Higher order aberrations across the horizontal visual field

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Abstract. The relationship between higher order aberrations and position in the horizontal visual field is investigated in normal and refractive corneal surgery subjects. Individual aberration coefficients are obtained from two studies using five untreated subjects and two myopic subjects following conventional laser assisted *in situ* keratomileusis (LASIK) surgery. Measurements are made out to 40 deg in the temporal and nasal visual fields. For the untreated subjects, horizontal coma is linearly influenced by position, and spherical aberration and secondary astigmatism are influenced quadratically by position (4/5 subjects). For the myopic LASIK subjects, the horizontal coma is opposite in sign from that for unoperated eyes at similar visual field positions, and this can be attributable largely to anterior corneal asphericity. Again, both spherical aberration and secondary astigmatism are influenced quadratically by position. To summarize, horizontal coma, spherical aberration, and secondary astigmatism change systemically across the horizontal visual field, and corneal asphericity has a major influence on the rate of change of coma and its sign.
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1 Introduction

In recent years, there have been many studies of higher order aberrations associated with foveal vision,[1] but only a few studies of these aberrations are in the periphery. Navarro, Moreno, and Dorronsoro[2] used a laser ray-tracing technique to measure aberrations at four positions in the nasal visual field, with aberration coefficients presented for only one of four subjects. The rate of change with the angle of the root mean square (rms) higher order aberration of the group was linear. Guirao and Artal[3] measured double-pass retinal images with unequal entrance and exit pupil to estimate off-axis astigmatism and defocus (both second-order aberrations) and horizontal coma at three positions in the nasal visual field out to 45 deg. The estimates for coma indicated a linear rate of change with visual field angle. Atchison and Scott[4] used the Hartmann-Shack technique in 5-deg steps out to ±40 deg along the horizontal visual field, but analyzed the higher order aberrations only in terms of rms aberrations in each order. Each subject showed a linear rate of change of third-order rms aberration, but the rates were different between subjects. Ma, Atchison, and Charman[5] did a similar study with two patients who had undergone myopic LASIK surgery, but again showed only the rms aberrations in different orders. Atchison et al.[6] measured aberrations up to the fourth order across the central 10 deg of the horizontal visual field, finding that horizontal coma changed linearly across this region but that there were negligible changes in other higher order aberrations.

Because individual aberrations are of interest in themselves, we have re-evaluated Atchison and Scott's and Ma, Atchison, and Charman's data[4,5] to investigate how the coefficients of these aberrations change across the central 80-deg horizontal visual field. This will enable appreciation of how refractive surgery affects off-axis as well as on-axis aberrations.

2 Methods

Abbreviated descriptions of the methods[4,5] are given here. Untreated right eyes were used for five normal subjects with spherical equivalent refractions between +1.50 and −2.00 diopters of sphere (DS) and with on-axis astigmatism ≤0.75D. The apparatus was a laboratory Hartmann-Shack wavefront system.[6,7] Pupils were dilated with 1% cyclopentolate. Subjects' heads were mounted in a movable bite bar and alignment was maintained with the help of a videocamera. Subjects rotated their eyes to view a set of fixation targets viewed through a pellicle beamsplitter placed closed to the eyes. One to four (usually three) images were taken for each fixation target, corresponding to visual field positions out to 40-deg temporal/nasal in 5-deg steps, except that no measurements were made at ±35 deg for three subjects. For two subjects, the images corresponding to 40-deg nasal were too poor to be processed.

Right eyes were used of two subjects a few years after conventional LASIK (Nidek EC-5000 excimer laser with a

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treated zone of ≈ 5.5 mm and a transition zone out to ≈ 7.5 mm). Measurements were made with a complete ophthalmic analysis system (COAS)/WASCA instrument (Wavefront Sciences, Asclepion). Pupils were dilated with 1% cyclopentolate. Subjects were mounted in a chinrest and headrest assembly. A similar system for varying fixation angle was used as for the untreated eyes.

For all subjects, wave aberration polynomials were analyzed for 6-mm-diam pupils up to the sixth Zernike aberration order using the OSA ANSI system,[7,8] taking into account the changing shapes of pupils and different sampling across them in horizontal and vertical directions as eccentricity increased.[4] For one subject, analysis was performed also for a 3-mm-diam pupil.

3 Results

Figures 1(a)–1(c) show third- to fifth-order Zernike aberration coefficients of untreated subject DAA with 6-mm pupils. Note the different vertical scales used for the different orders. For third-order aberrations, the most noted features are the high magnitudes of horizontal coma c_3^1 and its linear rate of change with visual field position [Fig. 1(a)]. For fourth-order coefficients, both spherical aberration c_4^0 and secondary astigmatism c_4^2 show quadratic dependences on visual field position [Fig. 1(b)]. There are no particular patterns for the fifth-order coefficients [Fig. 1(c)].

While there are patterns for combinations of many coefficients and subjects, only three coefficients have similar patterns for nearly all untreated subjects. Figures 2(a)–2(c) show c_3^1, c_4^0, and c_4^2 for the other four untreated subjects with 6-mm pupils. As for subject DAA, the most pronounced feature is the linear pattern for c_3^1 [Fig. 2(a)], although this is less pronounced for CSA than for the other subjects. This has the greatest magnitudes of any of the higher order aberration coefficients, reaching absolute values of 1.5 μm. Slopes vary considerably between the subjects from -0.021 to -0.032 μm/deg with R^2 values of 0.98 (4/5 subjects) and 0.81 (CSA). c_4^0 has peaks with positive values near the center of the visual field for four out of five subjects [Figs. 1(b) and 2(b)] and the higher the peak, generally the greater the rate at which the coefficient changes away from the peak. c_4^2 shows similar patterns to c_4^0 for three out of five subjects (DAA, DHS, CSA), except that rates of change are smaller and in one case, the peak has a negative value [Figs. 1(c) and 2(c)].

Figures 3(a) and 3(b) show third- and fourth-order Zernike aberration coefficients of subject DAA with a 3-mm pupil. The coefficients are much smaller than those for a 6-mm pupil (Fig. 1). The linear relationship between horizontal coma and visual field position is not as strong as for the large pupil [compare Fig. 3(a) with Fig. 1(a)], and other patterns occurring for the large pupil are not apparent.

Figures 4 and 5 show third- and fourth-order aberration coefficients for two myopic LASIK eyes (symbols joined by solid lines). There are also some theoretical values for c_3^1 and c_4^0 (diamonds joined by dots) that are mentioned in the discussion in Sec. 4. The presurgical refractions of the eyes were -8.50 DS/-1.00 DC$\times$85 (Fig. 4) and -5.25 DS (Fig. 5). As for the untreated eyes, there are obvious patterns for c_3^1, c_4^0, and c_4^2. The shapes for c_3^1 are very dissimilar from those for

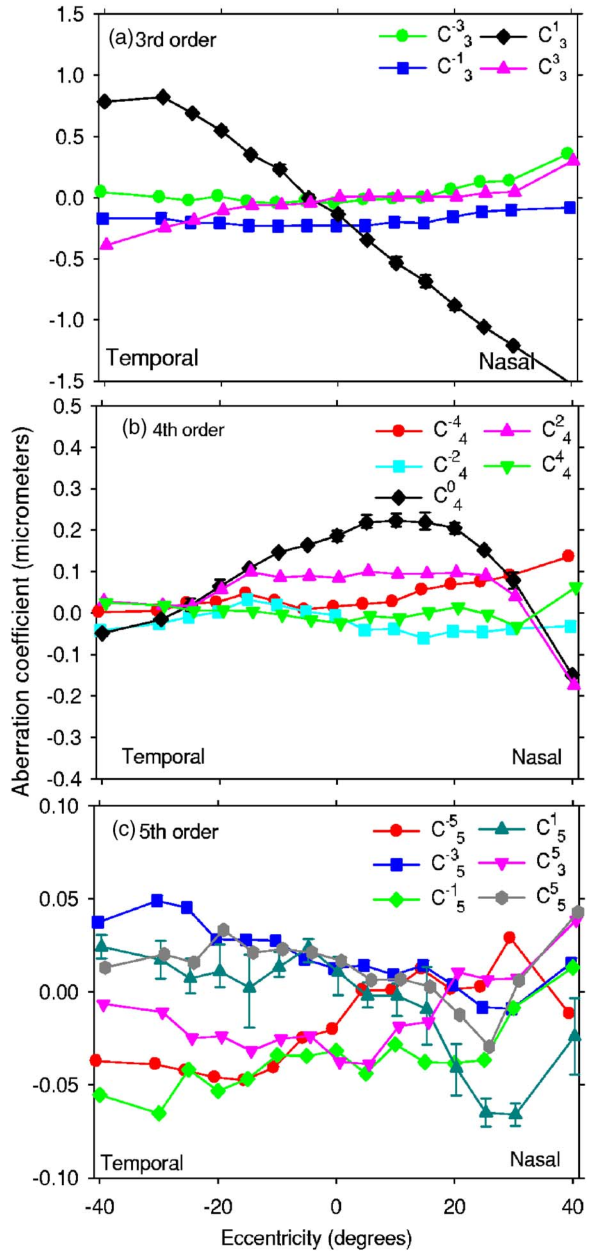

Fig. 1 Zernike aberration coefficients for untreated subject DAA as a function of horizontal visual field position in the (a) third, (b) fourth, and (c) fifth orders for a 6-mm entrance pupil. For clarity, small horizontal offsets have been made to the data. Errors bars show ranges of two to three measurements for coefficients c_3^1, c_4^0, and c_5^1. Note the differences in vertical scale between (a), (b), and (c).

the untreated eyes, being linear but with the opposite slope sign between approximately 25-deg temporal and 35-deg nasal for subject SR-H [Fig. 4(a)] and between approximately 20-deg temporal and 20-deg nasal for subject AW [Fig. 5(a)], beyond which the slopes changes sign and the aberration coefficients reduce in absolute magnitude. The patterns for c_4^0 and c_4^2 are similar to those for some of the untreated subjects [Figs. 1(b) and 2(c)], but with the patterns being much steeper than for the untreated subjects. Note the high levels of c_4^0 in the center of the visual field (0.8 and 0.4 μm), which are

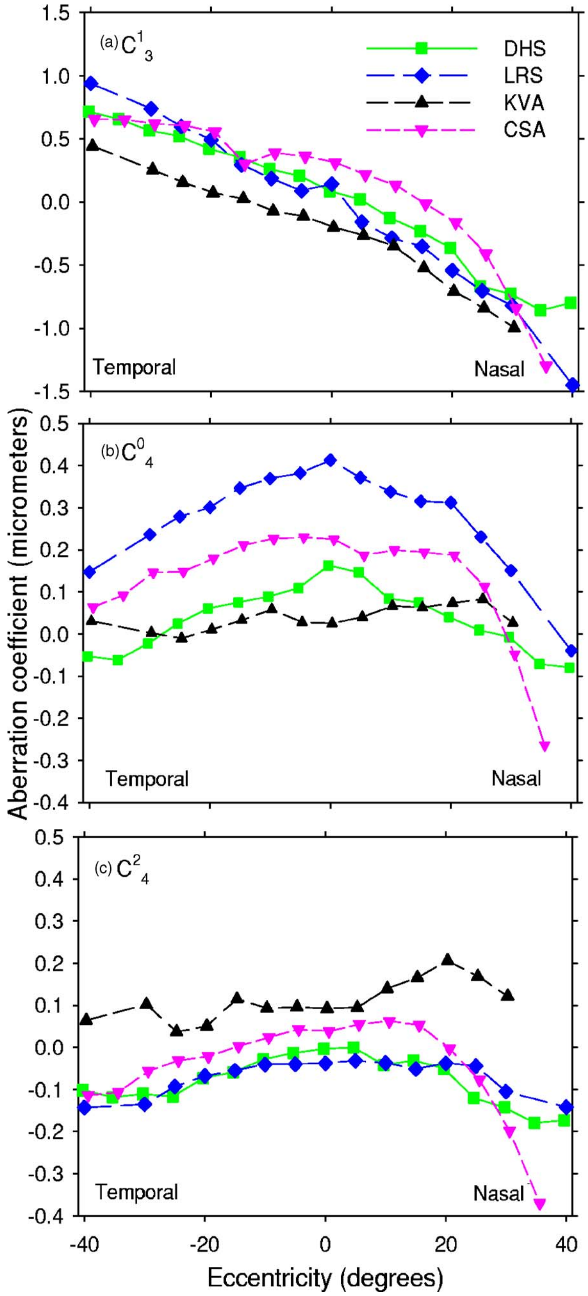

Fig. 2 Zernike aberration coefficients for four untreated subjects (other than DAA) as a function of horizontal visual field position for a 6-mm entrance pupil: (a) horizontal coma, (b) spherical aberration, and (c) secondary astigmatism. For clarity, small horizontal offsets have been made to the data. Note the difference in vertical scale between (a) and (b).

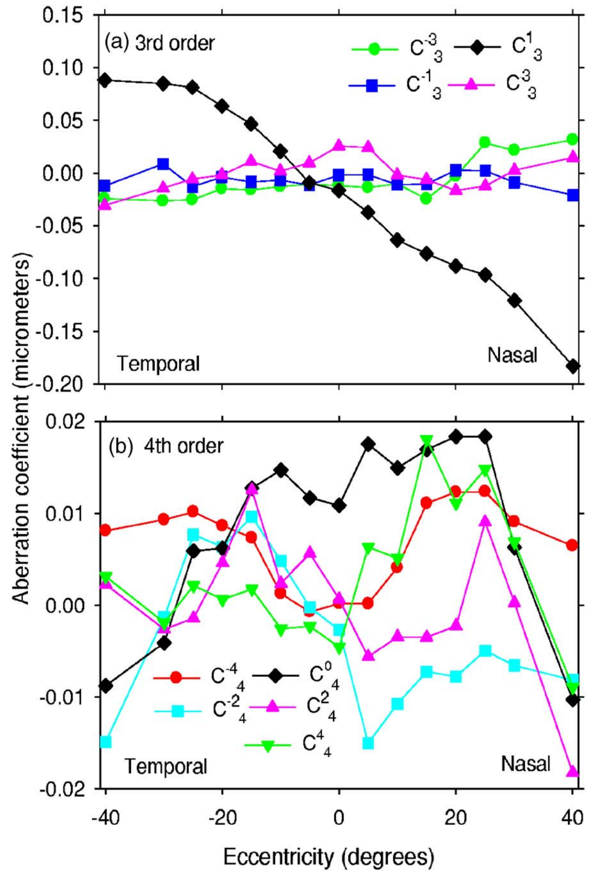

Fig. 3 Zernike aberration coefficients for untreated subject DAA as a function of horizontal visual field position in the (a) third and (b) fourth orders for a 3-mm entrance pupil. Errors bars show ranges of two to three measurements for coefficients c_3^1, c_4^0, and c_5^1. Note the difference in vertical scale between (a) and (b).

typical for conventionally treated myopic LASIK eyes.

4 Discussion

For the untreated eyes, the interesting findings are that horizontal coma is linearly affected by horizontal visual field position for all subjects, and that spherical aberration and secondary astigmatism are influenced quadratically by position for some subjects. Previously, Atchison et al.[6] found linearity for horizontal coma to occur across the central horizontal 10 deg of the visual field, and this study extends this finding to the central 80 deg. The Seidel theory[9] predicts that coma is linearly affected by field position, and this study bears this out for the eye. It is expected that a similar relationship will hold for the vertical visual field and vertical coma. Rate of change of coma with visual field position varies by a factor of 1.5 times across the five untreated subjects. Using eye models, it was shown previously that the rate of change of coma is affected considerably by the asphericity of ocular surfaces but not by magnitudes of surface tilts and decentrations.[6]

Patterns of higher order aberrations and visual field position are not as distinct with small pupils as with larger pupils (compare Figs. 3 and 1). This is due at least in part to the proportionately higher noise with the small pupil than for larger pupils.

For the two myopic LASIK eyes, horizontal coma is linear within a certain range of visual field positions, but its sign is reversed compared with those of the untreated eyes at similar positions. As for some of the untreated eyes, spherical aberration and secondary astigmatism are influenced quadratically by position. An eye modeling exercise[6] was undertaken for the two myopic LASIK subjects. The ellipsoidal parameters of vertex radius of curvature and asphericity were found by fitting the central 6 mm of anterior corneal topographic data

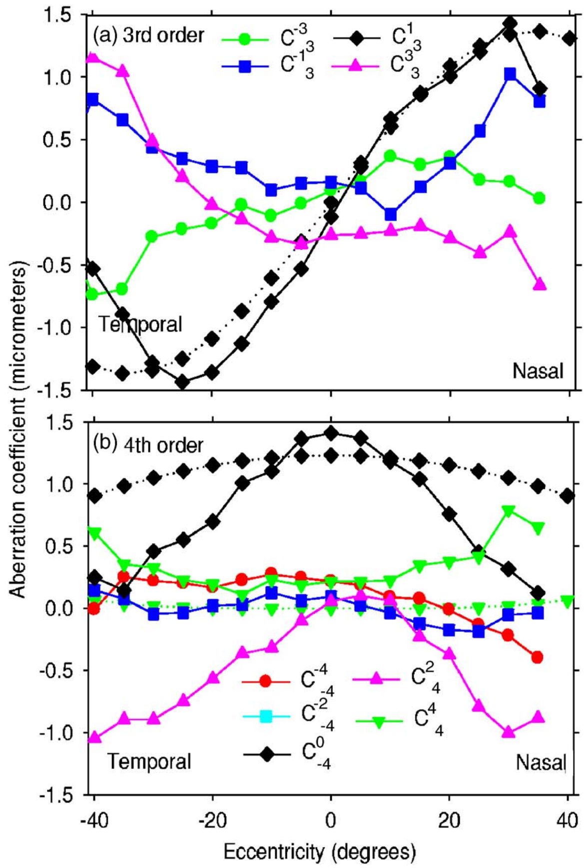

Fig. 4 Zernike aberration coefficients for myopic LASIK subject S-RH as a function of horizontal visual field position in (a) third and (b) fourth orders for a 6-mm entrance pupil (symbols joined by solid lines). Zernike aberration coefficients c_3^1 and c_4^0 for a Navarro model eye, modified to have an anterior cornea with the subject's conicoid parameters (R 8.43 mm, Q+1.49), and with a compensating change in axial length, are also shown (diamonds joined by dots).

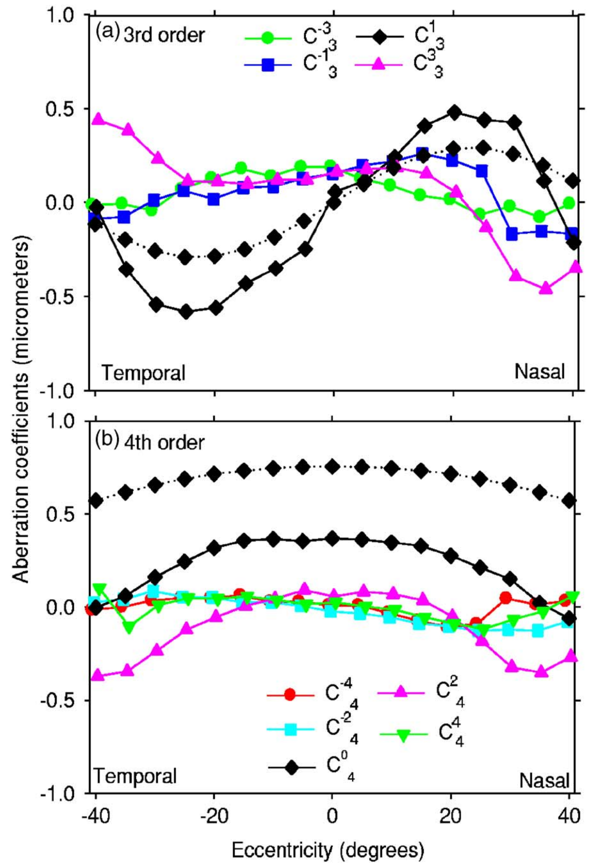

Fig. 5 Zernike aberration coefficients for myopic LASIK subject AW as a function of horizontal visual field position in (a) third and (b) fourth orders for a 6-mm entrance pupil (symbols joined by solid lines). Zernike aberration coefficients c_3^1 and c_4^0 for a Navarro model eye, modified to have an anterior cornea with the subject's conicoid parameters (R 8.38 mm, Q+0.73), and with a compensating change in axial length, are also shown (diamonds joined by dots).

for the two subjects. These were substituted into Navarro's model eye[10,11] with a compensating alteration in vitreous chamber length. As the model is rotationally symmetric and the investigation is along the horizontal meridian, only the coefficients for which the superscript is zero or positive have nonzero values. The theoretical results for c_3^1 and c_4^0 (diamonds connected by dots) are included with the experimental results for the two LASIK eyes in Figs. 4 and 5. While the rates of change for experimental and theoretical results are not in perfect agreement, the overall patterns are similar.

Studies going back more than 50 years have shown most people to have positive spherical aberration in the unaccommodated state for foveal vision.[1] This study finds that spherical aberration reduces in magnitude into the horizontal periphery and may become negative. The Seidel theory predicts no change in spherical aberration with visual field position. The Zernike spherical aberration polynomial includes a ρ^2 term (ρ being the relative position in the pupil relative to its center) as well as a ρ^4 term. In the Seidel theory, the ρ^2 term is defocus, and it may be that there is some interaction between the Zernike spherical aberration and defocus terms that changes with visual field position both for the untreated and treated eyes. The quadratic pattern for the secondary astigmatism coefficient for untreated and treated eyes may be due to an interaction with the astigmatism, which is the dominating off-axis second-order aberration (ignoring on-axis defocus accompanying spherical refractive errors).

There is considerable emphasis in ophthalmology on the importance of higher order aberrations to vision, particularly following refractive surgery. However, the emphasis has been limited to central (foveal) vision. This study shows that the higher order aberrations can be very large in the peripheral visual field. Although these are likely to be small relative to the second-order aberrations of defocus and astigmatism,[4] their correction may be necessary if near-diffraction-limited fundus imagery is to be obtained well into the periphery.

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