# Age-Related Changes in Monochromatic Wave Aberrations of the Human Eye

*James S. McLellan,*[1] *Susana Marcos,*[1,2] *and Stephen A. Burns*[1]

**Purpose.** To investigate the relations between age and the optical aberrations of the whole eye. The eye's optical quality, as measured by the modulation transfer function (MTF), degrades with age, but the MTF does not provide a means to assess the contributions of individual aberrations, such as coma, spherical aberration, and other higher order aberrations to changes in optical quality. The method used in this study provides measures of individual aberrations and overall optical quality.

**Methods.** Wave aberrations in 38 subjects were measured psychophysically using a spatially resolved refractometer. Data were fit with Zernike polynomials up to the seventh order to provide estimates of 35 individual aberration terms. MTFs and root mean square (RMS) wavefront errors were calculated. Subjects ranged in age from 22.9 to 64.5 years, with spherical equivalent corrections ranging from +0.5 to −6.0 D.

**Results.** Overall RMS wavefront error (excluding tilts, astigmatism, and defocus) was significantly positively correlated with age ($r = 0.33$, $P = 0.042$). RMS error for the highest order aberrations measured (fifth through seventh order) showed a strong positive correlation with age ($r = 0.57$, $P = 0.0002$). Image quality, as quantified by the MTF, also degraded with age.

**Conclusions.** Wave aberrations of the eye increase with age. This increase is consistent with the loss of contrast sensitivity with age observed by other investigators. (*Invest Ophthalmol Vis Sci.* 2001;42:1390–1395)

The reduction in photopic contrast sensitivity with age[1–3] has been attributed to both neural and optical factors. Studies using laser interferometric stimuli to bypass the eye's optics have led to conflicting conclusions concerning neural factors,[4,5] but losses in optical quality with age have been reliably demonstrated. Degradation in the modulation transfer function (MTF) with age has been shown by double-pass imaging,[6–8] and increases in light scattering in the eye with age have been psychophysically demonstrated.[9,10] Corneal topography has shown that asymmetric (odd order) corneal aberrations increase with age,[11] and aberroscope measurements have shown an increase of third- and fourth-order wave aberrations of the whole eye, including coma and spherical aberration.[3]

In the present study, we investigated further the relation between age and the optical quality of the eye. A psychophysical technique was used to measure wave aberrations through the seventh order. The advantage of our technique over double-pass imaging lies in its ability both to characterize the MTF of the eye and to measure the magnitudes of specific aberrations such as coma, spherical aberration, and higher order aberrations that are not usually measured with the aberroscope. Our results showed a strong positive correlation between the highest order aberrations (fifth through seventh order) and age.

## Methods

### Apparatus

Data were collected with a spatially resolved refractometer (SRR), described in detail elsewhere.[12–14] The SRR uses a psychophysical procedure to assess wave aberrations of the entire eye. For a series of different pupil entry locations, the subject uses a joystick to visually align a test spot to a fixed reference location on the retina. This reference location is provided by a fixation point that always enters through the center of the pupil. The movement of the test spot corresponds to a change in the angle at which the light enters the pupil. The angular deviation needed to align the spot to the reference location for each entry location provides an estimate of the local slope of the wavefront at that location. The SRR has three optical channels. The first channel consists of an oscilloscope to provide the test spot and a rotating wheel with 37 apertures (1 mm in diameter) used to sample the pupil at 1-mm intervals. The effective diameter of the entire pupil sampling array is 7.32 mm. The positioning of the wheel is motor driven and computer controlled. The wheel is optically conjugate to the observer's pupil. A 530-nm interference filter (10-nm half-width) is placed in the test channel to limit the spectral bandwidth of the oscilloscope image. In the second channel, an image of a cross and high spatial frequency information (text) are displayed through a small, centered pupil. The cross is used as the fixation target and as the reference point for aligning the test spot, and the text acts as an accommodative cue. The third channel provides an infrared (IR) video image of the subject's pupil used to align the pupil center to the optical axis of the apparatus. All channels pass through a translatable focusing block (Badal optometer) to correct for the subject's spherical refractive error over a range of −6 to +2 D.

### Subjects

Thirty-eight subjects participated in this study (19 women, 19 men; age range, 22.9–64.5 years). Although they were not screened at the time of testing, none of the subjects had a history of ocular abnormalities. Measurements were performed on the right eye in all but one subject. Subjects' pupils were dilated with 0.5% tropicamide solution to ensure that all test spots would be visible. Subjects did not wear refractive correction during experimental runs; most of their spherical refractive error was compensated by means of the Badal system. All subjects gave informed consent before participation. The research protocol adhered to the tenets of the Declaration of Helsinki.

### Procedure

The subject's head was stabilized with a dental impression bite bar and a head rest. The center of the subject's pupil was aligned to the optical axis of the apparatus by a three-dimensional translating stage. The experimenter monitored and controlled pupil alignment throughout the experimental runs using the IR video monitor. In each run, the test

From the [1]Schepens Eye Research Institute, Boston, Massachusetts; and [2]Instituto de Óptica, Daza de Valdés, Consejo Superior de Investigaciones Científicas, Madrid, Spain.

Supported by Grant EYO4395 from the National Institutes of Health and Human Frontiers Science Program LT0542/1997-B..

Submitted for publication August 17, 2000; revised December 18, 2000; accepted January 12, 2001.

Commercial relationships policy: N.

The publication costs of this article were defrayed in part by page charge payment. This article must therefore be marked "*advertisement*" in accordance with 18 U.S.C. §1734 solely to indicate this fact.

Corresponding author: James S. McLellan, Schepens Eye Research Institute, 20 Staniford Street, Boston, MA 02114. mclellan@vision.eri.harvard.edu



Investigative Ophthalmology & Visual Science, May 2001, Vol. 42, No. 6

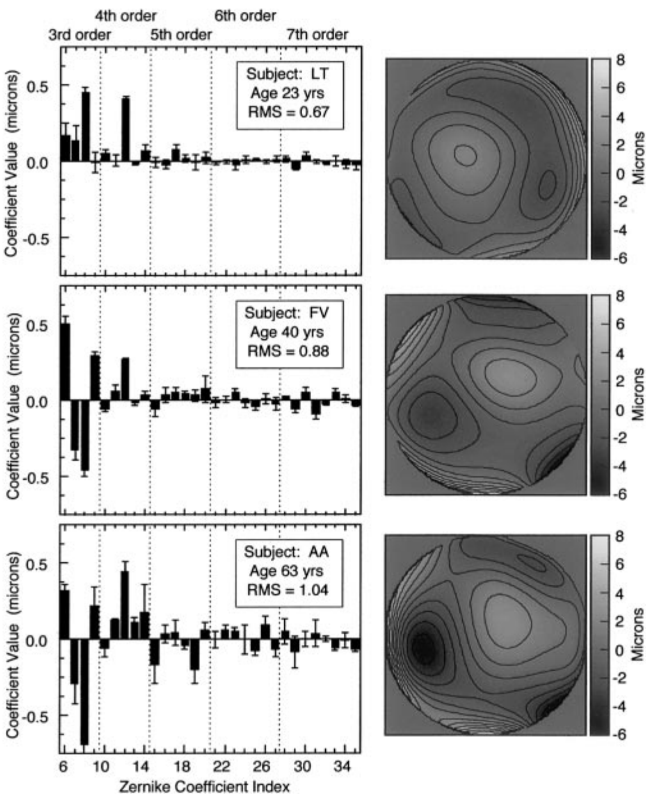


**FIGURE 1.** Zernike coefficients and pupil wavefront maps for three sample subjects chosen as typical of their age groups. The plots on the *left* show the coefficient values (in micrometers [microns]) of the third- through seventh-order Zernike polynomials for each subject. *Lines* on the wavefront maps indicate 1-$\mu$m contours.

spot was stepped through the set of 37 entrance pupil locations in pseudorandom order, and the subject used the joystick to move the spot's image to the center of the fixation cross for each pupil location. The subject indicated verbally when the spot was aligned. An experimental run lasted approximately 4 minutes. Each subject completed three runs. Spherical refractive error was subjectively corrected for each subject by translating the focusing block to bring the high frequency background into focus. The same spherical correction was used in each run.

## Data Analysis

The SRR data provide estimates of the local slope of the wave aberration. Zernike polynomial coefficients through the seventh order (35 Zernike terms) were determined by least-squares fits of the derivatives of the Zernike polynomials to these data. Each run was fit individually, and the mean Zernike coefficients across the three runs for each subject were then used to reconstruct the wave aberration in the pupil plane. This wave aberration was used to compute the point spread function and MTF for each subject.

Root mean square (RMS) wavefront error (i.e., the deviation of the wavefront from ideal) was used as a measure of optical quality. We calculated the RMS error corresponding to the third- through seventh-order Zernike coefficients (i.e., excluding tilts, defocus, and astigmatism). The RMS error was calculated separately for coma, spherical aberration, all third-order terms together, all fourth-order terms together, and the combination of fifth- through seventh-order terms. A pupil diameter of 7.32 mm was used for all computations.

Spherical equivalent refractive error in diopters was determined by combination of best focus correction (position of the focusing block) and residual paraxial defocus calculated as the appropriate combination of the Zernike terms for defocus (second order) and fourth- and sixth-order spherical aberration. Astigmatism was calculated from the

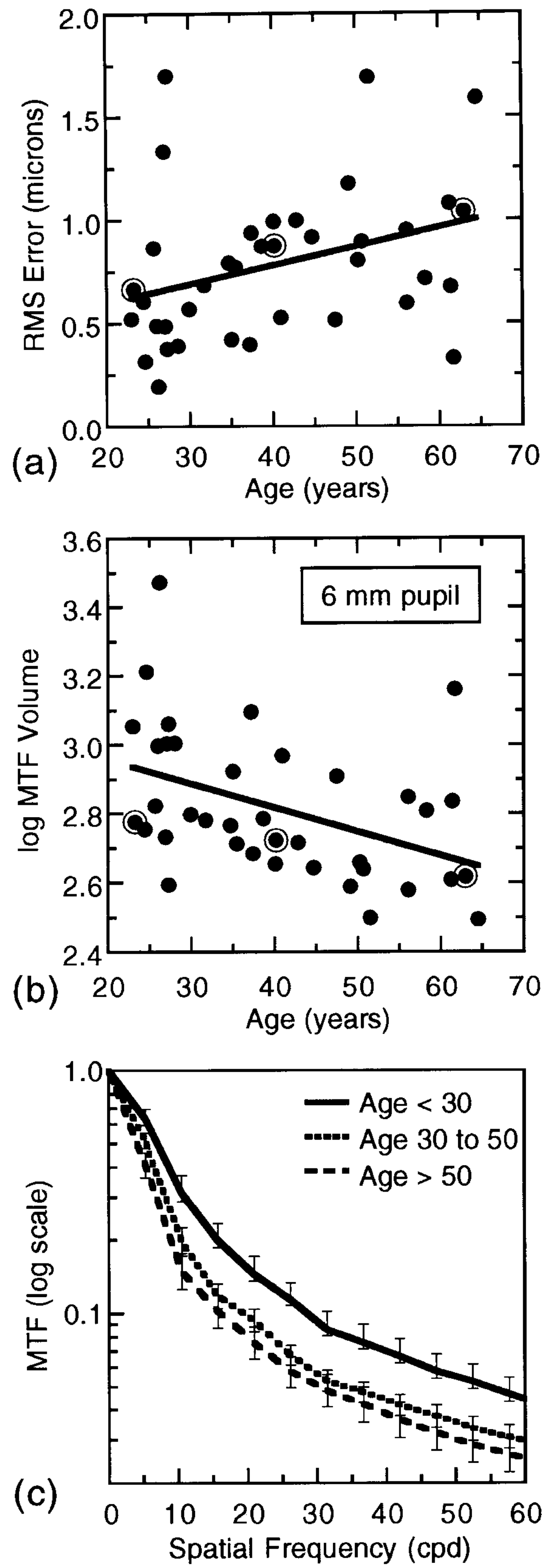


**FIGURE 2.** (**a**) Relation between age and the RMS wavefront error for third- through seventh-order Zernike coefficients. Correlation is significant: $r = 0.33$, $P = 0.042$. (**b**) Relation between age and log MTF volume, computed for a 6-mm pupil. Correlation is significant: $r = 0.44$, $P = 0.006$. *Circled points*: data from the sample subjects shown in Figure 1. (**c**) MTFs for subjects divided into three age groups. There is a significant difference between the groups ($F = 5.13$, $df = 2$, $P = 0.011$).

combination of the second-order Zernike coefficients that represent power on horizontal and vertical axes and on oblique axes.

Two-dimensional MTFs were derived from the wavefront maps for 6- and 3-mm pupils, again excluding correctable refractive errors. Overall optical quality was assessed by calculating the MTF volume. Pupil apodization by the Stiles–Crawford effect was not taken into account.[15] Estimates of the one-dimensional MTFs were calculated as the radial average of the two-dimensional MTFs.

## Results

Figure 1 illustrates the differences in wavefront error for various ages in three sample subjects (ages 23, 40, and 63) chosen as typical of their age groups. The plots on the left show the coefficient values (in micrometers) of the third- through seventh-order Zernike polynomials for each subject. Zernike coefficients 7 and 8 correspond to coma, and coefficient 12 corresponds to spherical aberration. In the recently standardized double-indexing scheme[16] these coefficients are terms $Z_3^{-1}$, $Z_3^{1}$, and $Z_4^{0}$, respectively. The breakdown of Zernike coefficients into orders is shown in the figure. The error bars indicate SE across the three experimental runs. The RMS error was lowest in the 23-year-old subject (Fig. 1, top) and highest in the 63-year-old subject (Fig. 1, bottom). The images on the right of the figure show pupil maps of the wave aberrations in each subject, excluding the tilts, defocus, and astigmatism. The wavefront maps show that the contour heights changed more abruptly in the eldest subject than in the other two, suggesting an increase in higher order aberrations.

Figure 2a shows the relation between age and overall RMS wavefront error, excluding tilts, defocus, and astigmatism. The variability in RMS error across subjects was large at all ages. The two eyes with lowest RMS error lay near the two extremes of the age range, as did the two eyes with highest RMS error. There was a significant increase in RMS error with age ($r$ = 0.33, $P$ = 0.042). Figure 2b shows the relation between age and log MTF volume computed for a 6-mm pupil. This correlation was significant ($r$ = 0.44, $P$ = 0.006). The circled data points in Figures 2a and 2b indicate the three subjects represented in Figure 1. To compare mean MTFs at different ages the subjects were split into three groups: (1) subjects less than 30 years of age ($n$ = 13); (2) subjects 30 to 50 years of age ($n$ = 14); and (3) subjects more than 50 years of age ($n$ = 11). The MTF was degraded with age at all spatial frequencies (Fig. 2c). In an analysis of variance (ANOVA), the difference in MTF across these groups is significant (F = 5.13, $df$ = 2, $P$ = 0.011). At 16 cyc/deg there was a difference of approximately 0.3 log units between the mean MTFs for the youngest and eldest groups. The error bars indicate SE within each group.

As shown in Figure 3a, there was a small, but not significant, correlation between age and spherical equivalent refractive error (Fig. 3a, filled symbols) among these subjects ($r$ = 0.12, $P$ = 0.46). Astigmatism (Fig. 3a, open symbols) increased significantly as a function of age ($r$ = 0.37, $P$ = 0.025). (This regression excludes an outlying astigmatism value of 4.6 D.) Figure 3b shows that RMS error for third- through seventh-order aberrations was not correlated with spherical equivalent ($r$ = 0.005, $P$ = 0.98).

The relations between age and the classic aberrations, coma and spherical aberration, are shown in the scatterplots in Figure 4. Spherical aberration increased significantly with age ($r$ = 0.33, $P$ = 0.041). Because of the higher intersubject variability across all ages, the increase in coma was not significant ($r$ = 0.19, $P$ = 0.26). Figure 5 shows the relation between age and RMS error for all third-order terms (Fig. 5a), all fourth-order terms (Fig. 5b), and all fifth- through seventh-order terms (Fig. 5c). The correlations with age increased as the order of the aberrations increased. Third- and fourth-order aberrations were highly variable across ages; total third-order aberrations were not significantly correlated with age ($r$ = 0.18, $P$ = 0.28), but total fourth-order aberrations were ($r$ = 0.47, $P$ = 0.003). The higher order aberrations (fifth through seventh) showed a robust, significant increase with age ($r$ = 0.57, $P$ = 0.0002).

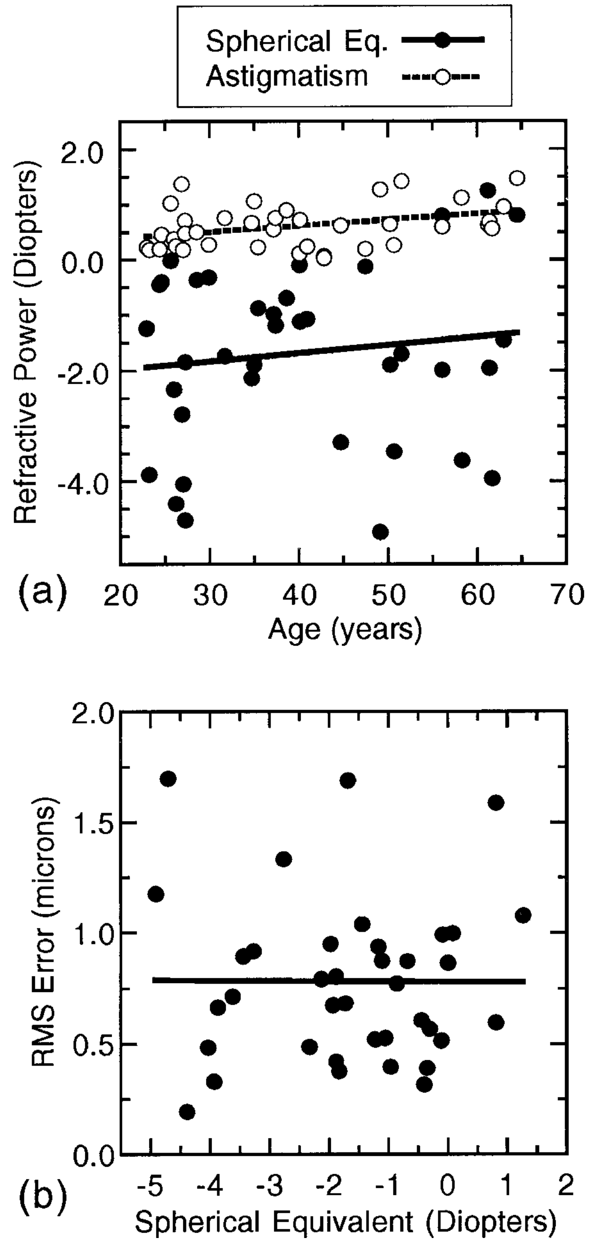


**Figure 3.** (**a**) Relations of age to spherical equivalent refractive error ($r$ = 0.12, $P$ = 0.46) and astigmatism ($r$ = 0.37, $P$ = 0.25) and (**b**) relation of spherical equivalent to RMS wavefront error for third- through seventh-order Zernike coefficients ($r$ = 0.005, $P$ = 0.98). *Circled points*: data from the sample subjects shown in Figure 1.

## Discussion

That there was no relationship between aberrations and refractive error may be due to the limited range of myopia in our subjects. Simonet et al.[17] and Marcos et al.[18] have reported that aberrations increase with increasing myopia. However, the latter group found that this effect was attributable to 7- to 13-D myopes. They found no relationship over the range of myopia represented in our sample.

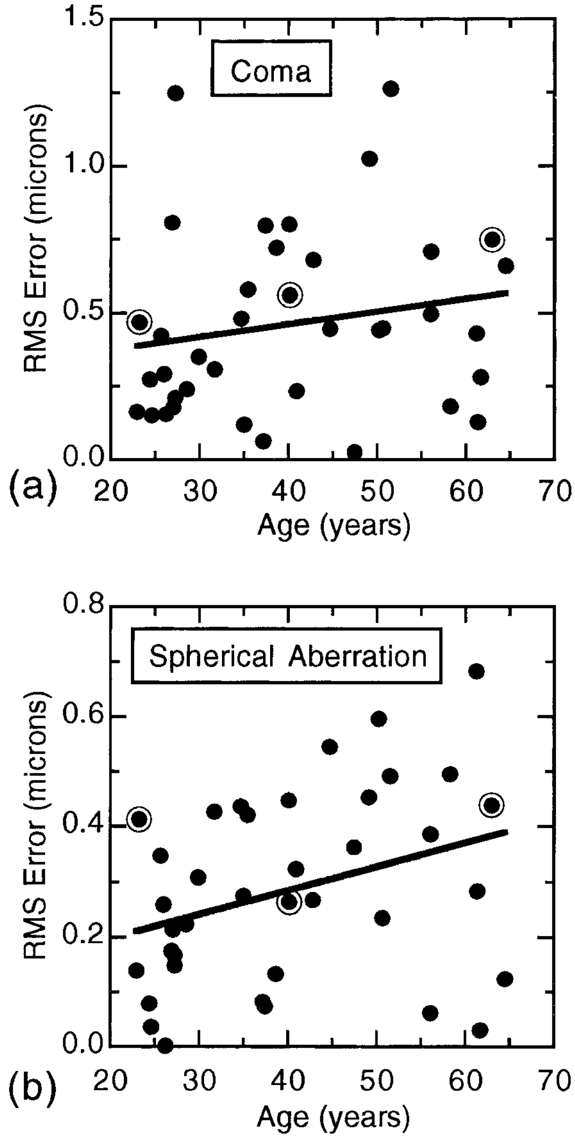


**FIGURE 4.** (**a**) Coma versus age: correlation is not significant ($r$ = 0.19, $P$ = 0.26). (**b**) Spherical aberration versus age: correlation is significant ($r$ = 0.33, $P$ = 0.041). *Circled points*: data from the sample subjects shown in Figure 1.

In our sample, third- and fourth-order aberrations were highly variable across all ages, although they both show an increase with age. The higher order aberrations (fifth through seventh orders), however, showed a robust increase with age. The proportional increase in both fourth-order and higher order aberrations with age was greater than for third-order aberrations.

The high degree of variability in third- and fourth-order aberrations is similar to the variability found in spherical equivalent and astigmatism. There are many potential sources of lower order aberrations, including shapes of optical components, decentering of the pupil, and misalignment of lens and cornea. However, higher order aberrations are likely to have more local causes such as small irregularities in shape and refractive indices of the eye's optical elements. Although our results cannot be tied to any specific locus (such as lens versus cornea) or cause, it is likely that the hardening of the lens[19] and thickening of the lenticular cortex[20] with age, as well as the early development of undiagnosed cataracts, contributed to the increase in both aberrations and ocular scattering. In addition, reduction with age in tear volume[21] and tear film stability[22]

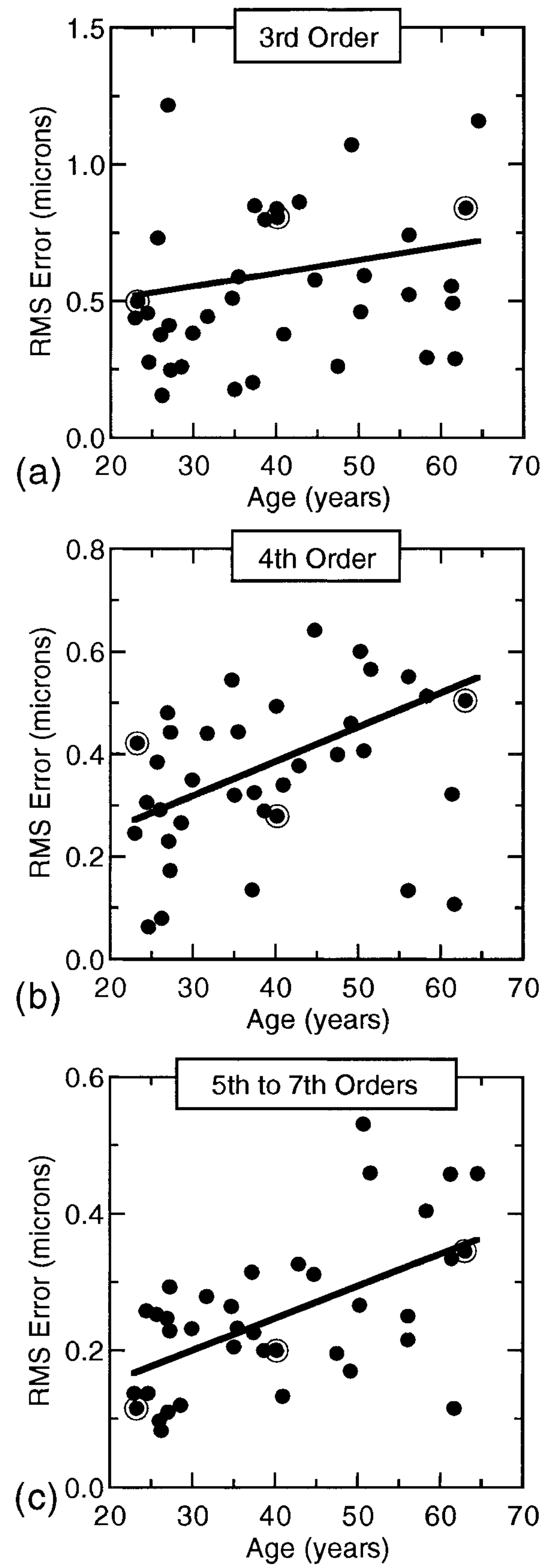


**FIGURE 5.** Relations between age and RMS wavefront errors for different Zernike orders. (**a**) Third order: correlation is not significant ($r$ = 0.18, $P$ = 0.28). (**b**) Fourth order: correlation is significant ($r$ = 0.47, $P$ = 0.003). (**c**) Fifth through seventh orders combined: correlation is significant ($r$ = 0.57, $P$ = 0.0002). *Circled points*: data from the sample subjects shown in Figure 1.

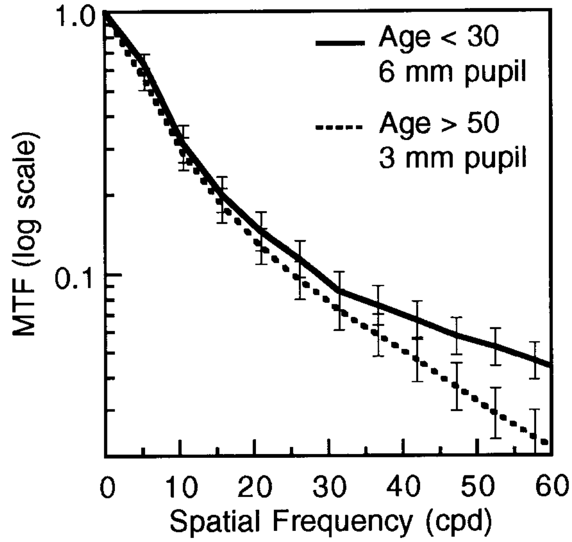


**FIGURE 6.** Comparison of the MTFs for subjects less than 30 years of age computed for a 6-mm pupil ($n$ = 13) and subjects more than 50 years of age computed for a 3-mm pupil ($n$ = 11). Error bars indicate SE. The MTF for the younger group was higher at all spatial frequencies.

could be related to an increase in corneal surface irregularities and therefore to increased amounts of high-order aberrations. Guirao et al.[23] have shown that corneal aberrations measured by videokeratography increase with age, but not to a degree sufficient to account for the losses in MTF.

It has been suggested that pupillary miosis, the decrease in natural pupil size with age, mitigates the effects of degraded optical quality in older eyes.[3] Although we did not collect data on natural pupil size for these subjects, it seems unlikely that differences in pupil size could eliminate the effects of the increases in aberrations that we found. Calver et al.[3] stated that a 1-mm difference in natural pupil size results in an average MTF in older subjects that is almost identical with that of the younger subjects. Their data show a high degree of variability in third- and fourth-order aberrations, as do ours. However, the fact that they did not take into account higher order aberrations, which in our sample increased very regularly with age, may have obscured the real differences between younger and older MTFs. The mean MTF of our younger subjects with a 6-mm pupil was compared with the mean MTF of our older group with 3-, 4-, and 5-mm pupils. Figure 6 shows the comparison for 3-mm pupils. The results for 4- and 5-mm pupils were similar and are not shown. Even with a difference of 3 mm in pupil diameters, the older group's MTF lay below the younger, although the difference was not significant ($F = 1.9$, $P = 0.18$). The interaction of age group with MTF was significant ($F = 10.4$, $P < 0.0001$), indicating that the shapes of the two functions are different, with the older group showing a more rapid decline in resolution at high spatial frequencies. However, this difference resulted primarily from diffraction effects for the smaller pupil size rather than from aberrations, per se. It should be noted that this analysis did not take into account the possibility that the pupil center moves as the pupil size changes, which could produce different MTFs for the 3-mm pupils. However, this decentration is expected to be small[24] and is unlikely to change the results. The effect of decentration would be even smaller for 4- and 5-mm pupils.

Unlike double-pass imaging, our psychophysical procedure was not sensitive to scattered light. Although aberrations occasionally caused blur in the test spot, the subject always aligned the brightest portion of the spot to the cross. Thus, scatter did not affect the alignment task. Figure 7 shows a

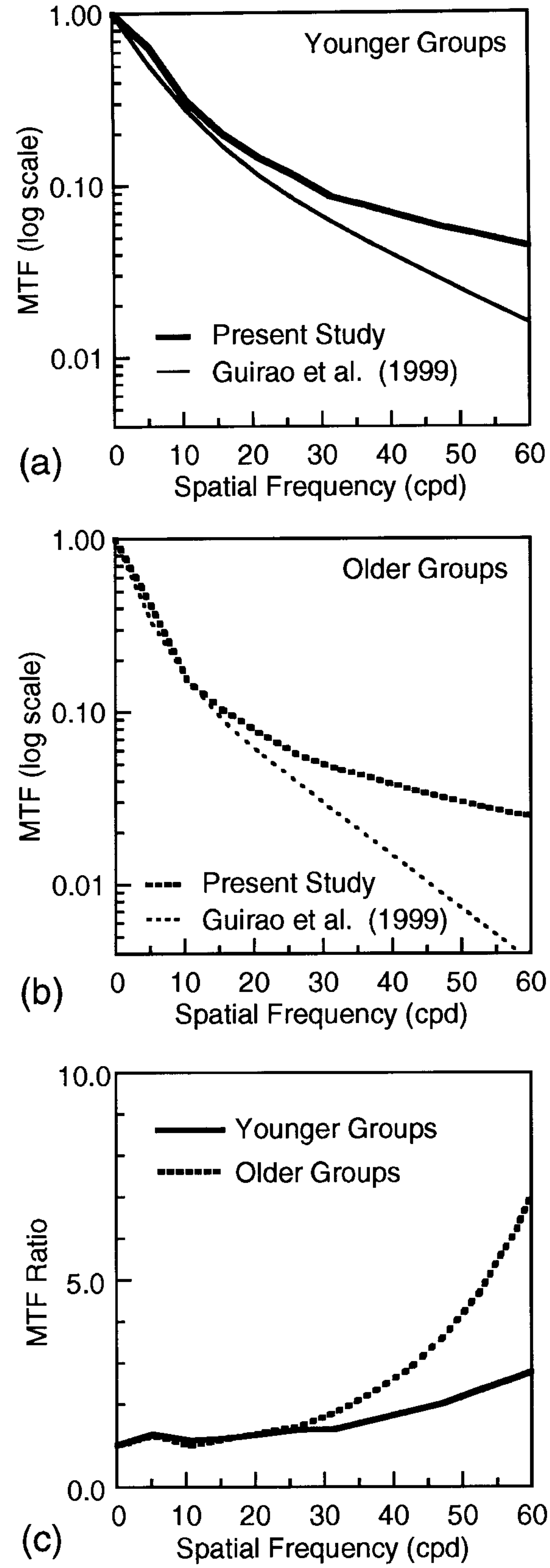


**FIGURE 7.** Comparison of MTFs (6-mm pupil) for the (**a**) youngest and (**b**) eldest groups from this study with MTFs for corresponding age groups from Guirao et al.[8] (**c**) MTF ratios for each group across these two studies. For the eldest subjects, the MTF ratio increased more rapidly at higher spatial frequencies.

comparison of the average MTFs for our youngest and eldest groups to group average MTFs derived from double-pass images from Guirao et al.[8] The MTFs from that study are based upon the parameters of exponential fits[25] provided in their paper. For both age groups, the MTFs of the present study lay above those computed from double-pass images (Figs. 7a, 7b). This is to be expected, because the double-pass MTFs include the effects of scatter and higher order aberrations, whereas our MTFs were reconstructed from a limited set of Zernike coefficients. Furthermore, temporal summation during the photographic exposure time may produce blur in the double-pass measurements, potentially resulting in underestimation of optical quality, whereas averaging runs in our technique may smooth the estimated wavefront, resulting in an overestimation of the MTF.[26] However, this cannot explain the difference in the ratios of the two kinds of MTFs for the two groups (Fig. 7c). For both groups, this ratio increased with spatial frequency, but the increase was especially pronounced in the older subjects. This increasing ratio was consistent with an increase in forward scattering in the optical media with age, suggesting increased amounts of very small-scale irregularities in the optical media.

## Conclusions

The RMS wavefront error of the eye increases as a normal function of aging, with higher order, more spatially localized aberrations showing the strongest relation to age. Lower order aberrations, including the classic aberrations of coma and spherical aberration, show a large degree of variability with age, although they also tend to increase. These increases result in poorer optical quality as measured by the MTF, especially at high spatial frequencies, even when pupillary miosis is taken into account. Although their practical visual effects could not be directly assessed in this study, it is likely that these increases in aberrations are a major contributing factor to the loss in contrast sensitivity with age.

### *Acknowledgments*

The authors thank Pedro Prieto for helpful discussions and all the subjects for their time and cooperation.

### *References*

1. Owsley C, Sekuler R, Siemsen D. Contrast sensitivity throughout adulthood. *Vision Res.* 1983;23:689–699.
2. Elliott D, Whitaker D, MacVeigh D. Neural contribution to spatiotemporal contrast sensitivity decline in healthy ageing eyes. *Vision Res.* 1990;30:541–547.
3. Calver RI, Cox MJ, Elliott DB. Effect of aging on the monochromatic aberrations of the human eye. *J Opt Soc Am A.* 1999;16:2069–2078.
4. Burton KB, Owsley C, Sloane ME. Aging and neural spatial contrast sensitivity: photopic vision. *Vision Res.* 1993;33:939–946.
5. Elliott DB. Contrast sensitivity decline with ageing: a neural or optical phenomenon? *Ophthalmic Physiol Opt.* 1987;7:415–419.
6. Artal P, Ferro M, Miranda I, Navarro R. Effects of aging in retinal image quality. *J Opt Soc Am A.* 1993;10:1656–1662.
7. Liang J, Westheimer G. Optical performances of human eyes derived from double-pass measurements. *J Opt Soc Am A.* 1995;12:1411–1416.
8. Guirao A, Gonzalez C, Redondo M, Geraghty E, Norrby S, Artal P. Average optical performance of the human eye as a function of age in a normal population. *Invest Ophthalmol Vis Sci.* 1999;40:203–213.
9. Westheimer G, Liang J. Influence of ocular light scatter on the eye's optical performance. *J Opt Soc Am A.* 1995;12:1417–1424.
10. IJspeert JK, de Waard PW, van den Berg TJ, de Jong PT. The intraocular straylight function in 129 healthy volunteers; dependence on angle, age and pigmentation. *Vision Res.* 1990;30:699–707.
11. Oshika T, Klyce SD, Applegate RA, Howland HC. Changes in corneal wavefront aberrations with aging. *Invest Ophthalmol Vis Sci.* 1999;40:1351–1355.
12. Webb RH, Penney CM, Thompson KP. Measurement of ocular local wavefront distortion with a spatially resolved refractometer. *Appl Opt.* 1992;31:3678–3686.
13. He JC, Marcos S, Webb RH, Burns SA. Measurement of the wavefront aberration of the eye by a fast psychophysical procedure. *J Opt Soc Am A.* 1998;15:2449–2456.
14. Marcos S, Burns SA, Moreno–Barriuso E, Navarro R. A new approach to the study of ocular chromatic aberrations. *Vision Res.* 1999;39:4309–4323.
15. Marcos S, Burns SA. Measurement of the image quality of the eye with the spatially resolved refractometer. In: MacRea S, Krueger RR, Applegate RA, eds. *Customized Corneal Ablations*. Thorofare, NJ: Slack; 2001.
16. Thibos LN, Applegate RA, Schwiegerling JT, Webb R, et al. Standards for reporting the optical aberrations of eyes. *OSA Trends in Optics and Photonics, Vision Science and its Applications.* 2000;35:232–244.
17. Simonet P, Hamam H, Brunette I, Campbell M. Influence of ametropia on the optical quality of the human eye [ARVO Abstract]. *Invest Ophthalmol Vis Sci*. 1999;40(4):S448. Abstract nr 2361.
18. Marcos S, Moreno–Barriuso E, Llorente L, Navarro R, Barbaro S. Do myopic eyes suffer from large amounts of aberration? *Proceedings of the VIII International Congress on Myopia.* 2000;8:118–121.
19. Glasser A, Campbell MC. Biometric, optical and physical changes in the isolated human crystalline lens with age in relation to presbyopia. *Vision Res.* 1999;39:1991–2015.
20. Cook CA, Koretz JF, Pfahnl A, Hyun J, Kaufman PL. Aging of the human crystalline lens and anterior segment. *Vision Res.* 1994;34:2945–2954.
21. Mathers WD, Lane JA, Zimmerman MB. Tear film changes associated with normal aging. *Cornea.* 1996;15:229–234.
22. Patel S, Farrell JC. Age-related changes in precorneal tear film stability. *Optom Vis Sci.* 1989;66:175–178.
23. Guirao A, Redondo M, Artal P. Optical aberrations of the human cornea as a function of age. *J Opt Soc Am A*. 2000;17:1697–1702.
24. Rynders M, Lidkea B, Chisholm W, Thibos LN. Statistical distribution of foveal transverse chromatic aberration, pupil centration, and angle psi in a population of young adult eyes. *J Opt Soc Am A.* 1995;12:2348–2357.
25. Artal P, Navarro R. Monochromatic modulation transfer function of the human eye for different pupil diameters: an analytical expression. *J Opt Soc Am A.* 1994;11:246–249.
26. Prieto PM, Vargas–Martin F, Goelz S, Artal P. Analysis of the performance of the Hartmann-Shack in the human eye. *J Opt Soc Am A.* 2000;17:1388–1398.