using the Hartmann-Shack sensor while the deformable mirror was actively flat. Full spherocylindrical correction (Full Spec): the correction was obtained by minimizing the RMS error of the wavefront. The correction was −2.00/−3.50 × 90° placed in the trial lens holder, and residual aberrations were recorded while the deformable mirror was actively flat. With this correction in place, the residual defocus and astigmatism terms were close to zero. The difference between habitual correction and this correction was −0.50 D and +1.25 D in the horizontal and vertical meridians, respectively. Habitual spherocylindrical correction plus higher-order correction (Hab Spec + AO): in this closed-loop situation, all Zernike coefficients were corrected continuously by the deformable mirror in real time under the entire duration of the vision evaluation procedure. She used her habitual spectacle correction, and the resulting residual aberrations and refractive errors over her spectacles were corrected by the deformable mirror in a closed loop. Full spherocylindrical correction plus higher-order aberration correction (Full Spec + AO): the full spherocylindrical correction was placed in the trial lens holder, and the resulting residual aberrations were corrected by the deformable mirror in a closed loop. The subject had a nearly diffraction-limited correction at her PRL.

Experimental Procedures

The subject positioned her head in a chin rest in front of the system. The CRT screen, on which visual stimuli were displayed, was located 2.6 m from the subject's eye. She viewed the CRT screen through the AO system with her left eye. Fixation on the grating stimulus was aided by an equiluminant concentric circle with a diameter of 5°, displayed on the same screen (Fig. 3). By placing the edge of her scotoma on this circle, projection of the visual stimuli on her PRL during the procedure was facilitated. No cycloplegic drugs were used, and her right eye was occluded during the procedure. The psychophysical vision evaluation commenced once the desired correction condition was met. The subject was asked to determine the orientation of the grating, to the right or left in a two-alternative forced choice paradigm, by pressing the corresponding key on a numerical keyboard. At the end of the each measurement, the resolution acuity threshold was displayed in logMAR units. Three repeated measurements of high- (100%) and low-contrast (25 and 10%) grating resolution acuity were evaluated for each of the four different correction conditions and were subsequently recorded.

RESULTS

The AO system was successful in recording and implementing the four different correction conditions. The Zernike coefficients of the third- and fourth-order aberrations as well as total HO RMS (third–sixth order) measured at the PRL of the subject's naked eye are shown in Table 1. Pupil diameter was 5 mm throughout the experiments, with only minor fluctuations. Resolution acuity at all contrast levels improved with AO aberration correction as shown in Fig. 4. The values presented in Fig. 4 show the mean visual acuity and individual values obtained with the four different correction conditions at all three contrast levels.

TABLE 1.
The Zernike coefficients of the third- and fourth-order aberrations as well as the total HO RMS (third to sixth order) measured at the PRL of the subject's naked eye for a pupil diameter of 5 mm

Zernike coefficients	Pre-correction
C_3^{-3}	0.18
C_3^{-1}	0.20[a]
C_3^{1}	−0.85[a]
C_3^{3}	−0.05
C_4^{-4}	0.07
C_4^{-2}	−0.02
C_4^{0}	−0.05
C_4^{2}	−0.01
C_4^{4}	0.02
Total HO RMS (third to sixth)	0.92

All the Zernike coefficients up to sixth order were targeted for correction in the adaptive optics system.

[a]Note that coma is the dominant aberration coefficient that constitutes 95% of the total HO RMS.

HO RMS, higher-order root mean square; PRL, preferred retinal locus.

High-Contrast (100%) Grating Resolution Acuity

The mean high-contrast (100%) visual acuity with her habitual correction was 1.06 logMAR, and improved to 1.00 logMAR with full spherocylindrical correction. With AO aberration correction, the high-contrast visual acuity improved further to 0.89/0.92 logMAR. The mean HO RMS wavefront error, recorded by the Hartmann-Shack sensor, during the first two correction conditions was 0.91 and 0.92 μm, respectively. With both AO aberration corrections, the mean HO RMS wavefront error reduced further to 0.19 μm.

Low-Contrast (25%) Grating Resolution Acuity

The mean low-contrast (25%) visual acuity with her habitual correction was 1.30 logMAR, and this improved markedly to 1.14 logMAR with full spherocylindrical correction. With AO aberration correction, the low-contrast visual acuity improved further to 1.04/1.06 logMAR. The mean HO RMS wavefront error for the first two correction conditions was 0.92 and 1.00 μm, respectively. With both AO aberration corrections, the mean HO RMS wavefront error reduced further to 0.22 μm.

Low-Contrast (10%) Grating Resolution Acuity

The mean low-contrast (10%) resolution acuity was 1.34/1.51 logMAR with AO aberration correction; however, with purely refractive error corrections, she was unable to identify the gratings.

DISCUSSION

To our knowledge, this is the first time that resolution acuity has been evaluated after correction of all ocular aberrations using AO

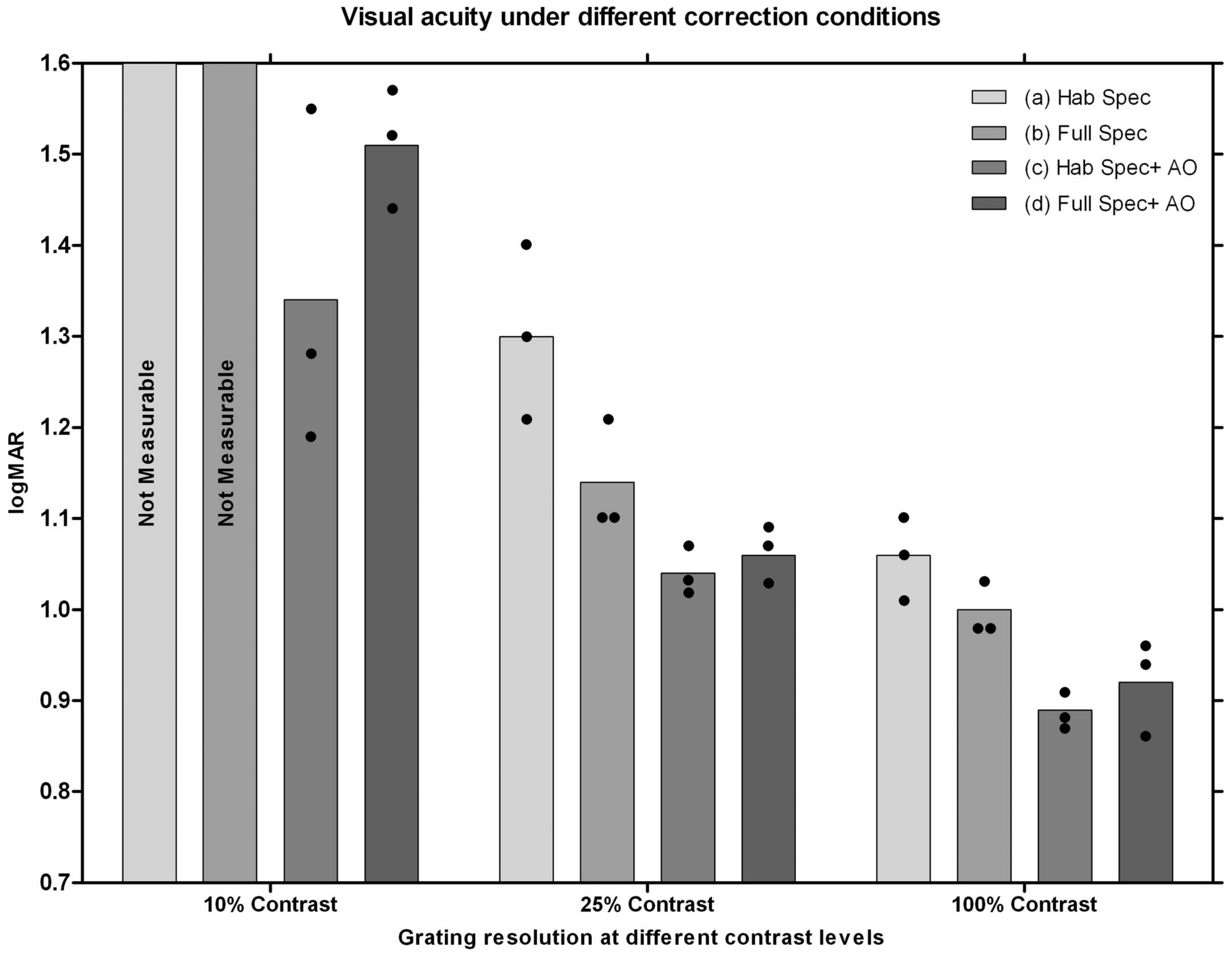

FIGURE 4.

Mean visual acuity and individual values (●) with the four different correction conditions at all three contrast levels. We were unable to determine her low-contrast (10%) resolution acuity with purely refractive error correction, and it has been noted as "not measurable" in the figure.

at the PRL of a low-vision subject. In this subject, there was an improvement in grating resolution acuity with full refractive error correction and a further improvement with aberration correction.

Considering the results in more detail, the high- (100%) and low-contrast (25%) resolution acuities improved by 0.06 and 0.16 logMAR, respectively, with full spherocylindrical correction as compared with values obtained with the habitual correction at her PRL. This finding is in agreement with a previous study by Lundström et al.,[8] who also reported improvements in both high- and low-contrast resolution acuity after correction of eccentric refractive errors. However, they compared resolution acuity between central refractive correction and eccentric refractive correction. The greater improvement of low-contrast resolution with full spherocylindrical correction is in agreement with a previous study by Rosen et al.,[15] in which they showed that low-contrast resolution is optically influenced in the peripheral vision even in normal healthy subjects. Based on our results, this subject has currently been prescribed new spectacles having a refractive correction of −2.00/−3.50 × 90° in the left eye.

With the AO, there was further improvement of 0.08 to 0.11 logMAR in both high- (100%) and low-contrast (25%) resolution. This shows that higher-order aberrations, primarily coma, play a role in degrading the image quality and that correction of these aberrations serves to further improve resolution acuity at the PRL. The relatively small difference in resolution acuity between the two AO corrections (which should theoretically be the same) could be explained by the reduction in light transmission through trial lenses compared with her habitual spectacle lens. The improvement in high-contrast resolution after AO correction suggests that this subject did not experience aliasing. One possible explanation for this is that her resolution in the PRL was much lower than that observed in healthy subjects at similar eccentricities. In her case, high-contrast resolution was 0.89 logMAR after AO correction, whereas Thibos et al.[23] have reported high-contrast resolution acuity at a corresponding eccentricity of approximately 0.7 logMAR (six cycles per degree). Similar differences in peripheral resolution acuity between healthy subjects and age-related macular degeneration patients have previously been reported by Eisenbarth et al.[24] Our subject may also have comparable degenerative changes in her PRL.

The low-contrast (10%) resolution task was difficult for the subject to perform even at the lowest spatial frequency available.

However, the AO correction improved the retinal image quality sufficiently, after which the subject was able to perceive the gratings and thereby respond to the task. The poor repeatability and variation in resolution acuity observed within and between AO corrections might be attributable to an increased frequency in eye movements with increasing task difficulty. The ability to perceive even very-low-contrast grating after aberration correction is owing to the improvement of image quality at the PRL, and this finding argues in favor of correcting the subject's aberrations to help her in performing low-contrast visual tasks, such as recognizing faces in a better way.

Apart from the obvious advantages offered by aberration correction, there are also certain limitations in this study that need to be brought to attention. These are the use of gratings for determining resolution acuity, not correcting for chromatic aberration, and only evaluating the vision of a single low-vision subject. Studies have shown that the grating acuity consistently overestimates letter acuity both in normal eyes and in the PRL of patients with age-related macular degeneration.[25,26] The visual acuity values obtained in this study would have, consequently, been slightly lower if we had instead adopted a letter identification task. Nevertheless, one could speculate that correction of eccentric refractive errors and aberrations may also improve visual performance even with a letter identification task. The improvements that we have observed under the four correction conditions apply for this subject only, and the results could be expected to vary in other subjects owing to variety of factors, such as the location of the PRL, size of the scotoma, underlying retinal disorder, and the magnitude of the eccentric refractive errors and higher-order aberrations. In addition, this technique may have limited usage in patients using multiple PRL's for different visual tasks.[27]

Further studies are required to investigate the degree of improvement in resolution acuity with aberration correction in a larger group of patients having central scotomas with an established PRL. Practical ways of correcting the aberrations at the PRL, particularly coma, for these patients should also be investigated. Until then, full correction of the eccentric refractive error, obtained by either using an open-view refractometer or an aberrometer, could be prescribed to these patients if an improvement in vision can be achieved with either a high- or low-contrast chart. This correction would also improve the detection acuity in these patients because studies have shown that detection is even more sensitive to optical errors.[8,15,28] In addition to the most common low-vision devices prescribed to these patients, such as magnifiers or CCTVs for reading and telescopes for distance, prescribing an eccentric correction could further help them to perform day to day visual tasks in a better way and thus improve their quality of life. In conclusion, correction of all aberrations using AO improves resolution acuity at the PRL of a single low-vision subject with long-standing absolute central scotoma.

ACKNOWLEDGMENTS

BK and RR contributed equally to the work and request acknowledgment of joint first authorship. We thank the subject for all her patience and understanding shown during the measurements. This research was supported by the Faculty of Natural Sciences and Technology, Linnaeus University, Kalmar.

Received January 10, 2012; accepted March 19, 2012.

REFERENCES

1. Timberlake GT, Mainster MA, Peli E, Augliere RA, Essock EA, Arend LE. Reading with a macular scotoma. I. Retinal location of scotoma and fixation area. Invest Ophthalmol Vis Sci 1986;27:1137–47.
2. Timberlake GT, Peli E, Essock EA, Augliere RA. Reading with a macular scotoma. II. Retinal locus for scanning text. Invest Ophthalmol Vis Sci 1987;28:1268–74.
3. Peli E, Goldstein RB, Young GM, Trempe CL, Buzney SM. Image enhancement for the visually impaired. Simulations and experimental results. Invest Ophthalmol Vis Sci 1991;32:2337–50.
4. Peli E, Lee E, Trempe CL, Buzney S. Image enhancement for the visually impaired: the effects of enhancement on face recognition. J Opt Soc Am (A) 1994;11:1929–39.
5. Crossland MD, Engel SA, Legge GE. The preferred retinal locus in macular disease: toward a consensus definition. Retina 2011;31: 2109–14.
6. Fletcher DC, Schuchard RA. Preferred retinal loci relationship to macular scotomas in a low-vision population. Ophthalmology 1997; 104:632–8.
7. Gustafsson J, Unsbo P. Eccentric correction for off-axis vision in central visual field loss. Optom Vis Sci 2003;80:535–41.
8. Lundström L, Gustafsson J, Unsbo P. Vision evaluation of eccentric refractive correction. Optom Vis Sci 2007;84:1046–52.
9. Lundström L, Unsbo P, Gustafsson J. Off-axis wave front measurements for optical correction in eccentric viewing. J Biomed Opt 2005;10:034002.
10. Lundström L, Gustafsson J, Unsbo P. Population distribution of wavefront aberrations in the peripheral human eye. J Opt Soc Am (A) 2009;26:2192–8.
11. Mathur A, Atchison DA, Scott DH. Ocular aberrations in the peripheral visual field. Opt Lett 2008;33:863–5.
12. Baskaran K, Unsbo P, Gustafsson J. Influence of age on peripheral ocular aberrations. Optom Vis Sci 2011;88:1088–98.
13. Mathur A, Atchison DA, Charman WN. Effects of age on peripheral ocular aberrations. Opt Express 2010;18:5840–53.
14. Berrio E, Tabernero J, Artal P. Optical aberrations and alignment of the eye with age. J Vis 2010;10.
15. Rosen R, Lundström L, Unsbo P. Influence of optical defocus on peripheral vision. Invest Ophthalmol Vis Sci 2011;52:318–23.
16. Thibos LN, Walsh DJ, Cheney FE. Vision beyond the resolution limit: aliasing in the periphery. Vision Res 1987;27:2193–7.
17. Coletta NJ, Williams DR, Tiana CL. Consequences of spatial sampling for human motion perception. Vision Res 1990;30:1631–48.
18. Artal P, Derrington AM, Colombo E. Refraction, aliasing, and the absence of motion reversals in peripheral vision. Vision Res 1995;35: 939–47.
19. Lundström L, Manzanera S, Prieto PM, Ayala DB, Gorceix N, Gustafsson J, Unsbo P, Artal P. Effect of optical correction and remaining aberrations on peripheral resolution acuity in the human eye. Opt Express 2007;15:12654–61.
20. Brainard DH. The Psychophysics Toolbox. Spat Vis 1997;10:433–6.
21. Pelli DG. The VideoToolbox software for visual psychophysics: transforming numbers into movies. Spat Vis 1997;10:437–42.
22. Kontsevich LL, Tyler CW. Bayesian adaptive estimation of psychometric slope and threshold. Vision Res 1999;39:2729–37.
23. Thibos LN, Cheney FE, Walsh DJ. Retinal limits to the detection and resolution of gratings. J Opt Soc Am (A) 1987;4:1524–9.
24. Eisenbarth W, Mackeben M, Poggel DA, Strasburger H. Characteristics of dynamic processing in the visual field of patients with age-related maculopathy. Graefes Arch Clin Exp Ophthalmol 2008;246:27–37.
25. White JM, Loshin DS. Grating acuity overestimates Snellen acuity in patients with age-related maculopathy. Optom Vis Sci 1989;66:751–5.

26. Virsu V, Nasanen R, Osmoviita K. Cortical magnification and peripheral vision. J Opt Soc Am (A) 1987;4:1568–78.
27. Crossland MD, Crabb DP, Rubin GS. Task-specific fixation behavior in macular disease. Invest Ophthalmol Vis Sci 2011;52:411–6.
28. Wang YZ, Thibos LN, Bradley A. Effects of refractive error on detection acuity and resolution acuity in peripheral vision. Invest Ophthalmol Vis Sci 1997;38:2134–43.

Karthikeyan Baskaran
Vision Enabling Laboratory
Section of Optometry and Vision Science
School of Natural Sciences
Linnaeus University
391 82 Kalmar, Sweden
e-mail: karthikeyan.baskaran@lnu.se