Corneal Topography and Myopia
A Cross-Sectional Study

Leo G. Carney,* Julia C. Mainstone,* and Beth A. Henderson†

Purpose. Central corneal curvature is known to vary with refractive error, but the relation between corneal topography and ametropia is less clear. The current study was conducted to determine whether a relation exists between corneal asphericity and myopia. Associations between corneal asphericity and each of the components of refraction also were examined.

Methods. Corneal asphericity and apical radius of curvature were determined for 113 eyes (spherical equivalent refractive error + 0.25 diopter [D] to −9.88 D) by fitting a conicoid equation to videokeratoscopic data. Computerized videokeratoscopic images were recorded using a Topographic Modeling System. Keratometry also was performed on each eye. Anterior chamber depth, lens thickness, vitreous chamber depth, and axial length were measured with a hand-held biometric ruler.

Results. A low but statistically significant positive correlation was found between corneal asphericity (Q) and spherical equivalent refractive error (r = 0.275, P < 0.01). Significant relations also were observed between Q and vitreous chamber depth (r = 0.17, P < 0.1) and between Q and axial length (r = 0.24, P < 0.05). The association between Q and corneal radius of curvature was found not to be significant. Eyes with higher levels of myopia had steeper central corneal curvatures, deeper anterior and vitreous chambers, and greater axial lengths.

Conclusions. A tendency for the cornea to flatten less rapidly in the periphery with increasing myopia was shown. Decreased peripheral corneal flattening also was observed in association with increasing vitreous chamber depth and increasing axial length. These findings have implications for refractive surgery outcomes, schematic eye modeling, contact lens design, and ocular aberration analysis. Invest Ophthalmol Vis Sci. 1997;38:311–320.

In recent years, the annual number of corneal refractive surgical procedures performed worldwide has been increasing progressively. Renewed interest in the analysis of human corneal topography has accompanied this growth, fueled by a desire for knowledge as to how corneal shape may influence postoperative outcome, and the resulting visual performance. Knowledge of the shape of the "normal" human cornea and the extent of interindividual variation in corneal topography also are important for contact lens design, schematic eye modeling, and ocular aberration analysis.1

Corneal curvature in both central and peripheral regions can be described by a point-by-point array of corneal radius values for various corneal positions, but it is difficult to gain an overall sense of corneal shape from a polar distribution such as this unless a contour map is constructed from the data.2 In addition, there are limitations with this mode of description in terms of intersubject comparisons, and the method does not lend itself to ocular aberration analysis. Another approach is to fit a curve to the array of data and to derive a mathematical expression to approximate corneal contour. Several aspheric mathematical models have been used to describe the complex shape of the anterior corneal surface.1,3–5 The simplest of these models assumes that corneal shape is represented by a rotationally symmetric conicoid of the form

\[ X^2 + Y^2 + (1 + Q)Z^2 - 2RZ = 0 \]  

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where the Z axis is the axis of revolution of the conicoid (coincident with the optic axis), R is the radius at the corneal apex, and Q is an asphericity parameter that may be used to specify the type of conicoid. \(^1\) For an ellipsoid with the major axis in the X–Y plane, \(Q > 0\); for a sphere, \(Q = 0\); for an ellipsoid with the major axis in the Z direction, \(-1 < Q < 0\); for a paraboloid with the axis along the Z axis, \(Q = -1\); and for a hyperboloid, \(Q < -1\) (Fig. 1). Two other parameters often have been used to classify conicoid form: (1) \(P\), the shape factor, where \(P = Q + 1\); and (2) \(e\), the eccentricity of the equivalent conic section, where \(Q = -e^2\).

Estimates of corneal asphericity from eight different studies have been summarized by Eghbali et al. \(^6\) The authors present results in terms of the mean shape factor \((P)\) for each study, with values ranging from 0.74 (Q = -0.26) \(^1\) to 0.89 (Q = -0.11). \(^7\) Both figures indicate a flattening of the corneal vertex toward the periphery. More recently, Eghbali et al. \(^6\) found a mean \(P\) value of 0.82 (Q = -0.18), and Lam and Douthwaite, \(^8\) in a study of 24 Hong Kong Chinese subjects reported \(P\) values of 0.82 (Q = -0.18) and 0.87 (Q = -0.13) for horizontal and vertical meridians, respectively. The minimum average shape factor reported in all 10 studies was 0.19 (Q = -0.81), \(^9\) and the maximum shape factor was 1.47 (Q = 0.47). \(^1,10\) The latter figure indicates a steepening of the cornea toward the periphery.

The association between corneal power and refractive error has been well established. A weak but statistically significant relation has been shown to exist between these two variables, such that corneal power increases (corneal radius decreases) with increasing myopia. \(^11-15\) Although this relation has been studied extensively, few investigators have attempted to address the question of whether an association exists between corneal shape and refractive error. Sheridan and Douthwaite \(^7\) calculated the corneal shape factor, \(P\), for 56 subjects using central and peripheral keratometric measurements (horizontal meridian only).

Subjects were divided into three refractive error groups: emmetropes \((n = 23)\), myopes \((n = 21)\), and hyperopes \((n = 12)\). No significant difference was found among results for the three groups. However, details were not given as to the refractive error distribution in each of the three categories.

In a study examining changes in corneal asphericity and visual function after radial keratotomy, Fleming \(^16\) found no correlation between preoperative refractive error and what he termed the “preoperative corneal aspheric index.” This latter parameter was determined by considering geometric corneal asphericity in a paracentral region between diameters 2.3 mm and 7.6 mm, as calculated from photokeratometric measurements. The preoperative spherical refractive error for the 81 eyes examined ranged from -1.00 to -5.00 diopters (D), with a mean of -3.28 D. No information was given regarding the level of preoperative astigmatism.

Rowsey et al. \(^17\) estimated preoperative corneal asphericity from photokeratoscope images in 368 patients with myopia participating in the Prospective Evaluation of Radial Keratotomy study. Corneal asphericity was defined as the change in corneal radius of curvature from ring three to ring nine of the photokeratoscope image. All subjects showed a flattening of the corneal radius of curvature from the center to the periphery. The cornea was seen to flatten by 0.27 mm in the high myope group (-4.50 D to -8.00 D, \(n = 145\)), by 0.30 mm in the middle myope group (-3.25 D to -4.37 D, \(n = 132\)), and by 0.28 mm in the low myope group (-2.00 D to -3.12 D, \(n = 122\)). There was no significant difference in “corneal asphericity” among the three groups.

If central corneal curvature is known to vary with refractive error, then it is reasonable to hypothesize that corneal asphericity may do the same. It is apparent, however, that at present, little is known of the association between corneal topography and ametropia. Of the studies that have attempted to address this issue, only one (that of Sheridan and Douthwaite \(^7\)) has produced data in a form such that legitimate and reliable comparison may be made with results from other investigations of corneal contour, and that study used techniques that have now been superseded.

The present study was conducted to compare corneal topography in emmetropic and myopic eyes, with the aim of determining whether a relation exists between corneal asphericity and myopic refractive error. Associations between corneal asphericity and each of the components of refraction also were examined.

**METHODS**

**Subjects**

One hundred thirteen subjects were selected for the study (69 males and 44 females). Informed consent...
TABLE 1. Age and Refractive Error Distributions for Male and Female Subjects

<table>
<thead>
<tr>
<th>Age (years)</th>
<th>Male (n = 69)</th>
<th>Female (n = 44)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean ± SD</td>
<td>26.1 ± 4.8</td>
<td>28.7 ± 7.6</td>
</tr>
<tr>
<td>Range</td>
<td>21 to 48</td>
<td>15 to 52</td>
</tr>
<tr>
<td>Spherical equivalent refractive error (D)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean ± SD</td>
<td>-2.25 ± 1.98</td>
<td>-2.32 ± 2.29</td>
</tr>
<tr>
<td>Range</td>
<td>-7.13 to 0.25</td>
<td>-9.88 to 0.25</td>
</tr>
</tbody>
</table>

for participation was gained from each subject after the nature of the experimental procedures had been explained. Research procedures adopted in this study followed the tenets of the Declaration of Helsinki.

All subjects satisfied the criteria set for inclusion in the study: corneal cylinder ≤ -1.50 D; best spectacle corrected distance Snellen acuity of 20/20 or better in the eye to be examined; and no ocular disease. No subject had worn contact lenses in the 24 hours preceding data collection. Age and refractive error distribution data for male and female subjects are listed in Table 1.

To facilitate later analysis of the relation between corneal topography and refractive error, subjects were divided into four refractive error groups: (1) emmetropes (spherical equivalent refractive error, SE -0.25 to +0.25 D), n = 30; (2) low myopes (SE ≥ 0.75 D and ≤ -2.00 D), n = 30; (3) moderate myopes (SE > -2.00 D and ≤ -4.00 D), n = 34; and (4) high myopes (SE > -4.00 D), n = 19. Age and gender distribution data for the four groups are listed in Table 2.

Apparatus and Procedures

All refractive and ocular component measurements were made on only one eye of each subject, and for consistency, all data were collected by the same examiner. Manifest subjective refraction was performed first, and the resultant visual acuity assessed to ensure that a visual acuity level of 20/20 or better was achieved in the examined eye. Three consecutive keratometric measurements then were made using a Bausch and Lomb keratometer (Bausch and Lomb, Rochester, NY), with values for the flattest and steepest corneal meridians being noted in each case. Corneal topography was measured with a computerized videokeratoscope (Topographic Modeling System, TMS-1, software version 1.1; Computed Anatomy, New York, NY).

Anterior chamber depth, lens thickness, vitreous chamber depth, and axial length were measured using a BIO-PEN hand-held biometric ruler (BIORAD, Glendale, CA). One drop of 0.5% proparacaine was instilled before ultrasonography. Subjects were instructed to fixate a distant target at all times while the BIO-PEN was being used to minimize accommodation-related changes in lens thickness and anterior chamber depth. Six readings were taken for each subject. Keratometry and axial dimension data were averaged to give a single value of each ocular component for each subject.

Statistical Analysis

The precision (and accuracy) of videokeratoscopic measurements on calibrated test spheres has been shown to be comparable to that of keratometric measurements on the same surfaces. Good reproducibility also has been shown for videokeratoscopic measurements of the central cornea (central 3- to 6-mm diameter zone), but the algorithms used for analysis are not valid for the more aspheric paracentral and peripheral zones and may lead to great variability in results in these regions. For this reason, only the central 6-mm diameter zone of the cornea was analyzed in the current study. One videokeratoscopic image for each subject was chosen for analysis, and images were selected on the basis of their clarity and the extent of unbroken mire coverage of the cornea.

The location of any point on the corneal surface may be described by three variables: chord radius,

TABLE 2. Age and Sex Distributions for the Four Refractive Error Groups

<table>
<thead>
<tr>
<th>Age (years)</th>
<th>Emmetropes (n = 30)</th>
<th>Low Myopes (n = 30)</th>
<th>Moderate Myopes (n = 34)</th>
<th>High Myopes (n = 19)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean ± SD</td>
<td>26.4 ± 5.9</td>
<td>27.1 ± 7.2</td>
<td>27.7 ± 6.4</td>
<td>27.0 ± 4.5</td>
</tr>
<tr>
<td>Range</td>
<td>15 to 49</td>
<td>22 to 52</td>
<td>22 to 48</td>
<td>23 to 38</td>
</tr>
<tr>
<td>Gender</td>
<td>male/ female</td>
<td>19:11</td>
<td>16:14</td>
<td>22:12</td>
</tr>
</tbody>
</table>

SD = standard deviation.
sagittal height, and azimuth. If the vertex of a conic section is coincident with the origin (e.g., a conic section taken through the apex of the cornea), equation 1 is reduced to

\[ Y^2 = 2RZ - (1 + Q)Z^2 \]  

where \( Y \) is the chord radius and \( Z \) is the sagittal height.

For each subject's videokeratoscopic image, sagittal height values for chord radii up to 3 mm were obtained from the data files of the TMS-1. A curve-fitting software program (TableCurve; Jandel Scientific, Corte Madera, CA) was used to solve equation 2, so that values of \( R \) and \( Q \) for each cornea could be calculated, with the best fit curve constrained to pass through the origin (chord radius = 0, sagittal height = 0).

The precision of these corneal radius and asphericity measurements was determined by analyzing a second videokeratoscopic image for 18 of the subjects, comparing the new radius and asphericity values with those obtained from the initial set of images for these subjects, and establishing a distribution of the differences in \( R \) and \( Q \) values for the sample.

**RESULTS**

Mean central corneal curvature measurements obtained by each of the two assessment methods used in this study (keratometry and videokeratoscopy) were compared to establish the validity of using the calculated videokeratoscopic values in further analyses. A strong degree of concordance was observed between the two measurements. Correlation analysis showed a coefficient of determination (\( r^2 \)) of 0.95 for the relation between keratometric and videokeratoscopic measurements (\( P = 0.0001 \)) and a regression line slope approaching unity (0.912). A plot of the difference between the measurements made with the two instruments versus the mean of the two measures for each subject is shown in Figure 2. The mean difference between the two radius measurements (−0.074 mm) was found to be significantly different from zero, with videokeratoscopic corneal radius measurements being slightly smaller than keratometric measurements (paired t-test, \( t = 12.078, P = 0.0001 \)). Linear regression analysis of the “difference versus mean” relation also showed a trend toward a greater difference between the two measurements as corneal radius decreased (\( r^2 = 0.08, P < 0.01 \)). However, the slope of the regression line for this relation was extremely small (0.067). Repeated measures analysis of videokeras-
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The mean corneal asphericity (± standard deviation) for 105 subjects was 

\[ y = -0.032x - 0.402, r^2 = 0.076 \]

atmospheric images for 18 of the subjects gave a mean difference in corneal radius values of 0.004 ± 0.054 mm, and a mean difference in corneal asphericity values of 0.033 ± 0.137.

Figures 3 and 4 show the relations between corneal radius of curvature and spherical equivalent refractive error \( (r^2 = 0.067, P = 0.0075) \), and axial length and spherical equivalent refractive error \( (r^2 = 0.363, P = 0.0001) \), respectively. A significant correlation with refractive error also was observed for two other ocular components: anterior chamber depth \( (r^2 = 0.042, P = 0.0295) \) and vitreous chamber depth \( (r^2 = 0.332, P = 0.0001) \). As the level of myopia increased, corneal radius of curvature decreased, whereas anterior chamber depth, vitreous chamber depth, and axial length all increased. Although these relations all were statistically significant \( (P < 0.05) \), the low coefficients of determination indicate that only a small percentage of the variance between any one of the ocular components and refractive error could be accounted for by the correlation between the two variables. There was no apparent relation between lens thickness and spherical equivalent refractive error \( (P = 0.9581) \).

The frequency histogram for corneal asphericity \( (Q) \) values is shown in Figure 5. The distribution is positively skewed, with 95% of values falling within the range —1.25 to 0.0 (i.e., 95% of the corneas flattened in the periphery). Only 5% of eyes had corneas that steepened in the periphery. The mean value for asphericity was 

-0.330 ± 0.229 (range, -1.028 to 0.288).

The association between anterior corneal asphericity and spherical equivalent refractive error was examined using linear regression analysis in the first instance. Figure 6 shows that there was a trend for \( Q \) to become more positive as the level of myopia increased \( (P = 0.0045) \), indicating a tendency for the cornea to flatten to a lesser degree in the periphery with increasing myopia. A marked degree of scatter

### TABLE 3. Ocular Component and Corneal Asphericity Data for the Four Refractive Error Groups

<table>
<thead>
<tr>
<th></th>
<th>Emmetropes</th>
<th>Low Myopes</th>
<th>Moderate Myopes</th>
<th>High Myopes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corneal asphericity (Q)</td>
<td>-0.402 ± 0.180</td>
<td>-0.371 ± 0.198</td>
<td>-0.306 ± 0.257</td>
<td>-0.199 ± 0.242</td>
</tr>
<tr>
<td>(n = 27)</td>
<td>(n = 28)</td>
<td>(n = 32)</td>
<td>(n = 18)</td>
<td></td>
</tr>
<tr>
<td>Corneal radius of curvature (mm)</td>
<td>7.74 ± 0.26</td>
<td>7.73 ± 0.29</td>
<td>7.66 ± 0.26</td>
<td>7.55 ± 0.28</td>
</tr>
<tr>
<td>(n = 27)</td>
<td>(n = 28)</td>
<td>(n = 32)</td>
<td>(n = 18)</td>
<td></td>
</tr>
<tr>
<td>Anterior chamber depth (mm)</td>
<td>3.60 ± 0.37</td>
<td>3.75 ± 0.29</td>
<td>3.78 ± 0.36</td>
<td>3.89 ± 0.43</td>
</tr>
<tr>
<td>(n = 30)</td>
<td>(n = 29)</td>
<td>(n = 34)</td>
<td>(n = 19)</td>
<td></td>
</tr>
<tr>
<td>Lens thickness (mm)</td>
<td>3.48 ± 0.21</td>
<td>3.56 ± 0.27</td>
<td>3.49 ± 0.27</td>
<td>3.46 ± 0.30</td>
</tr>
<tr>
<td>(n = 30)</td>
<td>(n = 29)</td>
<td>(n = 34)</td>
<td>(n = 19)</td>
<td></td>
</tr>
<tr>
<td>Vitreous chamber depth (mm)</td>
<td>16.60 ± 0.70</td>
<td>17.05 ± 0.67</td>
<td>17.58 ± 0.84</td>
<td>18.18 ± 0.77</td>
</tr>
<tr>
<td>(n = 30)</td>
<td>(n = 29)</td>
<td>(n = 34)</td>
<td>(n = 19)</td>
<td></td>
</tr>
<tr>
<td>Axial length (mm)</td>
<td>23.68 ± 0.71</td>
<td>24.36 ± 0.63</td>
<td>24.84 ± 0.92</td>
<td>25.53 ± 0.89</td>
</tr>
<tr>
<td>(n = 30)</td>
<td>(n = 30)</td>
<td>(n = 34)</td>
<td>(n = 19)</td>
<td></td>
</tr>
</tbody>
</table>

Values are mean ± standard deviation.
TABLE 4. Associations Between Corneal Asphericity and Five Ocular Components

<table>
<thead>
<tr>
<th>Association</th>
<th>Correlation Coefficient (r)</th>
<th>Coefficient of Determination (r^2)</th>
<th>n</th>
<th>P Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q versus corneal radius of curvature</td>
<td>+0.11</td>
<td>0.011</td>
<td>105</td>
<td>0.2822</td>
</tr>
<tr>
<td>Q versus anterior chamber depth</td>
<td>+0.16</td>
<td>0.026</td>
<td>104</td>
<td>0.1046</td>
</tr>
<tr>
<td>Q versus lens thickness</td>
<td>+0.10</td>
<td>0.010</td>
<td>104</td>
<td>0.3063</td>
</tr>
<tr>
<td>Q versus vitreous chamber depth</td>
<td>+0.17</td>
<td>0.029</td>
<td>104</td>
<td>0.0824</td>
</tr>
<tr>
<td>Q versus axial length</td>
<td>+0.24</td>
<td>0.056</td>
<td>105</td>
<td>0.0154</td>
</tr>
</tbody>
</table>

Q = asphericity.

The association between corneal asphericity and refractive error was examined further by determining mean values of asphericity for the four refractive error groups: emmetropes, low myopes, moderate myopes, and high myopes. Relations between each of the ocular components and refractive error were analyzed similarly. Results are listed in Table 3. Corneal asphericity for the high myope group was significantly more positive than that for either the emmetropic or the low myope group (analysis of variance [ANOVA], Fisher’s protected least significant difference test, P < 0.05).

A statistically significant difference also was found between mean corneal radius of curvature values for the emmetrope and high myope groups, as well as between those for the low myope and high myope groups (ANOVA, Fisher’s protected least significant difference test, P < 0.05), with mean corneal curvature being steepest in the high myope group. Mean anterior chamber depth for the high myope group was significantly greater than that for the emmetropic group (ANOVA, Fisher’s protected least significant difference test, P < 0.05). No significant differences in lens thickness were observed between any of the four refractive error groups. All myopic groups showed significantly greater vitreous chamber depths than did the emmetropic group, and there were statistically significant differences between results for each of the myopic groups (ANOVA, Fisher’s protected least significant difference test, P < 0.05). Similar results were observed for axial length.

Associations between mean corneal asphericity (Q) and the five ocular components—corneal radius of curvature, anterior chamber depth, lens thickness, vitreous chamber depth, and axial length—were examined using linear regression analysis. Correlation coefficients and coefficients of determination for these relations are listed in Table 4. The correlation between corneal asphericity and axial length was statistically significant (P < 0.05), whereas the relations between corneal asphericity and vitreous chamber depth (P < 0.1), and corneal asphericity and anterior chamber depth (P = 0.1), approached significance.

The association between corneal asphericity and axial length is illustrated in Figure 7. There was a trend toward decreased peripheral corneal flattening with increases in axial length. Similarly, there was a tendency for Q to become slightly more positive with increases in vitreous chamber depth and anterior chamber depth. The correlation between corneal asphericity and corneal radius of curvature was not statistically significant (P = 0.2822).

To develop a more detailed profile of the study population, intercorrelations between the main ocular components were examined (Table 5). Significant associations were observed in all cases, except for the relation between corneal radius of curvature and anterior chamber depth, and those between lens thickness and axial length and lens thickness and anterior chamber depth. Eyes with flatter corneas had deeper posterior chambers and thicker lenses. Thinner lenses were observed in those eyes with deeper vitreous chambers. Deeper anterior chambers were associated with deeper vitreous chambers. A strong correlation was
TABLE 5. Correlations Among the Components of Refraction

<table>
<thead>
<tr>
<th>Correlation</th>
<th>Correlation Coefficient (r)</th>
<th>Coefficient of Determination (r^2)</th>
<th>n</th>
<th>P Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corneal radius versus axial length</td>
<td>+0.409</td>
<td>0.167</td>
<td>105</td>
<td>0.0001</td>
</tr>
<tr>
<td>Corneal radius versus vitreous chamber depth</td>
<td>+0.385</td>
<td>0.148</td>
<td>104</td>
<td>0.0001</td>
</tr>
<tr>
<td>Corneal radius versus anterior chamber depth</td>
<td>+0.019</td>
<td>0.000</td>
<td>104</td>
<td>0.8446</td>
</tr>
<tr>
<td>Corneal radius versus lens thickness</td>
<td>+0.207</td>
<td>0.043</td>
<td>104</td>
<td>0.035</td>
</tr>
<tr>
<td>Lens thickness versus axial length</td>
<td>-0.089</td>
<td>0.008</td>
<td>112</td>
<td>0.3484</td>
</tr>
<tr>
<td>Lens thickness versus vitreous chamber depth</td>
<td>-0.307</td>
<td>0.094</td>
<td>112</td>
<td>0.001</td>
</tr>
<tr>
<td>Lens thickness versus anterior chamber depth</td>
<td>-0.177</td>
<td>0.091</td>
<td>112</td>
<td>0.0619</td>
</tr>
<tr>
<td>Anterior chamber depth versus axial length</td>
<td>+0.515</td>
<td>0.266</td>
<td>112</td>
<td>0.0001</td>
</tr>
<tr>
<td>Anterior chamber depth versus vitreous chamber depth</td>
<td>+0.215</td>
<td>0.046</td>
<td>112</td>
<td>0.0228</td>
</tr>
<tr>
<td>Vitreous chamber depth versus axial length</td>
<td>+0.914</td>
<td>0.835</td>
<td>112</td>
<td>0.0001</td>
</tr>
</tbody>
</table>

observed between vitreous chamber depth and axial length (r^2 = 0.835), but coefficients of determination for the remaining intercomponent analyses were all quite small (maximum r^2 value = 0.266). Thus, for this latter case (anterior chamber depth versus axial length), only 26.6% of the variance between the two components could be attributed to the correlation.

Analysis of the relation between corneal radius of curvature and vitreous chamber depth was repeated for each of the four refractive error groups (Fig. 8). Correlation coefficients and coefficients of determination for these four relations were as follows: (1) emmetropes, r = 0.621; r^2 = 0.385, P = 0.0006; (2) low myopes, r = 0.667, r^2 = 0.445, P = 0.0001; (3) moderate myopes, r = 0.687, r^2 = 0.472, P = 0.0001; and (4) high myopes, r = 0.728, r^2 = 0.529, P = 0.0006.

Figure 8 shows that although there was a consistent relation between corneal radius of curvature and vitreous chamber depth for each of the refractive error groups, such that flatter corneas were associated with deeper vitreous chambers, the four regression lines were by no means coincident. The differential locations of the regression lines on the corneal curvature—vitreous chamber depth graph reflect the trend for the mean corneal radius to decrease, and the mean vitreous chamber depth to increase, with increasing myopic refractive error.

**DISCUSSION**

The mean value of corneal asphericity determined in this study (Q = -0.330 ± 0.229) was slightly more negative than that found in previous studies of corneal topography (minimum average Q value -0.26, maximum average Q value -0.11), but was of the same order of magnitude and may be considered to be in general agreement with previous results, in view of the differing populations from which these data were obtained. We found that in the majority (95%) of cases, corneas flatten in the periphery. These results are consistent with the results of Kiely et al and Eghbali et al.

The low but statistically significant correlation observed between corneal asphericity and refractive error suggests that eyes with higher degrees of myopia have corneas that flatten less rapidly in the periphery, a trend supported by the ANOVA results for the four refractive error subgroups. This latter analysis, showing mean corneal asphericity for the high myope...
group to be significantly different from that for the emmetropic and low myope groups, would suggest that the small, but significant, association between corneal asphericity and refractive error that was found in this study was largely because of the corneal topography changes observed in those eyes with myopic refractive errors greater than −4.00 D. Although the coefficient of determination for the relation between corneal asphericity and refractive error found in this study was small (r² = 0.076), indicating a marked degree of scatter about the regression line, the dispersion of values about this line was less than that observed for the association between corneal radius of curvature and refractive error (r² = 0.067).

It generally is thought that peripheral flattening of the anterior surface of the cornea is the major contributor to spherical aberration control, and that the crystalline lens corrects its own spherical aberration, not only through peripheral flattening of its surfaces, but also by compensatory variations in lens refractive index. Applegate et al measured corneal aberrations before and after radial keratotomy in 32 eyes and showed that on average, myopic eyes exhibited positive spherical aberration of the cornea before surgery. They compared these results with that of a study of 18 normal eyes (spherical equivalent refractive error = ± 2.00 D), in which a trend toward negative spherical aberration of the cornea was shown, and suggested that these differences may indicate that the aberration structure of the cornea varies with refractive error.

Kiely et al., using calculations of the Seidel spherical aberration for objects at infinity, showed that corneal asphericity assumes a much greater contribution to the spherical aberration of the human cornea than does central corneal radius of curvature. They also showed that the theoretical corneal asphericity value necessary to reduce the Seidel spherical aberration to zero is Q = −0.528, with less negative Q values being associated with positive corneal spherical aberration. In the present study, the mean Q value was found to be −0.330, and corneal asphericity was seen to become less negative with increasing myopia. Therefore, in light of the results of Kiely et al., most subjects in the present study would be expected to possess positive corneal spherical aberration, the degree of positive spherical aberration increasing with increasing myopia. This trend for spherical aberration of the cornea to become more positive with increasing myopia is consistent with the observations of Applegate et al.

The association between corneal asphericity and central corneal radius of curvature has been examined previously. Kiely et al., in their study of 176 eyes, found a positive linear relation between these 2 variables, and hypothesized that this result could be explained by the notion that a steep central cornea may be expected to flatten to a greater extent in the periphery for its junction with the flatter sclera to remain smooth. In the present study, a similar relation was observed overall, although this correlation was not statistically significant.

Intercorrelations between the main ocular components, and their relations with refractive error, were examined because we thought that if corneal asphericity was found to vary with refractive error, or with any of the components of refraction, further analysis of this nature could help to shed light on the possible mechanisms involved.

As pointed out above, numerous cross-sectional studies have shown that corneal radius of curvature decreases with increasing myopia. This finding was confirmed in the present study, where a weak but statistically significant relation was observed between the two variables. Anterior chamber depth, vitreous chamber depth, and axial length were all seen to increase as the level of myopia increased. As before, these relations were predicted on the basis of previous reports.

A strong positive correlation between vitreous chamber depth and axial length has been shown by several authors, and weaker relations between anterior chamber depth and axial length (positive correlation) and lens thickness and vitreous chamber depth (negative correlation) also have been shown. The results of the present study are consistent with these findings.

Significant positive correlations between corneal radius of curvature and vitreous chamber depth, and between corneal radius of curvature and axial length, have been reported previously by numerous authors, but only Scott and Grosvenor have drawn attention to the paradox that such findings present: Although longer eyes have flatter corneas on average, myopic eyes have both steeper central corneas and greater axial lengths than do emmetropic eyes. These seemingly contradictory relations are well illustrated in Figure 8 of the present study. Scott and Grosvenor suggest that this paradox may be explained by considering the dichotomous ocular growth mechanisms postulated by van Alphen: normal growth (represented by what van Alphen termed "the size factor") and axial elongation leading to myopia (represented by the stretch factor). Based on the premise that growth in the normal emmetropic eye is a coordinated process, one would expect flatter corneas to be associated with deeper vitreous chambers, increases in both dimensions occurring in conjunction with an increase in the overall size of the globe. Scott and Grosvenor hypothesize that in addition to the stretch effect on axial length that is thought to occur in myopia, corneal steepening also occurs at some point during ocular growth, so that steeper cor-
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neas will be observed in myopes compared with emmetropes, despite the maintenance of a positive correlation between corneal radius and axial length in both groups.

Against this background then, how might the observed changes in corneal asphericity with increasing myopia be explained? As stated previously, a steeper cornea may be expected to flatten more rapidly in the periphery to maintain mechanical integrity with the flatter sclera. Indeed, a positive (although not statistically significant) correlation was observed between central corneal curvature and corneal asphericity in the current study. However, corneal radius of curvature also was shown to steepen with increasing myopia, and one would expect then that the cornea would flatten more rapidly in the periphery (i.e., show a more negative Q value) with increasing myopia. The opposite effect was in fact observed (Fig. 6). This observation is more consistent with the tendency for the cornea to flatten less rapidly in the periphery with increasing anterior chamber depth and increasing axial length, as both anterior chamber depth and axial length were seen to increase with increasing myopia. The apparently paradoxic associations between corneal asphericity and refractive error, and corneal asphericity and central corneal curvature, may perhaps be explained by the postulated existence of dichotomous ocular growth mechanisms, as referred to earlier in relation to the corneal radius–axial length paradox. It is possible that during normal, coordinated growth of the eye, the central cornea flattens as the globe increases in size, and the degree of peripheral corneal flattening either remains unchanged or increases to compensate for this growth. If, during the development and progression of myopia, there is an overall "stretch" effect, such that axial elongation of the eye occurs to a greater extent than does equatorial growth, the peripheral cornea may undergo a process of relative steepening to compensate for the increase in anterior chamber depth.

An extensive and well-controlled longitudinal study would be needed to confirm or disprove that such relations exist. To date, only one author has attempted to address the issue of whether corneal topography alters with the progression of myopia. In a 3-year study of changes in corneal refraction and topography in 145 children with myopia in Finland, Pärssinen found no significant change in either the horizontal or vertical corneal shape factor, despite an increase in mean spherical equivalent refractive error from −1.45 to −3.13 D. Horizontal and vertical shape factors were determined by calculating the rate of peripheral flattening (in millimeters) over ring 3 to ring 6 of the Wesley-Jessen System 2000 PEK photokeratoscope for the horizontal and vertical meridians.

The subject sample assessed in the present study was not homogeneous with respect to racial background or age. In addition, no attempt was made to distinguish between juvenile-onset and adult-onset myopia. Despite nominal differences in experimental design between the present study and previous cross-sectional studies of myopia, similar trends were observed when the results of intercorrelation component analysis were compared, as illustrated above. The concordance of results for the ocular component-refractive error analyses also suggests that the present sample was not greatly different from those examined in previous cross-sectional studies with regards to the distribution and correlation of ocular components.

In summary, this study has shown that for myopic eyes, a statistically significant relation exists between corneal asphericity and spherical equivalent refractive error, such that there is a tendency for the cornea to flatten less rapidly in the periphery with increasing myopia. The study also has confirmed that eyes with higher levels of myopia have steeper central corneal curvatures, deeper anterior and vitreous chambers, and greater axial lengths. A small trend toward decreased peripheral corneal flattening with increasing vitreous chamber depth and increasing axial length was observed. These findings have implications for refractive surgery outcomes, schematic eye modeling, contact lens design, and ocular aberration analysis.

Key Words

asphericity, corneal topography, myopia, refractive error, videokeratography

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