Age-Related changes in ocular aberrations with accommodation

Hema Radhakrishnan
Faculty of Life Sciences, University of Manchester, Manchester, UK

W. Neil Charman
Faculty of Life Sciences, University of Manchester, Manchester, UK

This study investigates the changes in aberrations with monocular accommodation as a function of age. Second-order and higher order wavefront aberrations and pupil size were measured as a function of accommodation demand over the range of 0–4 D in the right eyes of 47 normal subjects with ages between 17 and 56 years. Higher order ocular Zernike aberrations were analyzed for the natural pupil size in terms of their equivalent defocus and were also determined for fixed pupil diameters of 4.5 mm in the unaccommodated eyes and 2.5 mm in the accommodating eyes. With relaxed accommodation (0 D accommodation stimulus), the major change with age was in the value of $C_0^0$, which increased in positive value over the age range studied, although the total higher order RMS wavefront aberration did not increase. When the data were analyzed for natural pupils, spherical aberration was again found to change systematically in the positive direction with age. The equivalent defocus of total higher order RMS error for natural pupils showed no significant correlation with age ($p > .05$). With active accommodation, spherical aberration was found to decrease and become negative as the accommodative response increased in the younger subjects (<40 years). Near-zero spherical aberration was found at accommodation levels of about 0.50 D in the youngest subjects (<20 years) and at around 2–3 D in subjects between 20 and 39 years. In the older subjects (>40 years), the spherical aberration showed only small changes, some of which were positive, within the limited amplitude of accommodation available. Other higher order aberrations and the RMS of higher order aberrations did not appear to change systematically with accommodation, except in the oldest subjects. The change with age in the relationship between aberration and accommodation is interpreted in terms of the changing gradients of refractive index and surface curvatures of the crystalline lens.

Keywords: accommodation, ocular aberrations, age, pupil size, spherical aberration, coma


Introduction

Wave aberrations of the eye determine the quality of images formed on the retina. Because accommodation is achieved by changes in the shape and position of the lens, the aberrations of the eye would be expected to change with accommodation (Ivanoff, 1952; Tscherming, 1904). Moreover, at any level of accommodation, they would also be expected to change with age because the addition of new lens fibers throughout life alters both the external form of the lens and its internal gradients of refractive index (Dubbelman, Van der Heijde, & Weeber, 2001; Dubbelman, Van der Heijde, Weeber, & Vrensen, 2003; Glasser, Croft, & Kaufman, 2001; Jones, Atchison, Meder, & Pope, 2005; Koretz, Cook, & Kaufman, 1997; Koretz, Handelman, & Brown, 1984; Pierscionek & Weale, 1995). This study explores the combined effects of accommodation and age on the aberrations of pre-presbyopic eyes.

Early studies on changes in aberrations with accommodation looked at the changes in spherical aberration and showed that the spherical aberration tended to change from an initially positive value (undercorrected spherical aberration) toward a negative value with increasing accommodative effort (Ivanoff, 1952, 1956; Jenkins, 1963; Koomen, Tousey, & Scollnick, 1949; Van den Brink, 1962).

More recent studies have examined the changes in both spherical aberration and other higher order aberrations (Atchison, Collins, Wildsoet, Christensen, & Waterworth, 1995; H. Cheng et al., 2004; Hazel, Cox, & Strang, 2003; He, Burns, & Marcos, 2000; He, Marcos, Webb, & Burns, 1998; Howland & Buettner, 1989; Lu, Campbell, & Munger, 1994; Ninomiya et al., 2002; Plainis, Ginis, & Pallikaris, 2005), with somewhat equivocal results. Several groups (Hazel et al., 2003; He et al., 2000; H. Cheng et al., 2004; Plainis et al., 2005) found that spherical aberration changed in the negative direction with accommodation, whereas Atchison et al. (1995) found this in only half of their subjects. Several groups observed considerable changes in coma, but these varied in direction and magnitude (Atchison et al., 1995; H. Cheng et al., 2004; He et al., 2000; Howland & Buettner, 1989; Lu et al., 1994; Plainis et al., 2005). The average RMS error of all higher order aberrations at constant pupil size.
diameter was found to remain constant over accommodative levels of 0 to 4.00 D by H. Cheng et al. (2004) and 0 to 3.00 D by Atchison et al. (1995) and Ninomiya et al. (2002). He et al. (2000), however, concluded that average RMS decreased from 0 to 1 D of accommodation, remained at a minimum value between 1 and 3 D of accommodation, and then increased further with increasing accommodative effort. Some of these differences may be associated with different experimental methodologies. He et al. relied on natural pupil dilation and a subjective ray-tracing technique for their measurements, whereas most of the other studies used a mydriatic to dilate the pupils and an objective aberrometer. It is possible that the use of drugs may influence measurements of ocular aberration (Carkeet, Velaedan, Tan, Lee, & Tan, 2003): They undoubtedly affect accommodation (e.g., Mordi, Tucker, & Charman, 1986; Ward & Charman, 1986). Subjects were generally pre-presbyopic (<40 years of age), and no study analyzed its data in terms of patient age.

Some authors have suggested that corneal and lenticular changes occur during accommodation (He, Gwiazda, Thorn, & Held, 2003; Pierscionek, Popioleki-Masajada, & Kasprzak, 2001; Yasuda, Yamaguchi, & Ohkoshi, 2003), although others have found no evidence of corneal variations (Buehren, Collins, Loughridge, Carney, & Iskander, 2003; He, Gwiazda, Thorn, Held, & Huang, 2003). On balance, it appears likely that the changes in aberration during accommodation are mainly attributable to the changes in the lens (Strenk, Strenk, & Koretz, 2005).

As the lens ages, the changes in the thickness and other properties of the lens (e.g., Dubbelman et al., 2001, 2003; Glasser et al., 2001; Jones et al., 2005; Koretz et al., 1997, 1984; Pierscionek & Weale, 1995) are likely to affect the accommodation-dependent changes in optical aberrations. It is important to understand these effects because they may have a significant impact on visual perception and will also influence the choice of aberration correction by procedures such as excimer laser refractive surgery. In addition, they may help to clarify the nature of the changes in the gradients of refractive index of the crystalline lens, which are still poorly understood. The only information available on the effect of accommodation on aberration as a function of age appears to be contained in a brief abstract (Lopez-Gil, Legras, Lara, Fernandez-Sanchez, & Ponce, 2005), which confirms that age affects aberration changes, particularly those in spherical aberration.

In the relaxed eye, ocular monochromatic aberrations as measured at constant pupil diameter have been shown to increase with age (Artal, Ferro, Miranda, & Navarro, 1993; Brunette, Bueno, Parent, Hamam, & Simonet, 2003; Calver, Cox, & Elliott, 1999; McLellan, Marcos, & Burns, 2001; Neto, Ambrosio, Shen, & Wilson, 2005; Wang & Koch, 2003). However, under natural observing conditions, the reduction in pupil size with age alleviates the effect of increased aberrations on the optical quality of the retinal image in older subjects. Calver et al. (1999) suggested that a 1-mm difference in natural pupil size results in an average MTF in older subjects that is almost identical to that of younger subjects when measured at the same light level.

It is worth noting that, under normal viewing conditions, there may be not only age-dependent pupil variation but also, at any age, a reduction in pupil diameter with accommodation (accommodative miosis, e.g., Loewenfeld, 1999). Thus, to aid understanding of the actual changes in the retinal image under normal conditions, it is desirable to consider effects at both the natural pupil diameter for the observing conditions under which the eye accommodates and at a constant pupil diameter.

This study investigates the changes in aberrations with accommodation as a function of age for both the natural pupil size of each subject and at fixed pupil diameter, without the use of a mydriatic.

### Methods

Subjects were 47 students and staff of the University of Manchester. Their ages ranged between 17 and 56 years. All subjects were free of any pathology, had normal clinical amplitudes of accommodation for their age, and could achieve 6/5 visual acuity when corrected. Best-sphere corrections were in the range +1.25 to −9.25 D (mean ± SD = −1.48 ± 2.53 D). In all cases, astigmatism was ≤2.00 D. The research followed the tenets of the Declaration of Helsinki. All subjects gave their informed consent after being told of the purpose of the experiment. The project protocol was approved by the Senate Committee on the Ethics of Research on Human Beings of the University of Manchester.

Accommodation responses, ocular aberrations, and pupil diameters were measured with a Shack-Hartmann aberrometer (IRX-3, Imagine Eyes, Paris) with a 32 × 32 sampling. No corrections were worn. Wavefront errors were recorded under monocular conditions with the right eye, the left eye being occluded.

The instrument records pupil diameter at the same time as the aberrations and normally uses a dynamic fogging method to relax accommodation to the far point. It also contains an internal Badal system which allows the vergence of the fixation target to be systematically altered with respect to the subject’s far point (i.e., the target vergence providing a 0 D accommodative stimulus). Recordings were made with the stimulus, a black 6/12 Snellen letter “E” in an elliptical white background field subtending about 0.7 × 1.0° and having a luminance of about 85 cd/m², set at 0.50 D intervals to provide effective accommodation stimuli over the range from 0 to 4.00 D (strictly, the effective target vergences were negative, but the commonly used convention of treating them as positive was followed). A relatively small dioptic range of stimuli was used due to the limited amplitude of
accommodation of the older subjects. Subjects were encouraged to try to keep the letter as clear as possible at all times so that both reflex and voluntary accommodations were employed.

The measurements started with the determination of the aberrometer target position corresponding to the far point, followed by the measurement of the associated ocular aberrations. The accommodation demand was then increased in 0.50 D intervals up to 4.00 D with the built-in Badal system. Each axial change in target position took approximately 0.75 s, the target then being kept at a constant vergence for 1 s, after which a measurement of the wavefront aberration was made. This normally took several seconds. The initial time interval of 1 s was sufficient for any pupil constriction to be completed (Semmlow, Hansmann, & Stark, 1975; Semmlow & Stark, 1973) and for accommodation to reach its new level (e.g., Beers & Van der Heijde, 1996; Campbell & Westheimer, 1960; Kasthurirangan & Glasser, 2005; Tucker & Charman, 1979). The target was then moved again. Subjects were first given two practice runs to familiarize them with the task, after which three complete runs were recorded. The manufacturer’s software was used to calculate the Zernike wavefront aberration coefficients and total higher order RMS wavefront error from the Shack-Hartmann images for the full natural pupil diameter (coefficients up to the sixth order); coefficients were also determined for a 4.5-mm diameter in unaccommodated eyes (up to the eighth order) and a 2.5-mm diameter in accommodated eyes (up to the fifth order).

Data analysis

Accommodation responses

The “refraction” for each accommodative stimulus was deduced with the manufacturer’s software, which effectively fits the wavefront for the natural or any chosen smaller pupil with an appropriately tilted sphero cylinder (Thibos, Hong, Bradley, & Applegate, 2004). The wavefront-derived refractive results for the natural pupil diameter were vector averaged (Thibos, Wheeler, & Horner, 1997). The accommodative response to any near stimulus was taken as the difference between the mean-sphere refraction of the accommodated eyes and those at the far point, with sign reversed to make the response positive.

Wavefront aberrations

As well as using Zernike coefficients to characterize the wavefront errors associated with particular aberration types, two metrics derived from the coefficients (equivalent defocus, and coma and spherical aberration) were employed.

Equivalent defocus

Under natural observing conditions, most younger subjects show a reduction in pupil diameter as the accommodative stimulus is increased (accommodative miosis; Loewenfeld, 1999), although the degree of miosis varies widely between subjects of similar age (Kasthurirangan & Glasser, 2006; Plainis et al., 2005; Radhakrishnan & Charman, in press; Schaeffel, Wilhelm, & Zrenner, 1993; Wilhelm, Schaeffel, & Wilhelm, 1993). If we are to assess the impact of the changing higher order aberrations on the retinal image under natural accommodative conditions, it is important that the metric used is appropriate. Even if the optical structure of the eye is unchanged, the values of the Zernike coefficients will change with pupil diameter so that direct use of such coefficients is not justified when comparisons have to be made between values obtained with different natural pupil diameters. We first chose, then, to express the individual Zernike aberrations as determined with natural pupils in terms of the equivalent defocus, \( M \). This is the amount of spherical defocus required to produce the same wavefront variance that produced by one or more higher order aberrations at the same pupil diameter (Thibos, Hong, Bradley, & Cheng, 2002). The attraction of this metric is that it not only allows for changes in pupil diameter but also permits direct comparison of the importance of the aberrations with that of the lags and leads of accommodation corresponding to the second-order defocus errors of the accommodation response.

The equivalent defocus corresponding to any Zernike coefficient \( C_f \) for a pupil radius \( r \) is determined using the following formula:

\[
M = 4\sqrt{\frac{3}{\pi}} \frac{C_f}{r^2}
\]

(Thibos, Hong, et al., 2002).

When the aberration coefficient is measured in micrometers and pupil radius in millimeters, then the equivalent defocus \( M \) is in diopters.

The equivalent defocus was calculated from each Zernike coefficient as determined for the natural pupil for the particular subject and accommodation level.

Because equivalent defocus specifies the vergence of a spherical wavefront that has the same total wavefront variance across the pupil as does the higher order aberration, it is not strictly invariant with pupil diameter. However, Thibos, Bradley, and Hong (2002) empirically evaluated equivalent defocus in a large sample of eyes and found that, when the equivalent defocus of higher order aberrations for various pupil sizes ranging from 7.5 to 3 mm was plotted as a function of radial order or meridional frequency, the slopes of the regression lines equalled the amount of defocus. They therefore concluded that equivalent defocus is largely independent of pupil diameter and is thus likely to be indicative of the optical quality of an individual’s eye, irrespective of the pupil size. This makes it a useful metric for the comparison of the aberrations of different individuals under a variety of
accommodative conditions, when evaluated without the use of a mydriatic. Nevertheless, it has to be conceded that the equivalent defocus is calculated for each aberration mode independently, and it does not take into account the possible interactions between several ocular aberrations that may improve performance, for example, defocus and spherical aberration (Applegate, Marsack, Ramos, & Sarver, 2003; Applegate, Sarver, & Khemsara, 2002).

Coma and spherical aberration

Third-order coma and fourth-order spherical aberration can also conveniently be expressed in alternative dioptric forms that allow direct comparison of results obtained at different pupil diameters, that is, in terms of D/mm for coma and D/mm^2 for spherical aberration, where the mm refers to the zonal pupil radius. These values were calculated using the following formulae:

\[
\text{Coma (D/mm)} = \frac{9\sqrt{8}}{r^3} \sqrt{(C_3^{-1})^2 + (C_4^1)^2} \tag{2}
\]

and

\[
\text{Spherical aberration (D/mm^2)} = \frac{24\sqrt{5}}{r^4} C_4^0. \tag{3}
\]

Thus, for example, a spherical aberration of 0.50 D/mm^2 means that the shift in focus at the margin of a 2-mm-diameter pupil will be 0.50 D, whereas for a 4-mm pupil, it would be 2.00 D. Equal aberration values for the natural pupil in terms of this metric thus do not imply equal retinal image quality. Note that the dioptric metric for coma combines third-order horizontal and vertical coma and that only the magnitude of the coma is expressed, whereas the dioptric spherical aberration retains its appropriate sign.

Aberrations for fixed pupils

In the unaccommodated state, a fixed pupil diameter of 4.5 mm was used to compare the aberrations of different individuals. The smallest pupil diameter found in 46 of the 47 subjects at any accommodation level was 2.5 mm. Zernike coefficients were then also determined for this fixed pupil for all these subjects and at all the accommodation levels.

Results

Observations with relaxed accommodation

Changes in pupil diameter with age

Figure 1 shows the changes with age in the pupil diameter when the accommodation is relaxed for “distance” viewing, that is, for a 0 D accommodation stimulus. Although there is considerable intersubject scatter, there is a gradual decline in pupil diameter with increasing age (\(y = -0.0375x + 6.3548\), \(R^2 = .1856\), \(p < .01\)).

Ocular aberrations in relaxed eyes

The mean third- to sixth-order Zernike coefficients for a fixed 4.5-mm pupil size, measured with a stimulus vergence of 0 D in 41 subjects, are shown in Figure 2a (six subjects were excluded from these data because their pupil diameter was smaller than 4.5 mm; see Figure 1). The data show large variability between individuals for all aberration terms. Coefficients for all ocular aberrations terms, except those for fourth-order spherical aberrations and, possibly, third-order trefoil (\(C_3^{-3}\)), average to around 0 \(\mu\)m. Spherical aberration (\(C_4^0\)) averages to a positive mean value of +0.034 ± 0.05 \(\mu\)m.

Figure 2b shows the fourth-order spherical aberration coefficient, \(C_4^0\), and total higher order RMS error (third to sixth order) plotted as a function of age for the 4.5-mm pupil. Over the range of ages studied, spherical aberration in the relaxed eye became steadily more positive, whereas total RMS error did not change with age. The correlation between spherical aberration and age was significant (\(R^2 = .25, p < .01\)). Correlations in the case of the other third- and fourth-order coefficients were not significant. With a pupil diameter of 4.5 mm, an RMS wavefront error of 0.1 \(\mu\)m corresponds to an equivalent defocus of 0.14 D, so that the almost constant total RMS error of about 0.16 \(\mu\)m corresponds to an equivalent defocus of around 0.22 D, close to the limits of clinical significance.

The subjects were divided into four different groups depending on their age: <20 years \((n = 8, \text{ mean } \pm \text{ SD age} = 18.5 \pm 0.76 \text{ years}, \text{ mean } \pm \text{ SD refractive error} = -3.30 \pm 3.86), 20–29 years \((n = 14, \text{ mean } \pm \text{ SD age} = 24.86 \pm 3.51 \text{ years}, \text{ mean } \pm \text{ SD refractive error} = -0.75 \pm 1.45), 30–39 years \((n = 9, \text{ mean } \pm \text{ SD age} = 34.00 \pm 3.50 \text{ years}, \text{ mean } \pm \text{ SD refractive error} = 0.22 \pm 1.05), and \geq 40 years \((n = 14, \text{ mean } \pm \text{ SD age} = 42.98 \pm 4.50 \text{ years}, \text{ mean } \pm \text{ SD refractive error} = 1.30 \pm 1.30).
mean \pm SD refractive error = -1.86 \pm 2.82), and >39 years (n = 10, mean \pm SD age = 46.00 \pm 4.00 years, mean \pm SD refractive error = -1.28 \pm 2.35). Analysis of variance with the 4.5-mm pupil aberration coefficients as the dependent variables and age group as the independent variable gave the results shown in Table 1. There are significant differences in the case of \( C_3^1 \) and \( C_4^0 \), but not for the other coefficients.

Considering now the data for a relaxed accommodative state in the case where the aberrations are determined for the subjects' full natural pupils rather than for a fixed, smaller 4.5-mm pupil diameter, Figure 3a shows, as examples, the equivalent defocus for the coefficients of third-order coma and fourth-order spherical aberration as a function of age; all 47 subjects are included. There is a large degree of intersubject variability between the aberration values when expressed as equivalent defocus for higher order terms. Only in a minority of cases does the equivalent defocus due to a single aberration exceed 0.25 D, the approximate level at which defocus effects are considered to be clinically significant. The regression equations for the relationship between the equivalent defoci for all the third- and fourth-order Zernike aberration coefficients and the age of the subject are given in Table 2. A statistically significant level of correlation was found between age and equivalent defocus for the coefficients of fourth-order spherical aberration \( C_4^0 \) (p = .037) and quadrafoil \( C_4^4 \) (p = .021). As can be seen from the
regression equations, fourth-order spherical aberration tended to be always positive and to increase with age, whereas quadrafoil became less positive with age. The other third- and fourth-order aberrations showed no significant correlation with age.

The 47 subjects were divided into four different groups depending on their age: <20 years ($n = 8$, mean ± SD age = $18.5 ± 0.76$ years, mean ± SD refractive error = $−3.30 ± 3.86$), 20–29 years ($n = 15$, mean ± SD age = $24.80 ± 3.53$ years, mean ± SD refractive error = $−1.38 ± 2.11$), 30–39 years ($n = 11$, mean ± SD age = $33.64 ± 3.29$ years, mean ± SD refractive error = $−0.18 ± 1.10$), and >39 years ($n = 13$, mean ± SD age = $46.08 ± 4.87$ years, mean ± SD refractive error = $−1.58 ± 2.34$). Analysis of variance was performed with the age group (again <20, 20–29, 30–39, >39 years) as the independent variable and the equivalent

### Table 1

<table>
<thead>
<tr>
<th>Aberration coefficient</th>
<th>$F(3, 40)$</th>
<th>$p$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trefoil, $C_3^3$</td>
<td>1.59</td>
<td>.207</td>
</tr>
<tr>
<td>Vertical coma, $C_3^{-1}$</td>
<td>3.01</td>
<td>.043</td>
</tr>
<tr>
<td>Horizontal coma, $C_3^1$</td>
<td>1.11</td>
<td>.357</td>
</tr>
<tr>
<td>Trefoil, $C_3^3$</td>
<td>0.97</td>
<td>.416</td>
</tr>
<tr>
<td>Quadrafoil, $C_4^{-4}$</td>
<td>0.16</td>
<td>.922</td>
</tr>
<tr>
<td>Fourth-order astigmatism, $C_4^2$</td>
<td>1.37</td>
<td>.268</td>
</tr>
<tr>
<td>Spherical aberration, $C_4^4$</td>
<td>4.25</td>
<td>.011</td>
</tr>
<tr>
<td>Fourth-order astigmatism, $C_4^2$</td>
<td>1.07</td>
<td>.375</td>
</tr>
<tr>
<td>Quadrafoil, $C_4^4$</td>
<td>0.90</td>
<td>.542</td>
</tr>
</tbody>
</table>

Table 1. Analysis of variance results for the differences in third- and fourth-order Zernike aberration coefficients in the four age groups for a 4.5-mm pupil and relaxed accommodation. A total of 41 subjects are included because 6 subjects had pupil diameters of less than 4.5 mm in diameter.

![Figure 3](https://example.com/figure3.png)

Figure 3. Data for natural pupils (see Figure 1) in unaccommodated eyes. (a) Equivalent defocus of third-order coma ($C_3^{-1}$ and $C_3^1$) and fourth-order spherical aberration ($C_4^0$) coefficients as a function of age. (b) Total higher order RMS wavefront error, expressed in terms of equivalent defocus, as a function of age.
defocus of the third- and fourth-order aberrations as the dependent variable. The results showed no significant difference in third-order coma coefficients $C_3^1$, $F(3, 46) = 2.56, p = .067$, and $C_3^3$, $F(3, 46) = 0.31, p = .817$; trefoil coefficients $C_3^{-3}$, $F(3, 46) = 0.69, p = .562$, and $C_3^3$, $F(3, 46) = 0.29, p = .834$; fourth-order spherical aberration $C_4^0$, $F(3, 46) = 2.33, p = .093$; fourth-order astigmatism $C_4^{-2}$, $F(3, 46) = 0.57, p = .64$, and $C_4^2$, $F(3, 46) = 0.63, p = .60$; and quadrafoil $C_4^4$, $F(3, 46) = 0.03, p = .99$, and $C_4^2$, $F(3, 46) = 1.97, p = .133$, between the four age groups. Thus, only for third-order coma and fourth-order spherical aberration did the differences between the age groups approach (but not reach) statistical significance.

The dependence of the equivalent defocus (for natural pupil size) of the total RMS error (third to sixth order) on age is shown in Figure 3b. The differences in equivalent defocus with age are much smaller than the interobserver variability in any given age group. The slope of the regression-line fit to the data does not differ significantly from zero. It appears that, although some aberration modes like fourth-order spherical aberration may vary with age, overall RMS aberration does not. Analysis of variance showed no significant difference in equivalent defocus of RMS aberrations between the four age groups used previously, $F(3, 46) = 1.05, p = .381$.

Figure 4 shows the magnitude of the total third-order coma coefficient for natural pupils, obtained by taking the square root of the sum of the squares of the coefficients for vertical and horizontal coma, expressed in D/mm, and the signed fourth-order spherical aberration coefficient, in D/mm², as a function of age for the full set of 47 subjects. As noted earlier, quantifying aberrations in these ways allows valid comparisons to be made with different pupil diameters. When expressed in these terms, both spherical aberration and coma appear to increase with age. However, although the correlation between spherical aberration and age was found be statistically significant ($y = 0.0047x - 0.0433; R^2 = .162, p < .05$), that for coma was not ($y = 0.0019x + 0.144; R^2 = .024, p > .05$). Analysis of variance showed a significant difference in magnitude of spherical aberration between the four age groups, $F(3, 46) = 4.17, p = .011$. A post hoc test (Tukey’s HSD) showed a
significant difference in spherical aberration between the group with subjects aged over 39 years and the two groups under 30 years of age \((p < .05)\). No significant difference was found in the magnitude of coma between the four age groups, \(F(3, 46) = 0.817, p = .491\).

**Observations with active accommodation**

**Accommodative stimulus/response**

For each subject, accommodation response was plotted against the corresponding stimulus values. These accommodation response–stimulus plots all showed nonlinearity for low stimulus values: Those for the older subjects tended to show a nonlinear region for lower stimulus values and saturation at the higher levels (see, e.g., Ciuffreda, 1998; Kalsi, Heron, & Charman, 2001; Radhakrishnan & Charman, in press). To characterize the effectiveness of the responses, regression lines were fitted to the data over that part of the response–stimulus curve that appeared linear by eye. This usually occurred over a stimulus range of 0.5 to 4.0 D for younger subjects, the upper limit falling for older subjects.

Not surprisingly, the accommodative response–stimulus slopes varied with age (Kalsi et al., 2001; Mordi & Ciuffreda, 1998; Radhakrishnan & Charman, in press). Figure 5 shows the slopes of the regression lines as a function of age. Filled circles show slopes where the correlation coefficient was significant at the 5% level, whereas open circles show those where the correlation was not significant. Responses tended to be reasonably accurate up to the age of about 40 years, after which slope declined. As has been found in other accommodation studies (e.g., Heron, Charman, & Grey, 1999), some of our pre-presbyopic subjects responded very poorly for their age, even though they were given the same instructions and appeared clinically normal, with no near-vision symptoms or other difficulties.

Because those subjects with very low stimulus–response slope were effectively not accommodating, it was decided to exclude any subject with a slope of less than 0.1 from the aberration/accommodation study, leaving 42 subjects. As can be seen from Figure 5, those subjects whose data were excluded from this part of the study were over the age of 35 years.

**Changes in aberrations with accommodation**

**Natural pupil size data**

Changes in the accommodation stimulus elicited different changes in accommodation response, higher order aberration, and pupil diameter among the individual subjects. To allow intersubject comparisons to be made with different natural pupil diameters, wavefront aberrations were expressed in...
terms of equivalent defocus or, in the cases of spherical aberration and coma, in D/mm² or D/mm, respectively.

The 42 subjects having at least some accommodation were divided into four different groups depending on their age: <20 years (n = 8, mean ± SD age = 18.5 ± 0.76 years, mean ± SD refractive error = −3.30 ± 3.86), 20–29 years (n = 15, mean ± SD age = 25.13 ± 3.54 years, mean ± SD refractive error = −0.70 ± 1.41), 30–39 years (n = 10, mean ± SD age = 34.10 ± 3.31 years, mean ± SD refractive error = −1.67 ± 2.72), and >39 years (n = 9, mean ± SD age = 45.11 ± 3.48, mean ± SD refractive error = −1.71 ± 2.65).

The values of fourth-order spherical aberration (with the Zernike coefficients derived for the full natural pupil), expressed in terms of equivalent defocus and D/mm², as a function of accommodative response in the four age groups are shown in Figures 6a and 6b, respectively. Although there is considerable intersubject scatter, both

![Figure 6](image-url)

Figure 6. Fourth-order spherical aberration (natural pupils) expressed either (a) as equivalent defocus or (b) in D/mm², plotted as a function of accommodative response in the four age groups: <20 years, blue symbols; 20–29 years, purple symbols; 30–39 years, green symbols; and >39 years, red symbols.
plots suggest a general modest tendency for spherical aberration to change from a positive value in the relaxed eye toward a negative value as accommodation increases, although for a few subjects, spherical aberration becomes more positive. When the data are broken down into age groups, in both metrics, the least squares regression line fits indicate that typical spherical aberration in the youngest group (<20 years) changes from positive to negative at quite low levels of accommodation response (around 0.5 D), whereas that for the 20- to 29-year and 30- to 39-year groups makes the transition at a response of about 2.5 D. Subjects aged less than 20 years show the highest rate of change in spherical aberration with accommodation: When expressed by equivalent defocus, the typical rate of change is about −0.042 D per diopter of accommodation. This rate decreases in the older subjects, with the change in spherical aberration being −0.020 D per diopter of accommodation in 20- to 29-year-olds and −0.039 D per diopter of accommodation in 30- to 39-year-olds. Due partly to the highly reduced accommodative amplitudes and responses in the subjects aged over 39 years, the positive regression slope for this age group (+0.039 D per diopter) is not statistically significant (although it is when spherical aberration is expressed in D/mm² rather than equivalent defocus). Over the limited response range achieved, the oldest subjects tend to show relatively high levels of positive spherical aberration in comparison with the other age groups. Full details of the regression line fits are given in Table 3.

It is of interest to compare the changes in spherical aberration with accommodation for individual subjects. This may conveniently be done by plotting the amount of aberration against the accommodation response for each subject and characterizing this plot by the slope of the regression line linking the two variables (although this slope gives no information on the absolute level of the aberration). Figure 7 shows these individual rates of change in fourth-order spherical aberration (expressed in terms of either equivalent defocus or in D/mm²) per diopter of accommodation response, as a function of subject age. Filled symbols show slopes (spherical aberration/accommodative response) where the correlation coefficient for the individual subject was significant at the 5% level, whereas open symbols show those where the correlation was not significant. Although there is considerable scatter in the data and the trends fail to reach statistical significance, the slope of the change in spherical aberration per diopter of accommodation appears to be negative in the younger subjects and tends to become positive in the presbyopic subjects, with the transition at which spherical aberration remains constant with increasing accommodation being somewhere in the mid-thirties. This behavior appears to be similar to that found by Lopez-Gil et al. (2005) for fixed 4-mm pupils. However, analysis of variance with the change in spherical aberration (D/mm²) per diopter of accommodative response as the dependent variable and age group as the independent variable showed no significant difference between the groups, F(3, 41) = 0.30, p = .82.

The absolute values of total third-order coma, expressed either in terms of (a) equivalent defocus, D, for the full natural pupil or (b) in D/mm, as a function of accommodative response for the different age groups are shown in Figure 8. The individual variability is again high. Overall, there appears to be no systematic change in coma with accommodation: None of the regression lines in Figure 8 has a slope differing significantly from zero. Analysis of variance with the change in coma (D/mm) per diopter of accommodative response as the dependent variable and age group as the independent variable showed no significant difference between the groups, F(3, 41) = 2.55, p = .069.

Table 4 shows the mean rates of change of equivalent defocus of third-order horizontal and vertical coma and some additional higher order aberrations with accommodative response. In all age groups, no systematic accommodation-dependent changes were found in other higher order aberrations, which were all much smaller than third-order coma and fourth-order spherical aberration.

Figure 9 shows the equivalent defocus of the total higher order RMS error (third to sixth order) for natural pupils as a function of accommodative response in the four age groups. The subjects in the >39-year-old group show an

<table>
<thead>
<tr>
<th>Spherical aberration</th>
<th>Age group (years)</th>
<th>Regression equation</th>
<th>R²</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equivalent defocus (D)</td>
<td>&lt;20</td>
<td>y = −0.04x + 0.02</td>
<td>.1108</td>
<td>.008</td>
</tr>
<tr>
<td></td>
<td>20–29</td>
<td>y = −0.02x + 0.05</td>
<td>.0357</td>
<td>.023</td>
</tr>
<tr>
<td></td>
<td>30–39</td>
<td>y = −0.04x + 0.08</td>
<td>.1051</td>
<td>.001</td>
</tr>
<tr>
<td></td>
<td>&gt;39</td>
<td>y = 0.04x + 0.11</td>
<td>.0266</td>
<td>.211</td>
</tr>
<tr>
<td>D/mm²</td>
<td>&lt;20</td>
<td>y = −0.05x + 0.03</td>
<td>.1757</td>
<td>.001</td>
</tr>
<tr>
<td></td>
<td>20–29</td>
<td>y = −0.02x + 0.08</td>
<td>.0324</td>
<td>.031</td>
</tr>
<tr>
<td></td>
<td>30–39</td>
<td>y = −0.04x + 0.09</td>
<td>.0306</td>
<td>.102</td>
</tr>
<tr>
<td></td>
<td>&gt;39</td>
<td>y = 0.27x + 0.13</td>
<td>.1979</td>
<td>.001</td>
</tr>
</tbody>
</table>

Table 3. Regression equations for fourth-order spherical aberration, expressed either as equivalent defocus (D) or in D/mm², for natural pupils as a function of accommodative response in the four age groups.
increase in equivalent defocus of RMS with accommodation ($y = 0.260x + 0.413; R^2 = .111, p < .05$). The 30- to 39-year-old group appears to have a higher variability in RMS error with accommodation when compared with other groups and shows a systematic increase in equivalent defocus with accommodation ($y = 0.0837x + 0.4473; R^2 = .0614, p < .05$). Subjects in the 20- to 29-year ($y = 0.0396x + 0.3441; R^2 = .092, p > .05$) and 20-year ($y = 0.0268x + 0.3408; R^2 = .0709, p > .05$) age groups show no systematic change in total RMS error with accommodation.

Analysis of variance with the change in equivalent defocus of total higher order RMS error per diopter of accommodative response as the dependent variable and age group as the independent variable showed no significant difference between the four age groups, $F(3, 41) = 1.18, p = .328$.

Figure 7. Rates of change of fourth-order spherical aberration (for natural pupils) with accommodation response, as a function of age. Spherical aberration is expressed either (a) as equivalent defocus or (b) in D/mm². Filled symbols represent subjects showing a correlation between spherical aberration and response that was significant at the 5% level, and open symbols represent subjects for whom the correlations between aberration and stimulus failed to reach statistical significance.
Fixed pupil diameter data

The wavefront data were also analyzed for a fixed pupil diameter of 2.5 mm at all accommodative levels. One of the 42 subjects with active accommodation had a pupil size of less than 2.5 mm in the most accommodated state and was thus excluded from this data analysis. The subject was a 29-year-old emmetrope. As examples of the type of changes found, Figure 10 shows the rates of the change in RMS of combined third-order horizontal and vertical coma coefficients and the Zernike coefficient for fourth-order spherical aberration per diopter of accommodative response as a function of age. Once again, filled symbols show slopes (microns of spherical aberration or coma/accommodative response) where the correlation coefficient was significant at the 5% level, whereas open symbols show those where the correlation was not significant. Most presbyopic subjects accommodated poorly, and their regression slopes between aberrations and accommodative responses were not significant.

The low slope values in both parts of the figure show that neither third-order coma nor fourth-order spherical
aberration, when measured for the small, fixed 2.5-mm pupil, changes much with accommodation. There is some suggestion that the rate of change of each aberration may change as presbyopia is approached (>45 years), becoming more negative for coma and more positive for spherical aberration, but any effects are weak. Analysis of variance with the change in spherical aberration (μm) per diopter of accommodative response as the dependent variable and age group as the independent variable showed a significant difference between the age groups, \(F(3, 40) = 3.30, p = .03\). Post hoc analysis (Bonferroni) showed a significant difference between the oldest age group (>39 years) and the other age groups \(p < .05\). These differences between the age groups might be linked to the fact that most presbyopic subjects accommodated poorly and had slightly higher regression slopes which were not statistically significant. Analysis of variance with the changes in third-order coma (μm) per diopter of accommodative response as the dependent variable and age group as the independent variable showed no significant difference between the age groups, \(F(3, 40) = 2.84, p = .052\).

Figure 11 shows the total higher order RMS error (third to fifth order) as a function of accommodative response in each of the four age groups. The higher order RMS error

<table>
<thead>
<tr>
<th>Aberration</th>
<th>&lt;20 years</th>
<th>20–29 years</th>
<th>30–39 years</th>
<th>&gt;39 years</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trefoil, (C_3^3)</td>
<td>0.001 ± 0.045</td>
<td>−0.009 ± 0.028</td>
<td>−0.0017 ± 0.033</td>
<td>0.018 ± 0.055</td>
</tr>
<tr>
<td>Vertical coma, (C_3^1)</td>
<td>0.041 ± 0.068</td>
<td>0.013 ± 0.027</td>
<td>0.014 ± 0.048</td>
<td>0.023 ± 0.082</td>
</tr>
<tr>
<td>Horizontal coma, (C_3^1)</td>
<td>0.125 ± 0.19</td>
<td>0.009 ± 0.051</td>
<td>0.012 ± 0.043</td>
<td>0.252 ± 0.35</td>
</tr>
<tr>
<td>Trefoil, (C_4^3)</td>
<td>0.074 ± 0.085</td>
<td>0.02 ± 0.031</td>
<td>0.023 ± 0.023</td>
<td>0.172 ± 0.215</td>
</tr>
<tr>
<td>Quadrafoil, (C_4^{-4})</td>
<td>0.01 ± 0.022</td>
<td>0.004 ± 0.011</td>
<td>0.004 ± 0.015</td>
<td>−0.003 ± 0.042</td>
</tr>
<tr>
<td>Fourth-order astigmatism, (C_4^{2})</td>
<td>0.004 ± 0.011</td>
<td>−0.004 ± 0.009</td>
<td>−0.002 ± 0.011</td>
<td>−0.007 ± 0.019</td>
</tr>
<tr>
<td>Fourth-order astigmatism, (C_4^{2})</td>
<td>0.021 ± 0.06</td>
<td>0.001 ± 0.015</td>
<td>0.013 ± 0.020</td>
<td>0.013 ± 0.073</td>
</tr>
<tr>
<td>Quadrafoil, (C_4^{4})</td>
<td>−0.024 ± 0.055</td>
<td>−0.005 ± 0.018</td>
<td>−0.022 ± 0.024</td>
<td>−0.054 ± 0.081</td>
</tr>
</tbody>
</table>

Table 4. Mean ± SD rates of change of higher order aberrations (third-order coma, trefoil, fourth-order astigmatism, and quadrafoil), expressed in equivalent defocus (D) for natural pupil size, per diopter of accommodative response in the four age groups.
Figure 10. Individual rates of change with accommodation response in the Zernike coefficients for the (a) RMS of third-order vertical and horizontal coma and (b) fourth-order spherical aberration, analyzed over a fixed pupil diameter of 2.5 mm, as a function of age. Filled symbols represent subjects showing a correlation between aberration and response that was significant at the 5% level, and open symbols represent subjects for whom the correlations between response and stimulus failed to reach statistical significance.
appears to remain reasonably constant at around 0.05 \( \mu \text{m} \) with accommodation for a 2.5-mm pupil size. None of the regression-line slopes differ significantly from zero.

Discussion

The aim of this study was to explore changes in ocular aberration as a function of accommodation and age. In an attempt to maintain as natural conditions as possible, no mydriatic was used. Because accommodation demands photopic levels of target luminance and accommodative miosis occurs, this resulted in some subjects having quite small pupil sizes (<2.5 mm) under some accommodated conditions. Aberrations were then very small, and their measurements were less reliable. Thus, rather than using Zernike coefficients for a fixed pupil diameter to describe the aberrational changes, much of the analysis was carried out for the full natural pupil diameters, which varied with subject and conditions, employing equivalent defocus as the metric to describe the aberration or, in the cases of third-order coma and fourth-order spherical aberration, \( \text{D/mm} \) or \( \text{D/mm}^2 \), respectively.

In considering the data of the study, the limited reliability of aberrometer measurements must be borne in mind (e.g., X. Cheng et al., 2004; Davies, Diaz-Santana, & Lara-Saucedo, 2003; Rodriguez, Navarro, Gonzalez, & Hernandez, 2004). In general, reliability will depend upon the instrument, subject, and measurement conditions. Moreover, it may be expected that a variety of other factors, including small alignment errors, drifts in the measuring equipment, pupil fluctuations, and true short-term variations in the ocular aberrations, will play a role. In the present case, data from the complete presbyopes serve as controls for the aberrometer’s estimates of both refraction and higher order aberrations. In the light of the constancy of the Zernike estimates (means for three records) as the accommodation stimulus changed for these nonaccommodating subjects, we believe that the stimulus-dependent changes in the aberrations of younger subjects, as well as their intersubject differences, are real.

The observed distribution of higher order aberrations in relaxed eyes with a fixed pupil diameter (4.5 mm; see Figure 2) shows that each higher order Zernike coefficient averages to approximately 0 \( \text{D} \), except for spherical aberration, which has a positive mean \( (C_4^0) \) of about 0.035 \( \mu \text{m} \), equivalent to about 0.07 \( \text{D/mm}^2 \) of undercorrected spherical aberration). Several previous studies at broadly similar pupil diameters have shown a similar distribution of higher order aberrations and magnitude of spherical aberration (Cheng, Bradley, Hong, & Thibos, 2003; Howland & Howland, 1977; Netto et al., 2005; Porter, Guirao, Cox, & Williams, 2001; Smirnov, 1962; Thibos, Bradley, et al., 2002; Thibos, Hong, et al., 2002; Walsh & Charman, 1985; Wang & Koch, 2003). Table 5 gives the mean values of spherical aberration, expressed in \( \text{D/mm}^2 \). There is no evidence that the use of
mydriatics or cycloplegics has any major effect on measured aberrations.

With the fixed 4.5-mm pupil, fourth-order spherical aberration is also the only higher order aberration showing significant age dependency, becoming steadily more positive over the age range studied. It is difficult to compare this result with those of earlier workers. Most of them (e.g., Artal et al., 1993; Brunette et al., 2003; Calver et al., 1999; McLellan et al., 2001; Netto et al., 2005; Wang & Koch, 2003) found increases with age in most aberrations, but the significance of the trends found depended heavily on the inclusion of subjects aged 60 years or more, when aberrations become obviously higher. Like us, McLellan et al. (2001) found that the increase in fourth-order spherical aberration correlated significantly with age, whereas that for third-order coma did not. Interestingly, Brunette et al. (2003) found that aberrations remained almost constant between the ages of 20 and 40 years and only started to increase after the mid-forties. Given the scatter in the results of the different studies, the present data appear to fit within the same broad pattern of age dependence.

If the individual aberrations of the relaxed eye are considered as a function of age for the natural pupil, using the equivalent defocus as the metric, only fourth-order spherical aberration and quadrafoil ($C_4^4$) are found to increase significantly (Figure 3); spherical aberration also increases with age when expressed in terms of D/mm². The regression equations for equivalent defocus against age are given in Table 3.

Interestingly, when the RMS of total higher order (third to sixth) aberrations is expressed in terms of the equivalent defocus for the natural pupil, whose diameter tends to decrease with age, no systematic change with age is found (Figure 4). This supports the view (Calver et al., 1999) that, under natural observing conditions, the impact on retinal image of the increased level of aberration in the older eye is compensated for by the reduction in its pupil diameter (about 0.035 mm per year under our conditions; see Figure 1). Earlier work, which generally used mydriatics and larger fixed pupils (around 5 mm) for analysis, has tended to find an increase with age in both individual aberrations and overall higher order RMS wavefront error (Calver et al., 1999; McLellan et al., 2001).

When changes with both age and accommodation are considered, it is evident from Figures 6, 7, and 10 that the age of the subject has a significant effect on the magnitude and direction of change in spherical aberration with accommodation. In most younger subjects, the spherical aberration tends to change from an initially positive value for a zero stimulus to become more negative with accommodation. This finding is in agreement with several previous studies that also show such a shift in spherical aberration with accommodation (H. Cheng et al., 2004; He et al., 2000; Ivanoff, 1952, 1956; Jenkins, 1963; Koomen et al., 1949; Van den Brink, 1962). The rate of change in spherical aberration for our younger subjects (17–40 years) with natural pupils is about $-0.05$ D of equivalent defocus per diopter of accommodation response or about $-0.05$ D/mm² per diopter of accommodation (see Figure 6); these values are very similar to the values derived from data with fixed 5-mm pupils for a similar subject age range (H. Cheng et al., 2004), that is, $-0.047$ D of equivalent defocus per diopter of accommodation and $0.059$ D/mm² per diopter of accommodation. The present data show the change from positive to negative values of spherical aberration occurring at response levels of around 0.5 D in the youngest subjects (<20 years) and around 2.5 D in subjects between 20 and 39 years. This compares with findings of 1.0 to 1.5 D by Jenkins (1963), 2.0 D by Atchison et al. (1995), and 1.7 D by H. Cheng et al. (2004), whereas He et al. (2000) found the transition to occur at a stimulus level of around 3.5 D. This level of agreement appears satisfactory in view of the observed intersubject differences and the variations in age composition and other aspects of the various studies. In case of other higher order aberrations, the large intersubject variations found in the data may mask any trends related to age and accommodation.

<table>
<thead>
<tr>
<th>Author</th>
<th>Pupil diameter</th>
<th>Mean value for $C_4^4$ (µm)</th>
<th>Spherical aberration (D/mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Smirnov (1962)</td>
<td>0.055</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Howland and Howland (1977)</td>
<td>0.039</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Walsh and Charman (1985)</td>
<td>0.040</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Porter et al. (2001)</td>
<td>5.7 (natural)</td>
<td>$0.138 \pm 0.103$</td>
<td>$0.112 \pm 0.084$</td>
</tr>
<tr>
<td>Thibos, Bradley, et al. (2002)</td>
<td>6.0 (cyclo)</td>
<td>$0.12 \pm 0.12$</td>
<td>$0.080 \pm 0.080$</td>
</tr>
<tr>
<td>X. Cheng et al. (2003)</td>
<td>6.0 (cyclo)</td>
<td>$0.11 \pm 0.11$</td>
<td>$0.073 \pm 0.073$</td>
</tr>
<tr>
<td>Wang and Koch (2003)</td>
<td>6.0 (natural)</td>
<td>$0.101 \pm 0.103$</td>
<td>$0.067 \pm 0.068$</td>
</tr>
<tr>
<td>Netto et al. (2005)</td>
<td>6.0 (natural)</td>
<td>$0.09 \pm 0.04$</td>
<td>$0.060 \pm 0.027$</td>
</tr>
<tr>
<td>Present data</td>
<td>4.5 (natural)</td>
<td>$0.035 \pm 0.05$</td>
<td>$0.073 \pm 0.010$</td>
</tr>
</tbody>
</table>

Table 5. Values of wavefront-derived fourth-order spherical aberration as found by various authors, expressed either as Zernike coefficients for the measurement pupil diameters indicated or in terms of D/mm². The results from Howland and Howland (1977) and Smirnov (1962; in D/mm²) were derived using Equation 13 and Table B1 of Howland and Howland (1977).
within the limited residual objective amplitude of accommodation and may even show a positive shift in some subjects over 45 years of age. Because the subjects over 45 years of age only accommodated by approximately 1.00 D or less, the regression between changes in aberrations and accommodative response was not significant in most of the older subjects.

Aberrations other than fourth-order spherical aberration, together with total higher order RMS wavefront aberration, when expressed in terms of equivalent defocus for the natural pupil, show no significant changes with accommodation in any age group (Figures 8 and 9 and Table 4).

As noted earlier, the need to use a small 2.5-mm pupil, imposed by the small accommodated pupils of some subjects, for the fixed pupil analysis of aberrations made it difficult to demonstrate any strong effects of either age or accommodation under this condition. It has long been known that with such small pupils, the eye is almost diffraction limited (e.g., Berny & Slasky, 1969), so that monochromatic aberrations can only play a very minor role. The observed total higher order RMS aberration for most subjects and conditions was only around 0.05 μm (Figure 11), corresponding to an equivalent defocus of about 0.20 D, which would be expected to have little effect on retinal image quality with such a pupil diameter. The RMS wavefront error of about 1/10th of a wavelength for the center of the visible spectrum is very close to the value of the Marechal criterion (1/14th of a wavelength) defining a system whose optical performance is essentially diffraction limited.

How do the present data relate to our knowledge of the optical characteristics of the aging eye? Considering first the case of eyes with relaxed accommodation, it is generally accepted that, in most young eyes, the individual aberrations of the cornea and lens are each larger than those for the complete eye, implying that the cornea and lens have aberrations of opposite signs (e.g., Artal & Guirao, 1998; Artal, Guirao, Berrio, & Williams, 2001; el-Hage & Berny, 1973; Kelly, Mihashi, & Howland, 2004; Tomlinson, Hemenger, & Garriott, 1993). In the case of spherical aberration, for example, the cornea tends to have a positive aberration coefficient, whereas the lens has a negative aberration, leaving a low positive value for the whole eye. As the eye ages and the lens forms changes, this compensation breaks down. If corneal spherical aberrations remain approximately constant with age (Guirao, Redondo, & Artal, 2000; Oshika, Klyce, Applegate, & Howland, 1999), our observation of a change with age in total ocular spherical aberration toward more positive values implies that the lenticular aberration must be shifting in the same direction when under conditions of relaxed accommodation (see also Artal et al., 2001). With aging, several changes occur in the lens due to the addition of new fibers and other factors:

• The axial thickness increases (e.g., Dubbelman et al., 2001, 2003; Koretz et al., 1997).

The axial gradient of refractive index becomes flatter across the central region of the lens and steeper toward the lens surfaces (Jones et al., 2005; Smith & Pierscionek, 1998), so that the lens behaves more like a body with uniform index.

Thus, it is reasonable to speculate in qualitative terms that, in the young relaxed lens, the positive spherical aberration conferred by its biconvex shape and flatter anterior surface is largely, but not entirely, compensated for by the negative aberration associated with the extended index gradient through the lens volume, with the highest index at the lens center. Because, with aging, the refractive index becomes more constant through most of the lens volume, the compensating effect of the index gradient becomes weaker, and the overall oldest lens shows less positive spherical aberration. When accommodation occurs, the curvatures of the lens surfaces (particularly that of the anterior surface; e.g., Rosales, Dubbelman, Marcos, & Van der Heijde, 2006) increase. These changes would tend to increase the positive spherical aberration. However, in the young eye, the initially quasi-ellipsoidal iso-index surfaces within the accommodated lenses become more spheroidal, so that the internal refractive index gradients overcompensate for the positive spherical aberration introduced by the surfaces, resulting in an overall change toward negative (overcorrected) spherical aberration in the young accommodated eye. In contrast, the limited extent of the index gradients in the older lens means that it acts more like a lens with homogenous refractive index, so that its initially positive spherical aberration tends to remain constant or even to increase with accommodation. These suggested changes appear to be compatible with the in vitro experimental studies of Glasser and Campbell (1998).

Because the fourth-order spherical aberration interacts with defocus in determining the image quality of the eye, the stability or increase in spherical aberration with accommodation in the older age group might be advantageous in increasing the depth of focus and allowing the individual to detect a near target despite the presence of a large accommodative lag. In contrast, in the younger groups, the spherical aberration passes through zero at between 0.5 and 2.5 D of accommodation, close to the typical tonic level of accommodation at which accommodative leads and lags are minimal, thus helping to maintain optimal image quality under these conditions.

Although the levels of aberration are generally small, the systematic change in the way spherical aberration is altered with accommodation in different age groups should influence the strategy that should be used for correcting higher order aberrations, especially with refractive surgery. Artal, Fernandez, and Manzanera (2002) suggest that due to the dynamic nature of ocular optics, a static perfect correction of ocular aberrations performed in customized
refractive surgery would not remain perfect for every condition occurring during normal accommodation. H. Cheng et al. (2004) suggested that, at moderate levels of accommodation (1–3 D), correcting spherical aberration will have no significant effect, but at high accommodative levels, it is advantageous to leave the spherical aberration uncorrected. Our data support their view, as the changes in spherical aberration with accommodation vary greatly with age.

Conclusions

As the pre-presbyopic eye ages, the changes in aberration that occur over the same range of accommodation response alter. In younger eyes, spherical aberration tends to change with accommodation from a positive to a negative value: In older eyes (around 40 years and above), spherical aberration remains positive and may even increase over the small amplitude of available accommodation. It is suggested that these changes may relate to the changes with age in the form and extent of the gradients of refractive index within the lens.

Acknowledgments

Commercial relationships: none.
Corresponding author: Hema Radhakrishnan.
Email: Hema.Radhakrishnan@manchester.ac.uk.
Address: Faculty of Life Sciences, University of Manchester, Manchester, UK.

References


