Myopia and peripheral ocular aberrations

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We measured wave aberrations over the central 42° × 32° visual field for a 5-mm pupil for groups of 10 emmetropic (mean spherical equivalent = 0.11 ± 0.50 D) and 9 myopic (MSE = −3.67 ± 1.91 D) young adults. Relative peripheral refractive errors over the measured field were generally myopic in both groups. Mean values of $C_2^*$ were almost constant across the measured field and were more positive in emmetropes ($+0.023 ± 0.043 \mu m$) than in myopes ($−0.007 ± 0.045 \mu m$). Coma varied more rapidly with field angle in myopes: modeling suggested that this difference reflected the differences in mean anterior corneal shape and axial length in the two groups. In general, however, overall levels of RMS aberration differed only modestly between the two groups, implying that it is unlikely that high levels of aberration contribute to myopia development.

Keywords: emmetropia, peripheral aberrations, peripheral refraction, myopia


Introduction

In the quest for a better understanding of the multifactorial origins of myopia, it has been suggested that high levels of axial monochromatic aberration (Marcos, Barbero, & Llorente, 2002; Thorn, He, Thorn, Held, & Gwiazda, 2000; Wildsoet, 1998) or specific patterns of peripheral refraction (Hoogerheide, Rempt, & Hoogenboom, 1971) could play some role (Charman, 2005; Hoogerheide et al., 1971; Seidemann, Schaeffel, Guirao, Lopez-Gil, & Artal, 2002; Stone & Flitcroft, 2004; Wallman & Winawer, 2004). Thus, by analogy with the results of animal experiments (for reviews, see, e.g., Norton, 1999; Smith, 1998; Wildsoet, 1997), myopia might develop either as a result of form deprivation associated with a highly aberrated, blurred axial retinal image, or as a result of relative peripheral hyperopia, where abnormal axial growth of the eye is caused by the peripheral image lying behind the retina (Diether & Schaeffel, 1997; Smith, Hung, Ramamirtham, Huang, Qiao-Grider, 2007; Smith, Kee, Ramamirtham, Qiao-Grider, & Hung, 2005; Smith, Ramamirtham, et al., 2007).

Reports on the relationship between myopia and axial higher-order aberrations have been inconsistent, with some finding a moderate increase of aberrations in myopia (Buehren, Collins, & Carney, 2005; He et al., 2002; Paquin, Hamam, & Simonet, 2002) and others finding no increase (Atchison, Schmid, & Pritchard, 2006; Carkeet, Dong Luo, Tong, Mei Saw, & Tan, 2002; Cheng, Bradley, Hong, & Thibos, 2003; Porter, Guirao, Cox, & Williams, 2001; Zadok et al., 2005). Llorente, Barbero, Cano, Dorrorsoro, and Marcos (2004) found higher amounts of aberrations in hypermetropes compared with myopes. Thus, support for markedly higher levels of axial aberration in myopes is weak (Charman, 2005), although this does not eliminate the possibility that abnormal axial growth could be caused by the retinal image blur associated with relatively high aberration levels in the periphery.

In the peripheral visual field, image quality is found to be dominated by second-order aberrations of defocus and astigmatism. Early workers showed that, in the horizontal meridian, the relative peripheral refractive error (RPRE, i.e., the difference between the peripheral and axial mean sphere error) tended to be myopic in hyperopes and hyperopic in myopes (Hoogerheide et al., 1971; Millodot, 1981). Later studies have broadly confirmed these results (Atchison, Pritchard, & Schmid, 2006; Love, Gilmartin, & Dunne, 2000; Mutti, Sholtz, Friedman, & Zadnik, 2000; Seidemann et al., 2002). Hoogerheide et al.’s (1971) longitudinal study of young pilots led them to suggest that a hyperopic RPRE might be a precursor to the development of myopia, this suggestion receiving some support from the later longitudinal study of Mutti et al. (2007). Measurements of effects only in the horizontal meridian may, however, give too limited an impression of the relationship of the image surfaces to the retina: the work of Atchison et al. (2006) shows that RPRE in myopes is
similar to emmetropes in the vertical meridian, suggesting that the eyeball may lack rotational symmetry about its longitudinal axis.

Measurements of higher-order aberrations have been largely limited to the horizontal visual field (Atchison, 2006a, 2006b; Atchison & Scott, 2002; Navarro, Moreno, & Dorronsoro, 1998) or to a few locations in the visual field (Lundström, Unsoo, & Gustafsson, 2005; Sheehan, Goncharov, O’Dwyer, Toal, & Dainty, 2007). Aberrations are found to increase away from the center of the visual field and are dominated by defocus and astigmatism (Atchison, 2006b; Atchison & Scott, 2002; Guirao & Artal, 1999; Navarro et al., 1998). Atchison and Scott (2002) used a Hartmann–Shack wavefront sensor with five subjects to measure wave aberrations in 5° steps out to ±40° in the horizontal visual field. They noted higher amounts of third-order root-mean-square (RMS) aberrations in the nasal visual field than in the temporal field for 5 mm pupils. Oblique and with/against-the-rule astigmatism along the horizontal visual field. Recently, Mathur, Atchison, and Scott (2008) measured aberrations across the central 42° × 32° of the visual field in 5 emmetropes for 5 mm pupils. Oblique and with/against-the-rule astigmatism increased quadratically from the center to the periphery of the visual field along the 45°–225° meridian and 0°–180° meridian, respectively, and decreased along the meridians perpendicular to these. Vertical coma increased at a linear rate from the superior to the inferior visual field and horizontal coma increased at a linear rate from the nasal to the temporal visual field. Spherical aberration, higher-order RMS, and total RMS (excluding defocus) aberrations did not show any trend across the visual field.

Few specific measurements have been made of the higher-order aberrations in the peripheral field of myopes. Lundström, Mira-Agudelo, and Artal (2009) measured aberrations out to ±40° horizontally and ±20° vertically for two refractive error groups (emmetropes and myopes) and two different states of accommodation (targets at 0.5 and 4.0 D). While their emphasis was on the second-order coefficients, they noted statistically significant effects of refractive error group on some higher-order aberration coefficients. We now present data from a study in which the aberrations of emmetropes and myopes were compared over a 42° × 32° area of the central visual field. Additionally, corneal topography was measured and used in subsequent optical modeling.

**Methods**

The study was approved by Queensland University of Technology human ethics committee and complied with tenets of Declaration of Helsinki. Informed consent was obtained from each subject after verbal and written explanation of the risks involved.

Nineteen young, adult volunteers were recruited and were segregated into two groups, based on their refractive error. Group 1 contained 10 emmetropes (mean and standard deviation of spherical equivalent = +0.11 ± 0.50 D; spherical equivalent range = −0.50 to +0.75 D; mean age = 25 ± 3 years; age range = 20–30 years). Group 2 contained 9 myopes (spherical equivalent = −3.67 ± 1.91 D; spherical equivalent range = −6.75 to −0.75 D; mean age = 27 ± 4 years; age range = 22–35 years). Subjects were screened for any ocular pathology. All the subjects had visual acuity better than 6/6 and <0.75 D of astigmatism. Right eyes were assessed, while left eyes were occluded during measurement.

Peripheral aberrations were measured using a COAS-HD Hartmann–Shack aberrometer (Wavefront Sciences Inc., Albuquerque, USA) and fixation on 38 targets arranged in a 6 row × 7 column matrix, covering 42° × 32° of the central visual field. The targets were located on a back-projection screen 1.2 m from the eye (accommodative demand = 0.83 D). For each measurement, subjects placed their heads on the instrument’s chin rest and sequentially fixated the targets. Two measurements were taken at each field point, and their wave aberration coefficients were averaged. The center of the target matrix was aligned with the instrument’s internal fixation target. The pupil center was aligned with instrument’s measurement axis, and the cornea was made conjugate to the lenslet array prior to each measurement, using the instrument’s alignment camera. A detailed description of the methods has been given previously (Mathur et al., 2008).

Zernike coefficients up to sixth order for 555 nm wavelength as per the ANSI and ISO standards were estimated for 5.0 mm pupils, with allowance for the elliptical shape of the pupil during oblique viewing (ANSI, 2004; ISO, 2008). The room illumination was reduced to ensure that the pupil diameter was at least 5.0 mm. Spherical equivalent (M), with/against-the-rule astigmatism (J180), and oblique astigmatism (J45) were calculated from second, fourth, and sixth Zernike-order coefficients, as described by Atchison, Scott, and Charman (2007, 2008). Contour plots representing the magnitude of aberrations at each visual field location were generated using triangle-based interpolation.

Corneal topography for each subject was measured using a Medmont E300 corneal topographer (Medmont International Pvt. Limited, Australia). The pupil center was used as the reference point. Anterior corneal vertex radius of curvature R and asphericity Q were estimated from corneal height data across 36 equally spaced meridians for a 6-mm corneal diameter using least-squares fitting (Atchison, Markwell, et al., 2008) and the equation

\[ X^2 + Y^2 + (1 + Q)Z^2 - 2ZR = 0, \]
where the Z axis is the line of sight. The means of estimates of $R$ and $Q$ from four topographic images were used for further analysis. For the maximum visual field angle of 21°, the relevant corneal diameter exceeds the fitted 6 mm slightly (for $R = 7.8$ mm and entrance pupil depth 3.0 mm, the relevant diameter was 6.4 mm).

**Results**

The vector components of refraction were first calculated from the Zernike coefficients. There was some inconsistency between individual subjects within each group in the degree and direction of change in spherical equivalent across the visual field. Some of these individual differences are illustrated in Figure 1, which shows the variation in the mean spherical equivalent $M$ across the horizontal field for (a) emmetropes and (b) myopes. A few myopes had hyperopic RPRE in at least one semi-meridian. However, there does not appear to be a systematic trend towards a more hyperopic RPRE with increasing axial myopia, with regression analysis failing to show any trends for the myopes as a function of refraction error at any visual field location along either the horizontal or vertical visual field meridians.

Figure 2 shows the mean refractive components: (a) oblique astigmatism $J_{45}$, (b) change in spherical equivalent $M$ relative to axial spherical equivalent (i.e., RPRE), and (c) with/against the rule astigmatism $J_{180}$ for (A) emmetropes and (B) myopes. In both groups, the astigmatic components $J_{45}$ (Aa, Ba) and $J_{180}$ (Ac, Bc) increased approximately quadratically along the $135^\circ$–$315^\circ$ meridian and $90^\circ$–$270^\circ$ meridians, respectively, and decreased along the meridians perpendicular to these. This implies that, locally, the astigmatism tends to be oriented along the visual field meridian and increases as the square of the field angle. For both groups, RPRE moved generally in the negative direction in the periphery (i.e., relative peripheral myopia). Effects were not the same in all semi-meridians, however, tending to be higher in the nasal field (temporal retina).

To explore any systematic differences between the means of the two refractive groups in more detail, Figure 2C includes plots of the differences in mean astigmatic components and RPRE. It can be seen that, although these are not large, the differences are maximal along approximately the superior/temporal to inferior/nasal meridian for $J_{45}$ (linear regression estimate 140 to 320 deg meridian, rate of change 0.013 D/deg of field), along approximately the vertical meridian for RPRE (105 to 285 deg meridian, rate of change 0.023 D/deg of field) and along approximately the inferior/temporal to superior/nasal meridian for $J_{180}$ (210 to 30 meridian, rate of change 0.008 D/deg of field).

Figure 3 shows the mean higher-order elliptical wavefront maps across the pupil at each visual field location for (a) young emmetropes and (b) young myopes. The combination of horizontal and vertical coma dominates across the visual field for both groups. Coma increases in magnitude from the center to the periphery of the visual field and changes orientation with the visual field meridian, being oriented approximately radially with respect to the center of the visual field.

Myopic levels of aberration appear to be relatively higher in the periphery, but in general the differences are quite small, as can be appreciated in Figure 3c, which shows the differences between the corresponding wavefront maps in Figures 3a and 3b.

Figure 4 shows some mean higher-order aberration coefficients, higher-order root-mean-squared aberrations (HORMS) and total RMS aberrations excluding defocus (total RMS) for the two groups across the visual field. Other higher-order coefficients are not shown, as they had little or no regular pattern across the visual field and were small in magnitude. For each refractive group, oblique trefoil $C_{33}$ decreased from the top to the bottom of the
field (Aa, Ba). It was more negative, or less positive, for the myopic group than for the emmetropic group (Aa, Ba).

The most prominent differences between the two groups were seen in the vertical $C_{3j}^1$ (Ab, Bb) and horizontal $C_{3j}^3$ coma (Ac, Bc) coefficients, both of which tended to be relatively large in comparison to the other higher-order coefficients. Vertical coma $C_{3j}^1$ increased linearly from the superior to the inferior visual field and horizontal coma $C_{3j}^3$ increased from the nasal to the temporal visual field. Emmetropes had slightly lower rates of change in coma coefficients (see below). For each refractive group, spherical aberration $C_{40}^0$ (Ad, Bd) varied only slightly across the visual field and showed no obvious spatial pattern of variation. Mean spherical aberration was weakly positive in the young emmetropic group and weakly negative in the young myopes. HORMS (Ae, Be) and total RMS excluding defocus (Af, Bf) showed approximately quadratic rates of change across the field with the minimum approximately at the center of the field. The rate of increase in HORMS with field angle was more rapid in myopes, as also was the total RMS, excluding spherical defocus.

The differences in aberration between the two groups are more clearly illustrated in Figure 4C (i.e., $B - A$). They appear to be relatively modest in magnitude, but there are definite differences in $C_{3j}^1$, $C_{3j}^3$, and $C_{40}^0$, with a consequent difference in HORMS and total RMS (Figures 4Ce and 4Cf, respectively).

The rate of change of coma coefficients along vertical and horizontal visual field meridians and the spherical aberration across the field were analyzed further. Figure 5 shows vertical coma coefficients $C_{3j}^3$ and horizontal coma coefficients $C_{3j}^1$ along the vertical and horizontal visual field meridians, respectively, for the two refractive groups. The slopes for the coma coefficients ($\mu m/deg$) varied significantly between the groups (Table 1), using independent sample $t$-tests. Vertical and horizontal coma slopes were more than two times greater for the myopes.

Figure 2. Mean refractive components (a) oblique astigmatism $J_{45}$, (b) spherical equivalent $M$, and (c) with/against the rule astigmatism $J_{180}$ in (A) young emmetropes, (B) young myopes, and (C) difference $B - A$. The spherical equivalent $M$ across the field for any group is relative to the mean axial spherical equivalent for that group (i.e., the RPRE is plotted). The color scales represent the magnitude of each refractive component in diopters and are same for a given refractive component in panels A and B. Note the color scales in panel C are same for all the refractive components. S, I, N, and T represent superior, inferior, nasal, and temporal visual fields, respectively. Pupil size = 5 mm.
Figure 3. Higher-order aberration elliptical wavefront maps at each visual field location for (a) young emmetropes, (b) young myopes, and (c) the difference $B - A$. The minor axis of the elliptical wavefront maps is cosine of visual field angle times the major axis. I, N, S, and T represent inferior, nasal, superior, and temporal visual fields, respectively.
Figure 4. Individual higher-order aberration coefficients across the visual field for (A) young emmetropes, (B) young myopes, and (C) Difference (B – A) (a) trefoil coefficient $C_{3}^{-3}$, (b) vertical coma coefficient $C_{3}^{-1}$, (c) horizontal coma coefficient $C_{3}^{1}$, (d) spherical aberration coefficient $C_{4}^{0}$, (e) higher-order root-mean-squared aberration (HORMS), and (f) total root-mean-squared aberration (total RMS). The color scales represent the magnitude of each aberration in $\mu$m and are same for a given aberration in panels A and B. Note that the color scales in panel C are same for all the aberrations except for total RMS. N, T, S, and I represent nasal, temporal, superior, and inferior visual fields, respectively. Pupil size is 5 mm.
than for the emmetropes ($p < 0.02$). Note again that coma values approximate to zero around the center of the field and that the slopes along the horizontal and vertical field meridians are very similar. This implies that, if the horizontal and vertical coma coefficients are combined, the resultant total coma is always oriented approximately radially with respect to the visual axis and its magnitude increases linearly with the field angle in all meridians.

Trefoil $C_3^{-1}$ and spherical aberration $C_4^0$ across the field were significantly lower and higher, respectively, for emmetropes than for myopes (repeated measures analysis of variance with field angle as within-subject factor and refractive group as between-subject factor, $p < 0.001$) (Table 1). Mean $C_4^0$ was correlated significantly with the mean spherical refraction of the myopes (Figure 6).

Data on anterior corneal radii and asphericities are shown in Table 2.

There were only minor differences between the corneal shape data for the two groups. The myopic group had slightly steeper and more negatively aspheric anterior corneas than the emmetropic group, with the latter difference being statistically significant with an independent sample $t$-test ($p = 0.04$). Although the change in radius of curvature with myopia does not reach significance for the relatively small numbers of subjects involved, its value ($-0.020$ mm per diopter of myopia) is similar to that found ($-0.022$ mm per diopter) in a recent large-scale investigation in this laboratory (Atchison, 2006c). However, the latter investigation found no change in asphericity with increase in myopia.

<table>
<thead>
<tr>
<th>Refractive group</th>
<th>Coma slope ($\mu m$/deg)</th>
<th>Mean $C_3^{-1}$ ($\mu m$)</th>
<th>Mean $C_4^0$ ($\mu m$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Emmetropes ($N = 10$)</td>
<td>$-0.006 \pm 0.002$</td>
<td>$-0.060 \pm 0.074$</td>
<td>$+0.023 \pm 0.043$</td>
</tr>
<tr>
<td>Myopes ($N = 9$)</td>
<td>$-0.014 \pm 0.007$</td>
<td>$+0.002 \pm 0.052$</td>
<td>$-0.007 \pm 0.045$</td>
</tr>
</tbody>
</table>

Table 1. Mean values of the rate of change of coma with field angle and mean values for oblique trefoil $C_3^{-1}$ and spherical aberration $C_4^0$ across the visual field in the two refractive groups (coma slopes are averages for vertical and horizontal meridians).
Some of the differences in aberrations between emmetropes and myopes might be due to accommodation, particularly as the 1.2-m distance provided a small stimulus to accommodation for the emmetropic group. Mean accommodation response in the emmetropes was 0.44 ± 0.49 D, calculated as the difference between spherical equivalents using the COAS internal “fogged” target (designed to relax accommodation) and the center of the screen at 1.2 m target distance, whereas the accommodation response for the myopes was 0.05 ± 0.19 D. As a check on the possible effects of the small amount of accommodation exerted by the emmetropes, the peripheral aberrations of seven of them were measured at an object distance of 3.0 m (0.3 D stimulus) with targets on a wall. The spherical aberation across the field changed from the 0.3-D stimulus to the 0.8-D stimulus by a non-significant −0.01 ± 0.01 μm for a change in accommodation response of 0.29 ± 0.53 D. Changes in other coefficients were not significant, as was also the case in a study of emmetropes with 0.3 and 4.0 D stimuli (Mathur et al., submitted for publication). It can be concluded that the effects of accommodation on aberrations were negligible and of no consequence to the differences between the groups.

Coma in myopes increases more rapidly with peripheral angle and spherical aberration may be slightly more negative (Figure 5 and Table 1). In an attempt to model these differences, ray tracing was carried out using a model eye incorporating the observed corneal asphericities and radii. The Liou and Brennan (1997) model eye was used and out-of-the-eye ray-tracing was performed with Zemax optical design software (Zemax Development Corporation, USA), tracing rays evenly across the 5-mm entrance pupil of the eye (exit pupil as viewed from the retina). The pupil becomes elliptical in any off-axis case, as in the experimental observations. The model eye was modified by removing its asymmetry about the vertical meridian and using values of corneal radius and asphericity typical of those observed in the experimental subjects. The paraxial refraction of a −4.00-D myopic eye (referred to the spectacle plane 15 mm from the entrance pupil) was matched by changing the vitreous length from 16.27 to 17.74 mm, or by changing the anterior radius of curvature from 7.77 to 7.70 mm to reasonably match the changes for our subject groups along with the vitreous length becoming 17.56 mm (Navarro, Santamaria, & Bescós, 1985). The retina was given a 12-mm radius of curvature. Larger changes in retinal radius of curvature (±2 mm) and asphericity (±2) that might be expected to occur in extreme cases (Atchison, Pritchard, Schmid, et al., 2005) were also considered, but these had only minor effects on coma and spherical aberration out to 25° visual field angle and will not be discussed further here.

Figure 8 shows the theoretical effects, as found by ray-tracing with and without 4 D of myopia on coma and spherical aberration across the visual field. The results

<table>
<thead>
<tr>
<th>Refractive group</th>
<th>Vertex radius $R$ (mm)</th>
<th>Asphericity $Q$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Emmetropes ($N = 10$)</td>
<td>$7.73 \pm 0.26$</td>
<td>$-0.08 \pm 0.04$</td>
</tr>
<tr>
<td>Myopes ($N = 9$)</td>
<td>$7.65 \pm 0.21$</td>
<td>$-0.16 \pm 0.09$</td>
</tr>
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Table 2. Means and SDs of the characteristics of the anterior corneas of the two refractive groups.

The slopes as a function of field angle in the coma coefficients $C_3$ and $C_4$ showed no significant correlation with either (a) the corneal radius $R$ or (b) the corneal asphericity $Q$ (Figure 7).

**Discussion**

It appears that, in general, the aberrations of young, adult myopes over the central field show only minor differences from those of emmetropes of similar age. Both groups generally showed slight myopic shifts into the peripheral visual field (Figure 1). While a myopic RPRE was expected for the young emmetropes (Atchison, Markwell, et al., 2008; Atchison, Pritchard, White, & Griffiths, 2005), we had expected obvious peripheral hypermetropia in young myopes (horizontal visual field) (Atchison, Pritchard, et al., 2006; Hoogerheide et al., 1971). Most previous studies of peripheral refraction measured further into the visual field (e.g., out to ±30° or ±40°) than was done here (±21° horizontally and ±16° vertically), and it is possible that the expected pattern would have asserted itself had we measured at larger angles. However, our data suggest that differences in RPRE between myopes and emmetropes over the central 20° radius of visual field are generally small and are unlikely to be capable of providing an explanation for myopia development (see also Calver, Radhakrishnan, Osuobeni, & O’Leary, 2007).

Some of the differences in aberrations between emmetropes and myopes might be due to accommodation, particularly as the 1.2-m distance provided a small stimulus to accommodation for the emmetropic group. Mean accommodation response in the emmetropes was 0.44 ± 0.49 D, calculated as the difference between spherical equivalents using the COAS internal “fogged” target...
have been developed in stages in which the anterior corneal asphericity is increased from the emmetropic mean value of \(-0.08\) (black solid curve) to the myopic mean value of \(-0.16\) (black dashed curve), the eye becomes myopic by increasing the vitreous length alone (green solid curve), and the eye becomes myopic by decreasing the anterior radius of curvature from 7.77 to 7.69 mm along with the necessary change in vitreous length (green dashed curve). Note that the corneal radius values used for ray-tracing were slightly greater than those found experimentally (Table 2) since we did not want to depart too far from the parameters of the original Liou and Brennan (1997) model eye.

As can be seen in Figure 8, for coma, at each step of change in parameters, the rate of change in coma with field angle increases. The theoretical emmetropic slope of \(-0.004\) \(\mu\text{m}/\text{deg}\) is reasonably similar to the mean experimental value of \(-0.006\) \(\mu\text{m}/\text{deg}\). The changes in asphericity and vitreous length increase the negative slope to about \(-0.008\) \(\mu\text{m}/\text{deg}\): together with a small contribution from a decrease in anterior radius of curvature they result in a slope of about \(-0.009\) \(\mu\text{m}/\text{deg}\). Thus, the modeling suggests that the majority of the greater experimental coma slopes of about \(-0.014\) \(\mu\text{m}/\text{deg}\) with myopes (Figure 5), as compared to emmetropes (\(-0.006\) \(\mu\text{m}/\text{deg}\)), can be explained by differences in anterior corneal shape and axial length.

As can be seen in Figure 8, modeling predicts positive spherical aberration \(C_4^0\) and with slight increase with field angle. Changing the asphericity from \(-0.08\) to \(-0.16\) decreases the spherical aberration at all field angles with respect to that for the original emmetropic eye by \(-0.02\) \(\mu\text{m}\). The combined length and radius of curvature changes to the myopic eye reduce the aberration difference between the original \((Q = -0.08)\) emmetropic eye and the myopic eye to about \(-0.01\) \(\mu\text{m}\), considerably smaller than the experimental difference of \(-0.03\) \(\mu\text{m}\). The predicted slightly positive change in spherical aberration towards the periphery does not match the experimental results, where spherical aberration changed very little with field angle (Figures 4Ad and 4Bd). This is presumably because factors other than the anterior cornea, such as the lens, also play an important role.

Figure 8. Theoretical effects of changes in anterior corneal asphericity, vitreous length, and anterior corneal radius of curvature on coma and spherical aberration (SA). \(R, Q,\) and \(VL\) represent anterior corneal radius of curvature, corneal asphericity, and vitreous length, respectively.
We note that it is of interest to consider the overall pattern of higher-order aberrations when coma is subtracted. Figure 9 shows that for both emmetropes and myopes, total amounts of the remaining higher-order aberrations are relatively small across the field studied and vary by less than a factor of 2 across this field. The magnitudes of these residual HORMS are comparable to those of the third-order coma coefficients. Although the observed asymmetries across the field could reflect such factors as lid pressure and forces produced by the extraocular muscles, it is difficult to see why these should produce markedly different effects in the two refractive groups and the origin of these asymmetries deserves further investigation.

In this study, the off-axis Zernike coefficients were calculated over an elliptical pupil by expanding it along its minor axis to form a circle. An alternate approach would be to use a circular pupil with the same diameter as the major axis of the elliptical pupil (e.g., Lundström et al., 2009). This gives larger absolute coefficients than those shown reported here, but does not affect the conclusions.

Conclusions

We found no substantial systematic differences between the RPREs of young adult myopes and emmetropes over the central approximately 20° radius of visual field. In both groups, mean RPRE tended to be myopic, although there was substantial variation in different semi-meridians and between subjects. Peripheral higher-order ocular aberrations, in particular coma and spherical aberration, differed modestly in emmetropes and myopes. Coma increased linearly with field angle, at a more rapid rate in myopic eyes than in those of emmetropes. Spherical aberration varied little across the field and showed a slight negative shift across the field with myopia, with a mean value of about $-0.01$ μm for our myopes who had an overall mean spherical error of $-3.7$ D (5-mm pupil). In general, however, the magnitude of the higher-order wave aberration was always small compared with that of second-order aberrations.

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