Changes in Corneal Wavefront Aberrations with Aging

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PURPOSE. To investigate whether corneal wavefront aberrations vary with aging.

METHODS. One hundred two eyes of 102 normal subjects were evaluated with videokeratography. The data were decomposed using Taylor and Zernike polynomials to calculate the monochromatic aberrations of the cornea for both small (3-mm) and large (7-mm) pupils.

RESULTS. For a 3-mm pupil, the amount of total aberrations (Spearman rank correlation coefficient \( r_s = 0.145; P = 0.103 \)) and spherical-like aberrations \( r_s = -0.068; P = 0.448 \) did not change with aging, whereas coma-like aberrations exhibited a weak but statistically significant correlation with age \( r_s = 0.256; P = 0.004 \). For a 7-mm pupil, total aberrations \( r_s = 0.552; P < 0.001 \) and coma-like aberrations \( r_s = 0.561; P < 0.001 \) significantly increased with aging, but spherical-like aberrations showed no age-related changes \( r_s = 0.124; P = 0.166 \). Simulated pupillary dilation from 3 mm to 7 mm caused a 38.0 ± 28.5-fold increase in the total aberrations, and the extent of increases significantly correlated with age \( r_s = 0.354; P < 0.001 \). Pupillary dilation influenced the coma-like aberrations more in the older subjects than in the younger subjects \( r_s = 0.243; P = 0.006 \), but such age dependence was not found for spherical-like aberrations \( r_s = 0.141; P = 0.115 \).

CONCLUSIONS. Coma-like aberrations of the cornea correlate with age, implying that the corneas become less symmetrical along with aging. Spherical-like aberrations do not vary significantly with aging. Pupillary dilation markedly increases wavefront aberrations, and those effects are more prominent in older subjects than in younger subjects. (Invest Ophthalmol Vis Sci. 1999;40:1351-1355)

It has been well documented that naturally occurring astigmatism, in either keratometry1-7 or refraction,8-10 shifts from a pattern of "with-the-rule" to "against-the-rule" with aging. Age-related changes in chromatic aberrations of the eye have been investigated11-13 However, no studies are available on the relationship between monochromatic aberrations and age.

With an increasing number of keratorefractive surgical procedures performed annually, their influence on the optical quality of the cornea gathers more attention. Recent studies have indicated that higher-order monochromatic aberrations of the cornea significantly increased after radial keratotomy.14-16 Photorefractive keratectomy,17-20 and laser in situ keratomileusis20 Further, it has been shown that the increase in corneal aberrations is associated with a decrease in visual performance after radial keratotomy.21 Thus, the wavefront aberrations of the cornea are now not only of investigational interest, but also of clinical interest.22,23 In this situation, basic data regarding monochromatic aberrations, such as changes due to aging, are essential. We conducted the present study to assess the influence of aging on the aberrations of the cornea.

SUBJECTS AND METHODS

The study was conducted according to the tenets of the Declaration of Helsinki. One hundred two eyes of 102 subjects were evaluated. They did not have any ocular disease except for age-related cataract and mild refractive errors, including myopia, hyperopia, and regular forms of astigmatism (less than 1.5 D). None of them was wearing contact lenses. They were selected from the patients who visited the Department of Ophthalmology, University of Tokyo School of Medicine, for ocular examination. Their ages ranged from 9 to 85 years (Table 1). All the subjects were Japanese; there were 48 men and 54 women.

Videokeratographic data were obtained with computerized videokeratography (TMS-I; Computed Anatomy, New York, NY). For each eye, measurements were repeated at least three times to obtain a well-focused, properly aligned image of the eye. The files containing information about corneal elevation, curvature, power, and position of the pupil were downloaded on a removable media and used for the following analysis.

The calculation of wavefront aberrations was performed using the descriptive polynomial method of Howland and...
TABLE 1. Age Range and Refractive Status of Subjects

<table>
<thead>
<tr>
<th>Age</th>
<th>Eyes</th>
<th>Spherical equivalent (D)</th>
<th>Astigmatism (D)</th>
</tr>
</thead>
<tbody>
<tr>
<td>≤20</td>
<td>16</td>
<td>-1.0 ± 1.3</td>
<td>0.15 ± 0.19</td>
</tr>
<tr>
<td>21–30</td>
<td>15</td>
<td>-0.8 ± 1.4</td>
<td>0.17 ± 0.24</td>
</tr>
<tr>
<td>31–40</td>
<td>14</td>
<td>-1.2 ± 2.0</td>
<td>0.18 ± 0.37</td>
</tr>
<tr>
<td>41–50</td>
<td>15</td>
<td>-1.4 ± 0.8</td>
<td>0.26 ± 0.26</td>
</tr>
<tr>
<td>51–60</td>
<td>14</td>
<td>-1.1 ± 1.6</td>
<td>0.19 ± 0.36</td>
</tr>
<tr>
<td>61–70</td>
<td>15</td>
<td>-0.7 ± 1.1</td>
<td>0.21 ± 0.44</td>
</tr>
<tr>
<td>≥71</td>
<td>13</td>
<td>-0.9 ± 1.2</td>
<td>0.25 ± 0.35</td>
</tr>
<tr>
<td>Total group</td>
<td>102</td>
<td>-1.1 ± 1.6</td>
<td>0.19 ± 0.37</td>
</tr>
</tbody>
</table>

Data are expressed as means ± SD.

Howland. The center of the pupil was identified on the topography video screen, and its deviation from the videokeratographic axis was measured. Using the method of least squares, the reference sphere for each eye was calculated by determining the best-fit sphere to the elevation data over the 3-mm area centered on the pupil. The elevations of the best-fit sphere were subtracted from the measured elevations to define a surface termed the remainder lens. To calculate the optical effects of the remainder lens, the elevations of that lens were multiplied by 0.3375 (the keratometric index of refraction of the cornea minus the refractive index of air). Using the method of least squares, the resultant data were fit with the Taylor polynomial of the form

$$W(x, y) = A + Bx + Cy + Dx^2 + Exy + Fy^2 + Gx^3 + Hx^2y + Ixy^2 + Jx^3y + Kx^4 + Lx^3y^2 + Mx^2y^3 + Nxy^3 + Oy^4 + Pxy^4 + Qx^3y^3 + Rx^3y^2 + Sx^3y + Txy^4 + Uy^5 + Vx^6 + Wx^5y + Xx^4y^2 + Yx^4y + Zx^3y^2 + Ax^2y^3 + Axy^4 + Ay^6 \tag{1}$$

where \((x, y)\) are Cartesian coordinates of the cornea in millimeters with their origin being taken on the pupil center. This is a two-dimensional, sixth-order Taylor representation of the wave-aberration surface with the positive axis pointing away from the retina. The coefficients were scaled so that the function \(W(x, y)\) was expressed in micrometers when \(x\) and \(y\) were expressed in millimeters. \(A\) represents a shift of the entire wavefront along the optical axis; \(B\) and \(C\) represent the vertical and horizontal prism components. \(D\) through \(E\) include the conventional ophthalmic prescription: sphere, cylinder, and axis. \(G\) through \(J\) express comalike aberration, and \(K\) through \(O\) express spherical-like aberration. \(P\) through \(U\) are the fifth-order Taylor coefficients, and \(V\) through \(A_6\) denote the sixth-order Taylor coefficients.

The Taylor polynomial was then converted to the Zernike polynomial to obtain orthogonal coefficients. Zernike coefficients 7 through 28 (\(Z_7\) through \(Z_{28}\)) were calculated from linear combinations of Taylor coefficients as described by Howland and Howland. Coefficients \(Z_7\) through \(Z_{10}\) correspond to comalike aberration, \(Z_{11}\) through \(Z_{15}\) correspond to spherical-like aberration, \(Z_{16}\) through \(Z_{21}\) express the fifth-order Zernike coefficients, and \(Z_{22}\) through \(Z_{28}\) are the sixth-order Zernike coefficients.

These Zernike coefficients were then used to calculate the global descriptors of monochromatic corneal aberrations, which are represented by the terms, \(S_6, S_8, S_{14},\) and \(S_{16}\). Because spherical and coma aberrations refer to symmetrical systems and the eye is not rotationally symmetrical, the terms spherical-like and comalike aberrations are used in this article. The \(S_6\) (third-order component of the wavefront aberration) represents the mean squared wavefront variance from that of a perfect spherocylinder caused by coma-like aberration. Similarly, \(S_8\) (fourth-order component of the wavefront aberration) represents the mean squared wavefront variance from that of a perfect spherocylinder caused by spherical-like aberration. \(S_6\) and \(S_8\) are the fifth- and sixth-order components of the wavefront aberrations, respectively. Because the variances of each term are independent, the total wavefront variance was computed by summing the individual variances and served as a parameter of total wavefront aberrations (Su).

RESULTS

For a 3-mm pupil, the amount of total aberrations (Su) did not change with aging (Spearman rank correlation coefficient \(r_s = 0.145; P = 0.103; \) Fig. 1), whereas coma-like aberrations \((S_6 + S_8)\) exhibited a weak, but statistically significant correlation with age \((r_s = 0.256; P = 0.004; \) Fig. 2). Spherical-like aberrations \((S_6 + S_8)\) did not correlate with age \((r_s = -0.068; P = 0.448; \) Fig. 3).

For a 7-mm pupil, total aberrations \((r_s = 0.552; P < 0.001; \) Fig. 4) and coma-like aberrations \((r_s = 0.561; P < 0.001; \) Fig. 5) exhibited statistically significant positive correlations with age. Even when two extremely large values in Figures 4 and 5 were excluded from the analyses, the correlations remained statistically significant for total aberrations \((r_s = 0.533; P < 0.001)\) and comalike aberrations \((r_s = 0.543; P < 0.001)\). Spherical-like aberrations showed no age-related changes \((r_s = 0.124; P = 0.166; \) Fig. 6).

Simulated pupillary dilation from 3 mm to 7 mm caused a 38.0 ± 28.5-fold increase (mean ± SD) in total aberrations, and

FIGURE 1. Correlation between age and total wavefront aberrations (Su) for a 3-mm pupil (nonsignificant; Spearman rank correlation coefficient \(r_s = 0.145; P = 0.103).\)
the extent of increases by pupillary dilation showed statistically significant correlation with age ($r_s = 0.354; P < 0.001$; Fig. 7). Similarly, pupillary dilation influenced the comalike aberrations more in the older subjects than in the younger subjects ($r_s = 0.243; P = 0.006$; Fig. 8), but such age dependence was not found for spherical-like aberrations ($r_s = 0.141; P = 0.115$; Fig. 9).

**DISCUSSION**

In our study population of 102 eyes, we found a weak but statistically significant correlation ($r_s = 0.256; P = 0.004$) between age and comalike aberrations for a 3-mm pupil. For a 7-mm pupil, comalike aberrations exhibited significant positive correlations with age ($r_s = 0.561; P < 0.001$). Although we may not be able to apply the current results to subjects of all races and refractive status, it is suggested that comalike aberrations of the cornea tend to show age-related changes. Because comalike aberrations consist of tilt and/or asymmetry, these results imply that the corneas become less symmetric along with aging. On the contrary, spherical-like aberrations did not show any age-related changes for both 3- and 7-mm pupils, implying that the central-to-peripheral balance of the corneal curvature is not significantly affected by increasing age.

It should be noted that increases in the corneal comalike aberrations in the elderly do not directly indicate the deterioration of visual function in their eyes for several reasons. First, the pupils of older subjects tend to be more miotic, resulting in a smaller influence of the corneal wavefront aberrations on visual performance. Secondly, aberrations of the crystalline lens were not considered in the present study. In contrast to the spherical aberrations of the lens, little is known about the lenticular coma aberrations. It was anticipated that comalike aberrations introduced by corneal asymmetries are similar in magnitude to those measured for the eye as a whole, suggesting that these aberrations originate mainly in the cornea. However, proof of this hypothesis must wait until the relative contributions of cornea and crystalline lens are elucidated. Thirdly, the Stiles-Crawford effect was not considered in these calculations. However, the Stiles-Crawford effect is retinal in origin and does not alter the aberration or the change of aberration with age of the cornea or eye. Although it has
been claimed that the Stiles-Crawford effect reduces the impact of optical aberrations on vision, a recent analysis showed that the effect on vision is very small.35

Simulated pupillary dilation from 3 mm to 7 mm markedly increased the total aberrations and comalike aberrations; those influences were significantly larger in the older subjects than in the younger subjects (Figs. 7, 8). The data, especially in those with a 7-mm pupil, may have been influenced by the limitations of the Placido-based videokeratography in accurately capturing data from the peripheral cornea, although the obvious increases (38.0-fold increases) associated with pupillary dilation seemed to be sufficiently meaningful. These results have clinical relevance in situations in which pupillary abnormalities are encountered as a consequence of complications of intraocular surgery, such as atonic,36 eccentric,39’40 and overly stretched pupils.41’42 It has been known that when the pupil is made eccentric, spherical aberrations cause coma,43 which adds to the preexisting comalike aberrations. Even under normal concessions, the pupillary size increases with dim illumination in all age groups.44 Applegate et al.41 have reported that

![Figure 6](image6.png)  
**Figure 6.** Statistically significant correlation between age and spherical-like aberrations \((S_5 + S_6)\) for a 7-mm pupil (Spearman rank correlation coefficient \(r_s = 0.124; P = 0.166\)).

![Figure 8](image8.png)  
**Figure 8.** Statistically significant correlation between age and the magnitude of increases in comalike aberrations \((S_3 + S_5)\) induced by simulated pupillary dilation from 3 mm to 7 mm (Spearman rank correlation coefficient \(r_s = 0.243; P = 0.006\)).

a 1-log-unit change in wavefront variance induces a 0.23 change in the area under the log contrast-sensitivity function. They also reported that a 1-log-unit change in wavefront variance induces a 0.22 logarithmic minimum angle of resolution (logMAR) loss in high-contrast Bailey-Lovie visual acuity (2+ line) and a 0.32 logMAR loss in low-contrast Bailey-Lovie visual acuity (3+ line) for a 7-mm pupil.35 With this in mind, it is interesting that contrast sensitivity has been reported to be stable through the fifth decade,46-47 followed by a monotonic decrease from the sixth decade on.48 In the present study, we found little, if any, systemic changes in the aberration through the fifth decade, with most large aberration values occurring after the age of 60 (Fig. 4). Although this armchair analysis is intriguing and worth noting in passing, it is likely that other factors such as lens scattering may play a significant role in the loss of visual function in the over-60 group. We offer the current results as a reference for future studies on the monochromatic aberrations of the cornea and their contribution to the total aberrations of the eye.
References


