The Influence of Eyelid Morphology on Normal Corneal Shape

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Purpose. To investigate associations between the topography of the cornea and the morphology of the eyelids in a population of young adult subjects with a range of refractive errors.

Methods. Corneal topography data and digital images of the anterior eye were acquired for 100 young adult subjects. The corneal topography data and palpebral fissure images were analyzed to determine a range of parameters describing the shape of the cornea and the morphology of the palpebral fissure. Correlation analysis was carried out to investigate for significant associations between the parameters describing the topography of the cornea and the parameters describing the morphology of the palpebral fissure.

Results. A number of highly significant correlations were found between the best-fitting corneal spherocylinder and the eyelid morphology parameters. The corneal best-fit sphere (M) was significantly correlated with the horizontal palpebral fissure width ($r = -0.428$; $P < 0.001$). Corneal astigmatism power vector J45 was significantly correlated with the angle of the palpebral fissure ($r = 0.392$; $P < 0.001$). The axis of corneal astigmatism was also found to be significantly correlated with the angle of the palpebral fissure ($r = 0.317$; $P = 0.005$).

Conclusions. A number of significant associations exist between the corneal spherocylinder and the morphology of the eyelids in a normal adult population. (*Invest Ophthalmol Vis Sci.* 2007;48:112–119) DOI:10.1167/iovs.06-0675

Astigmatism is one of the most commonly encountered refractive errors, but its cause remains unknown. Although some evidence suggests a genetic factor in the development of astigmatism, particularly high astigmatism,[1,2] there are also indications that environmental factors such as eyelid pressure may play a role.

Pressure from the eyelids has been implicated in a range of short- and long-term corneal topographical changes. Reports have appeared since the 1960s relating episodes of monocular diplopia to corneal distortions caused by pressure from the eyelids.[3–8] More recent studies have shown that significant changes to corneal topography and astigmatism can occur as a result of eyelid pressure after reading[9] and other visual tasks involving downward gaze.[10] Altering the normal eyelid position has also been shown to cause changes in corneal topography[11] and astigmatism.[12]

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Changes in corneal topography and corneal astigmatism accompany certain eyelid abnormalities, such as chalazia[13–15] and capillary hemangioma,[16,17] and result from lid-loading procedures for the treatment of lagophthalmos.[18] Disorders of eyelid position (e.g., ptosis) and surgery on the eyelids have also been found to cause changes in corneal topography and astigmatism.[19–23]

Theories also propose that pressure from the eyelids may be involved in the etiology of corneal astigmatism. Grosvenor[24] suggested that "bandlike" pressure from the upper lid on the cornea may cause the cornea to assume its typically with-the-rule (WTR) astigmatic shape. A range of indirect evidence supports this theory.

Ethnic groups (such as American Indian and East Asian populations) whose eyelid morphology is different from that of white persons typically exhibit a higher prevalence of WTR corneal astigmatism.[25–29] Congenital malformation syndromes such as Downs syndrome,[30,31] Treacher-Collins syndrome,[32] and spina bifida[33] are all associated with a high prevalence of astigmatism and characteristic abnormal slanting of the palpebral fissure. The degree of slanting of the fissure is sometimes associated with the axis of astigmatism.[31–33] Patients with nystagmus also tend to exhibit a high prevalence of WTR corneal astigmatism,[34,35] which may relate to increased mechanical pressure between the eyelids and the cornea as a result of typical horizontal eye movements (Ohmi G, et al. *IOVS* 1993;34:ARVO Abstract 1125).[35,36] A recent study of children with high degrees of WTR astigmatism found a number of associations between the angle of the palpebral fissure and the magnitude and axis of astigmatism.[37]

The evidence for eyelid pressure as an etiological factor in corneal astigmatism is particularly compelling from studies in children with high astigmatism and in certain syndromes and diseases associated with abnormal palpebral fissure morphology. On the assumption that eyelid pressure does play a role in the development of corneal astigmatism, we wanted to investigate whether associations exist between the morphology of the eyelids and the topography of the cornea in a population of young healthy adult subjects with a range of refractive errors.

Methods

Subjects and Procedures

Corneal topography measurements and digital images of the anterior eye and adnexae were captured for 100 young adult subjects. Subjects were recruited for this experiment primarily from the students and staff of the Queensland University of Technology. All subjects had normal ocular health, were free of any ocular disease or systemic disease or syndrome that might have altered anterior eye appearance, and had no history of ocular or eyelid surgery or trauma. Each subject underwent initial slit lamp examination to rule out anterior eye disease. Wearers of rigid gas-permeable (RGP) contact lenses were excluded from the study. Nine subjects wore soft contact lenses part time, and these subjects were instructed not to wear their lenses on the day of testing. Subjects' ages ranged from 18 to 35 years and averaged 24 ± 4 years. Fifty-nine of the 100 subjects were women. Eighty of the 100 subjects were white, and 20 were East Asian. All subjects had best-corrected visual acuity of 6/7.5 or better in the measured eye.

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Subjects exhibited a normal range of refractive errors; the mean best-sphere refraction was −1.13 ± 1.85 D (range, +0.63 D to −8.13 D). The mean astigmatic refractive error was −0.32 ± 0.58 (range, 0 D to −2.75 D). To allow for statistical analysis of the subjective refraction results, each subject's refractive error was broken down into the power vectors M (best sphere), J0 (astigmatism 90/180), and J45 (astigmatism 45/135).[38] Approval from the university human research ethics committee was obtained before the study, and informed consent was obtained from all the subjects. All subjects were treated in accordance with the tenets of the Declaration of Helsinki.

Corneal topography[39,40] and palpebral fissure[41] measures have a tendency to exhibit a high degree of symmetry between right and left eyes. For this reason, only the right eye of each subject was used for all measurements. To minimize any short-term effects on corneal topography as a result of eyelid pressure,[9,42] all measurements were taken in the morning, and subjects were asked to refrain from substantial amounts of close work before testing.

The corneal topography of each subject was measured with a videokeratoscope (Medmont E300; Medmont Pty. Ltd., Victoria, Australia) built on the Placido disk principle and exhibiting highly accurate and repeatable measurements on inanimate test surfaces[43] and highly repeatable measurements on human corneas.[44] The corneal topography of each subject was measured with a technique that allows central and peripheral corneal topography data to be captured and then subsequently combines these data to produce one large, extended corneal topography map for each subject. This method for measuring corneal topography, described in detail elsewhere,[45,46] evaluates a much larger area of the cornea than standard techniques (approximately 30% increase of topography map dimensions). Subjects exhibiting poor correlation between central and peripheral corneal topographical data (i.e., subjects showing greater than a ±0.2-mm difference in axial curvature between actual data and that predicted by a 2nd-order polynomial function at the junction between central and peripheral corneal data in more than 40 semi-meridians) were excluded from further analysis.[46] Of the 100 subjects participating, eight subjects were excluded from subsequent analyses because of poor correlation between central and peripheral corneal topography maps.

Each extended corneal topography map was rotated to make the corneal geometric center the reference axis for the maps; corneal height, axial power, and axial radius of curvature were analyzed in detail.[46] This provided a range of parameters to describe the corneal topography of the central and peripheral cornea, including the best-fitting corneal axial power spherocylinder (defined by power vectors M, J0, and J45) and the best-fitting conic section (defined by apical radius r_o and asphericity parameter Q). Each corneal axial power map was then classified according to the amount of astigmatism present in the central 4-mm diameter as either central spherical (<0.75 DC) or central astigmatic (>0.75 DC). Axial power maps were also classified according to the central corneal cylinder axis as having either WTR central axis (central corneal cylinder axis 30°–150°; $n = 67$), against-the-rule central axis (ATR; central corneal cylinder axis 60°–120°; $n = 11$), or oblique central axis (OBL; central cylinder axis 30°–60° or 120°–150°; $n = 12$).[47] The most common central corneal cylinder axis was WTR. Figure 1 displays a frequency histogram of the subjects' central corneal cylinder axes.

Each subject's central videokeratoscope image was also analyzed to determine the diameter of the cornea. Customized software allowed the user to locate 16 points at the corneal edge. An ellipse was then fitted to the 16 points defined as the edge of the cornea according to an orthogonal least squares fitting procedure.[48] This corneal ellipse is defined by its major or longest diameter (A), minor or shortest diam-

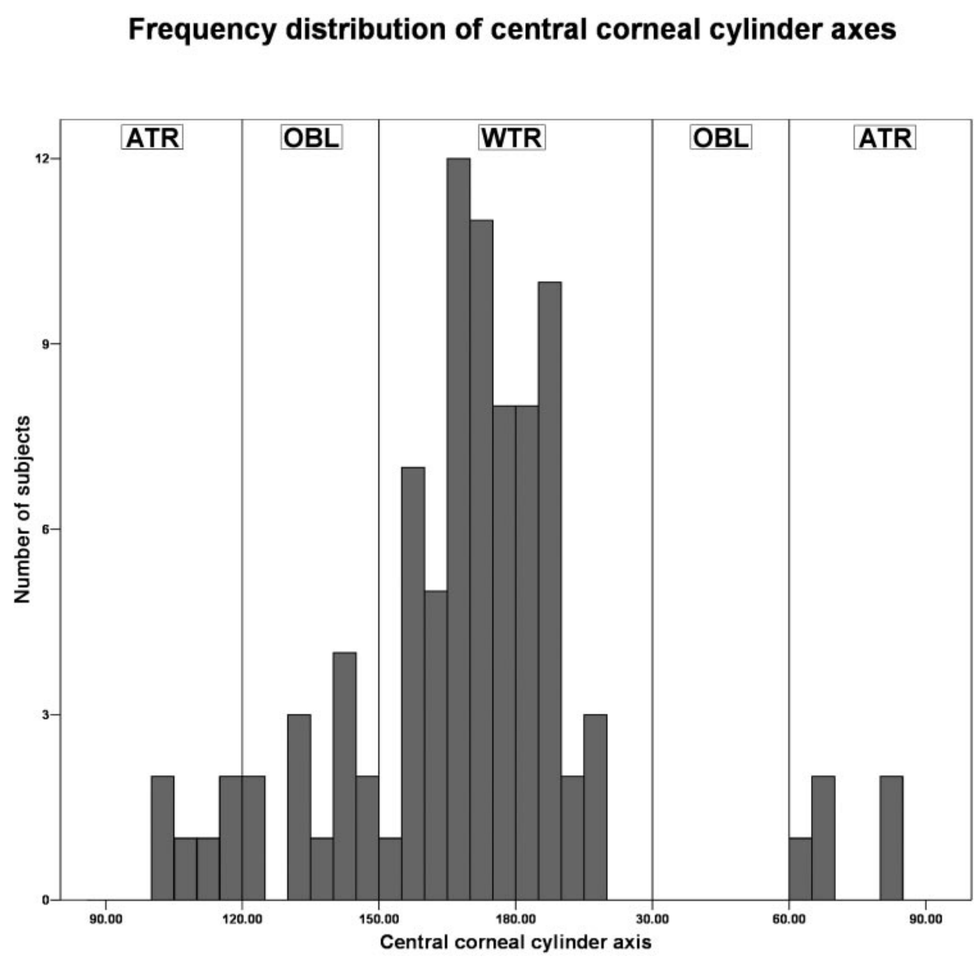

FIGURE 1. Frequency histogram of central corneal cylinder axes (i.e., minus correcting cylinder for right eye) for the 90 subjects with valid corneal topography and digital image data.

eter (B), and theta (i.e., the angle between the major diameter "A" and the horizontal).

After the measurement of corneal topography, high-resolution digital images (3072 × 2068 pixels) of the right eye in the frontal plane were captured for each subject in primary gaze (0°), 20° downgaze, and 40° downgaze. All digital images were captured with a 6.3 mega pixel digital SLR camera (Canon 300D; Canon Inc., Tokyo, Japan) and a 100-mm macro lens. Digital images from four subjects were excluded completely from analysis because of poor image quality. Each digital image was analyzed with customized software to determine a wide range of biometric measures of the palpebral fissure and the anterior eye for each subject in each of the three different angles of vertical gaze. A detailed description of the method of image capture and analysis is provided elsewhere.[49] Measures of the palpebral aperture's vertical and horizontal dimensions, angle of the palpebral fissure, and contour of the upper and lower eyelid were calculated for each subject. Eyelid contour was quantified by fitting a polynomial function of the form $Y = Ax^2 + Bx + C$ to the upper and lower eyelids.[50] In this polynomial, the coefficient A refers to the curvature of the eyelid, B refers to the tilt or angle of the eyelid, and the constant C refers to the height of the eyelid above or below the corneal geometric center.

Analysis

After data collection and analysis of the corneal topography data and anterior eye images, a range of parameters defining the morphology of the palpebral fissure and the topography of the cornea was attained for each subject. Table 1 describes this range of parameters. To investigate the associations between the corneal topography measures and palpebral fissure morphology, bivariate correlation analysis was carried out. Each of the corneal topography parameters (for each of the corneal analysis diameters tested) was compared in turn with each of the palpebral fissure morphology parameters (for each of the vertical angles of gaze measured), and Pearson correlation coefficient (r) and significance (P) were calculated. Correlation analysis was first carried out for all subjects with valid corneal topography and eyelid morphology data ($n = 90$).

Subjects with central astigmatic corneas (>0.75 DC; $n = 42$) and subjects with central spherical corneas (<0.75 DC; $n = 48$) were subsequently analyzed separately to determine any differences in correlation between corneal topography and eyelid morphology for these two groups. To determine whether eyelid morphology parameters differed significantly between the astigmatic central corneas and the spherical central corneas, repeated-measures ANOVA was carried out for each of the eyelid morphology parameters with one within-subjects factor (angle of gaze) and one between-subjects factor (central corneal astigmatic type). Subjects exhibiting WTR central corneal cylinder axes were also analyzed separately. Given that few subjects exhibited ATR or OBL cylinder axes, it was difficult to draw firm conclusions regarding the data from these specific groups of subjects.

We were also interested in whether the meridional characteristics of the corneal diameter influenced central corneal astigmatism. Correlation analysis was performed between the corneal diameter parameters and the corneal axial power data. The corneal best-fit spherocylinder for the 8-mm corneal diameter was compared with the corneal diameter A, the toricity of the corneal diameter (Dtor, defined as the difference between the major and minor axes A and B), and corneal diameter theta (i.e., the angle between the major diameter A and the horizontal).

Results

Corneal Topography and Eyelid Morphology

A number of highly significant associations were observed between the eyelid morphology measures and the best-fitting corneal axial power spherocylinder. Although correlations were similar for the different corneal analysis diameters, the strongest and most significant correlations were generally found for the larger corneal analysis diameters (8-mm corneal diameter). The correlation between the corneal spherocylinder data and the eyelid morphology data was also found to be strongest for the primary gaze eyelid parameters. Correlations became progressively weaker for the 20° and 40° downgaze eyelid parameters. Therefore, we focused on results for the correlations between the primary gaze eyelid measures and 8-mm corneal topography analysis.

The corneal axial power best-sphere M showed a highly significant correlation with the horizontal palpebral fissure width ($r = -0.428$; $P < 0.001$), indicating that the larger the horizontal eyelid dimensions, the flatter the cornea (Table 2). Figure 2 displays a scatterplot of the corneal best-sphere M (8-mm diameter) and the horizontal palpebral aperture width measure (horizontal eyelid fissure [HEF] width, primary gaze).

Corneal J45 was found to exhibit highly significant correlations with the angle of the palpebral fissure in primary gaze. The palpebral fissure angle (Theta_HEF; $r = 0.392$; $P < 0.001$), the angle of the upper lid (Theta_UL; $r = 0.232$; $P = 0.044$), and the angle of the lower lid (Theta_LL; $r = 0.48$; $P < 0.001$) showed significant correlations with corneal J45 (8-mm diameter). These correlations indicated that subjects with more upward slanting palpebral fissures exhibit more negative J45 (and vice versa). Figure 3 illustrates the relationship between corneal J45 (8-mm analysis diameter) and the angle of the palpebral fissure (Theta_HEF, primary gaze). The amount and sign of corneal J45 determined each subject's cylinder axis. A positive J45 indicated a cylinder axis between 0° and 90°, and a negative J45 indicated a cylinder axis between 90° and 180°. The highly significant associations between the eyelid angles and corneal J45, therefore, indicated a significant association between the axis of astigmatism and the angle of the eyelids.

We also examined the correlation between corneal cylinder axis and eyelid angle. For this analysis, cylinder axes were transposed so that the horizontal cylinder axes were continuous (i.e., a cylinder axis of 170° was transposed to be −10° so that the axes were continuous around the horizontal). The corneal cylinder axis also showed significant correlations with

Table 1. Palpebral Fissure and Corneal Topography Parameters Measured for Each Subject

Palpebral Fissure Parameters (0°, 20°, 40° down gaze)	Corneal Topography Parameters
HEF — Horizontal eyelid fissure width	r_o — Corneal Apical Radius (6 mm, 8 mm 10 mm)
Theta_HEF—Angle of the palpebral fissure	Q — Asphericity Parameter (6 mm, 8 mm, 10 mm)
PC_UL — Vertical distance from upper lid to pupil center	Corneal Best Sphere M (4 mm, 6 mm, 8 mm)
PC_LL — Vertical distance from lower lid to pupil center	Corneal Astigmatism 90/180 — J0 (4 mm, 6 mm, 8 mm)
PA — Vertical distance between upper and lower lid	Corneal Astigmatism 45/135 — J45 (4 mm, 6 mm, 8 mm)
Theta_Upper Lid — Angle of the upper eyelid	—
Theta_Lower Lid — Angle of the lower eyelid	—
Upper eyelid contour polynomial terms A, B and C	—
Lower eyelid contour polynomial terms A, B and C	—

Table 2. Results from Correlation Analysis between Corneal Axial Power Spherocylinder Data and Primary Gaze Eyelid Morphology Parameters

	Primary Gaze Eyelid Parameters												
								Upper Eyelid Contour			Lower Eyelid Contour		
Topography Measures	**HEF**	**Theta_HEF**	**PC_UL**	**PC_LL**	**PA**	**Theta_UL**	**Theta_LL**	**A**	**B**	**C**	**A**	**B**	**C**
M													
r	**−0.428**		−0.249		−0.275								
P	**<0.001**		0.03		0.016								
J0													
r							0.298					0.288	
P							0.009					0.012	
J45													
r		**0.392**				0.232	**0.48**		0.246			**0.473**	
P		**<0.001**				0.044	**<0.001**		0.036			**<0.001**	

Only significant correlations ($P<0.05$) are shown. Highly significant correlations ($P<0.001$) are highlighted in bold. Spherocylinder data for 8 mm analysis diameter ($n = 78$).

primary gaze eyelid angles Theta_HEF ($r = 0.317$, $P = 0.005$) and the upper (Theta_UL, $r = 0.308$, $P = 0.007$) and lower eyelid angles (Theta_LL; $r = 0.364$; $P = 0.001$). The correlation between the corneal cylinder axis and the palpebral fissure angles indicated a tendency for the cylinder axis to be at an angle similar to that of the angle of the palpebral fissure in primary gaze. Correlations between lid angle and cylinder axis were strongest for the lower eyelid angles, indicating that the flattest corneal meridian had a tendency to be aligned parallel to the angle of the lower eyelid. This is evident in Figure 4, which displays the corneal axial power maps for two subjects overlaid with their primary gaze eyelid images.

The best-fitting conic section to the corneal height data showed some associations with eyelid parameters. Steeper corneas were associated with smaller horizontal palpebral fissure widths. The apical radius r_o (8-mm diameter) was significantly correlated with the primary gaze palpebral fissure width (HEF; $r = 0.449$; $P < 0.001$). The asphericity parameter Q showed no significant correlation with any of the eyelid parameters for any of the corneal analysis diameters.

When subjects were grouped according to central corneal astigmatism magnitude (i.e., central spherical corneas <0.75 DC or central astigmatic corneas >0.75 DC), correlation analysis between the corneal topography parameters and the eyelid morphology parameters revealed trends similar to those when all subject data were analyzed as a group. Both groups still exhibited a highly significant correlation between the corneal J45 (8-mm diameter) and primary gaze palpebral fissure angle Theta_HEF ($r = 0.41$ and $P = 0.014$ for the astigmatic central group; $r = 0.42$ and $P = 0.006$ for the spherical central group). Repeated-measures ANOVA revealed no significant between-subjects effect caused by central corneal astigmatism type for any of the eyelid parameters (i.e., no eyelid morphology parameter was significantly different between the central astigmatic cornea group and the central spherical cornea group).

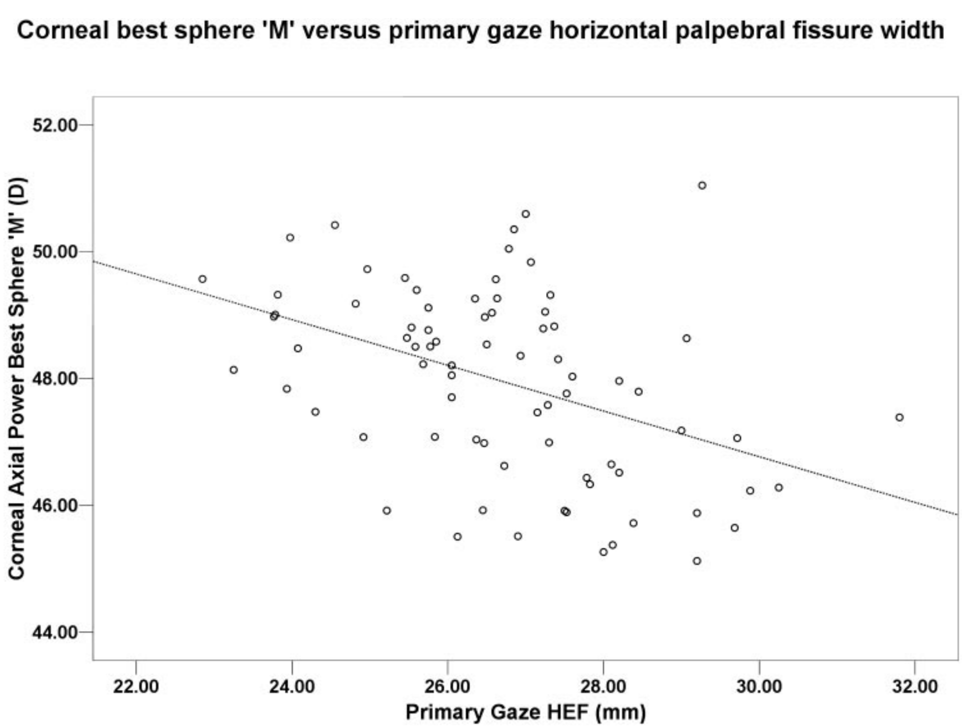

Figure 2. Corneal best-sphere M for 8-mm analysis diameter compared with primary gaze horizontal palpebral fissure width (HEF).

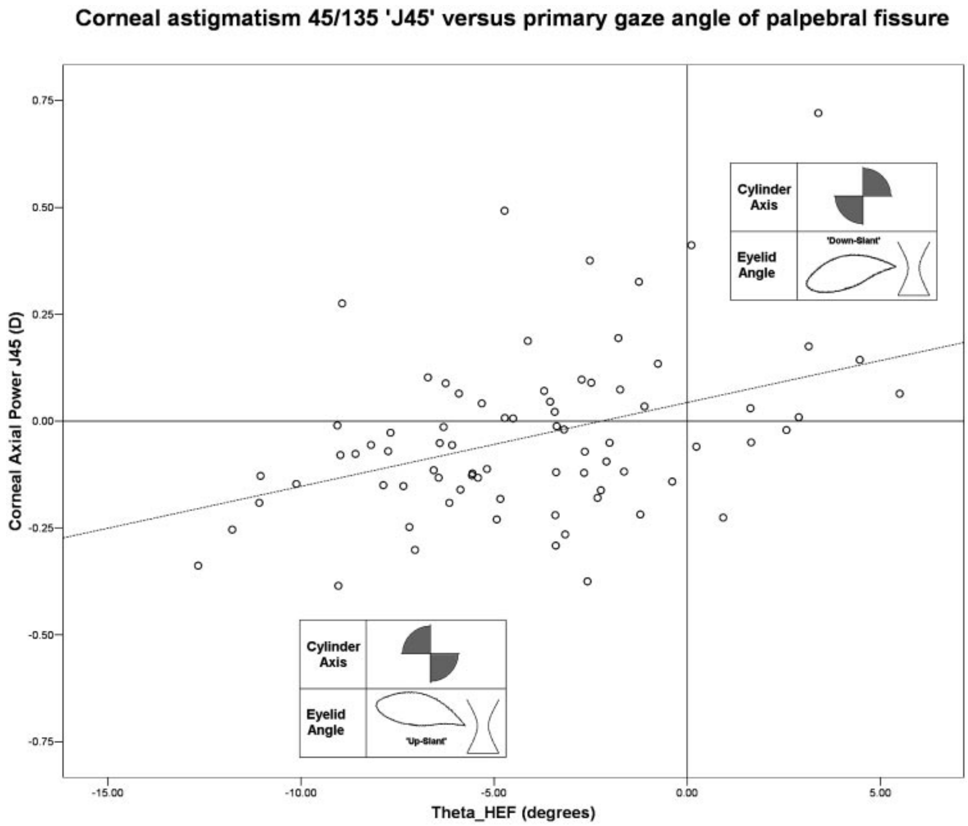

Figure 3. Corneal J45 for 8-mm analysis diameter compared with primary gaze Theta_HEF. Note the more up-slanted palpebral fissure is associated with a more negative J45 (indicating a minus cylinder axis between 90 and 180), and more down-slanting palpebral fissure is associated with a more positive J45 (indicating a minus cylinder axis between 0 and 90).

Correlation analysis was performed only for subjects exhibiting WTR central corneal cylinder axes. When all the WTR subjects were analyzed together, corneal M (8-mm diameter) showed significant correlation with the primary gaze palpebral fissure width (HEF; $r = -0.422$; $P = 0.001$). Corneal J0 (8-mm diameter) showed a significant correlation with the curvature of the lower lid in primary gaze (lower lid A; $r = -0.335$; $P = 0.001$), indicating that subjects with more WTR corneal astigmatism exhibited a flatter curve of the lower eyelid. Corneal J45 (8-mm diameter) showed significant correlation with Theta_HEF ($r = 0.374$; $P = 0.004$) and with the angle of the lower eyelid Theta_LL ($r = 0.511$; $P < 0.001$) in primary gaze.

Corneal Diameter and Corneal Topography

The population mean corneal ellipse major diameter A was found to be 11.9 ± 0.4 mm, and minor diameter B was found to be 11.5 ± 0.4 mm. The mean angle between major diameter A and the horizontal (theta) was 175°. Therefore, based on analysis of the videokeratoscope images (which was essentially an estimate of the visible iris diameter), most corneas were elliptical and were slightly wider in the horizontal meridian.

Some associations were found between corneal topography parameters and diameters. The corneal axial power best-sphere (8-mm analysis diameter) was found to be significantly correlated with the corneal diameter A ($r = -0.39$; $P < 0.001$), indicating that larger corneas tended to be flatter. A significant correlation was also found between the magnitude of corneal astigmatism and the toricity of the corneal diameter ($r = 0.429$; $P < 0.001$), indicating that the diameters of astigmatic corneas tended to be more toric than normal corneas (i.e., a greater difference existed between the major and minor corneal diameters). Surprisingly, no significant association was found between the axis of astigmatism and the axis of the corneal diameter ellipse.

Figure 4. Example of the correlation between the angle of the palpebral fissure and the angle of the corneal cylinder axis for two subjects. Subject 62 has a slightly up-slanted palpebral fissure (Theta_HEF, −7°) and a cylinder axis of 173°. Subject 91 has a slightly downward slanted palpebral fissure (Theta_HEF, 4.5°) and a cylinder axis of 15°. Note also the tendency for the steepest corneal meridian to align at right angles to the angle of the lower eyelid.

Correlation analysis was also carried out between the corneal diameter and the eyelid parameters. In general, only weak correlations were found between the eyelid parameters and the corneal diameter. The strongest correlation was that between the major diameter A and the primary gaze horizontal palpebral fissure width, HEF ($r = 0.435$; $P < 0.001$), indicating that subjects with larger horizontal eyelid measures exhibited larger corneas.

Discussion

In a young population with normal corneas, we found that significant correlations do exist between certain parameters of the morphology of the eyelid and the topography of the cornea. Significant associations were found between spherical corneal power and eyelid morphology and between corneal astigmatism and certain eyelid parameters. Previous investigators have shown correlations between corneal astigmatism and eyelid parameters in subjects with eyelid abnormalities[16] and with congenital malformation syndromes associated with abnormal palpebral fissure slanting[31–33] and in children with high degrees of astigmatism.[37] We have shown that associations between eyelid morphology and corneal astigmatism also occur in a population of healthy young adult subjects.

Corneal spherical power tended to correlate with measures of overall eye size, both the horizontal palpebral fissure width and the corneal diameter. Corneal best-sphere M was significantly correlated with the corneal diameter, and both these parameters were significantly correlated with the horizontal width of the palpebral fissure. These associations suggest some parallels in the growth of the different anterior eye ocular components (i.e., subjects with larger palpebral fissures tend to also have larger corneas and subsequently a flatter central corneal curvature). A previous study into fetal facial growth in humans has found significant correlations between many orbito-facial measures (including the palpebral fissure width) and the diameter of the cornea.[51] Denis et al.[51] suggest that horizontal growth of the eye, as measured by the corneal diameter, is related to that of the face and the body as a whole. Rasooly and Zauberman[52] also found a significant correlation among corneal curvature, subject height, and head diameter in adult subjects (larger head diameter was associated with a flatter cornea).

Correlations found between corneal astigmatism and eyelid parameters indicated that in general the angle of the eyelids was associated with the axis of corneal astigmatism. Correlations between palpebral fissure angles and corneal J45 were significant for subjects with low (<0.75 DC) and higher (>0.75 DC) degrees of corneal astigmatism. Most of the significant correlations between corneal astigmatism and the eyelid parameters in our population related to the axis of astigmatism rather than the magnitude. Correlation coefficients (r) between the angle of astigmatism (i.e., corneal J45 and corneal cylinder axis) and the eyelid angles ranged from 0.3 to 0.5. Although these correlations were relatively weak, they did indicate that 10% to 25% of the variance in the angle of astigmatism could be accounted for by the eyelid angles. A number of unknown factors (e.g., eyelid tension, corneal rigidity, and genetic factors associated with corneal shape) may have also contributed to the angle of astigmatism in these subjects.

Eyelid morphology parameters relating to the lower eyelid often showed stronger correlations with corneal astigmatism than those of the upper eyelid. This is an interesting finding because pressure from the upper eyelid has been implicated in the cause of astigmatism.[24] Although limited correlations were found between the eyelid parameters and the magnitude of corneal astigmatism, a significant correlation was found between the magnitude of corneal J0 and the curvature of the lower eyelid for subjects exhibiting WTR corneal astigmatism. Flatter lower eyelid curvature was associated with greater degrees of WTR astigmatism. It is conceivable that the curve of the eyelid is related to eyelid tension. If it is, one would expect that a tighter lid would be associated with a flatter lower eyelid curve. Thus, the tension in the lower eyelid may be related to the magnitude of WTR astigmatism. The literature is limited regarding the tension of the lower eyelid and its possible association with corneal astigmatism. Our results suggest that the angle and curvature of the lower eyelid have an influence on the angle and magnitude of corneal astigmatism in some subjects. Further research on the tension of the lower eyelid and its possible association with astigmatism is needed to fully clarify the reasons for the correlations found.

No significant difference was observed between the eyelid morphology parameters of the subjects exhibiting central spherical corneas and the subjects exhibiting central astigmatic corneas. Corneas might have been more astigmatic, not because they were related directly to the measured eyelid parameters in this study but because of differences in corneal anatomy or physiology (e.g., differences in stromal collagen architecture or corneal rigidity) or perhaps because of an eyelid factor that was not measured (e.g., eyelid tension). Therefore, though the subjects with astigmatic and spherical central corneas might collectively have exhibited similar eyelid morphology, they might have differed in their responses to eyelid pressure.

We found the amount of toricity of the corneal diameter to be significantly correlated with the magnitude of corneal astigmatism. Edmund[53] also investigated the relationship between corneal diameter and central corneal curvature and found a similar correlation between central corneal astigmatism and toricity of the corneal diameter in healthy subjects. The fact that the magnitude of the corneal astigmatism tended to be associated with the magnitude of toricity of the corneal diameter suggested that astigmatic subjects have corneas with an astigmatic overall form (i.e., a cornea that is inherently astigmatic). The axis of the astigmatism did not correlate significantly with the angle of the corneal diameter ellipse. This might have been because of differences between central and peripheral corneal astigmatism. We have previously shown that subjects can exhibit different characteristics of astigmatism in the central and peripheral cornea,[46] possibly because of changes in stromal collagen orientation in the peripheral cornea.[54,55] The lack of correlation between the angle of astigmatism and the angle of the corneal diameter (i.e., visible iris diameter) might also have resulted from differences in a subject's peripheral corneal transparency (unrelated to the level of corneal astigmatism) or from inaccuracy in the ellipse fitting procedure.

Only small numbers of subjects exhibited ATR and OBL central corneal cylinder axes. Therefore, we were unable to draw any reliable conclusions regarding the association between eyelid parameters and corneal topography for these subjects. It is difficult to envisage how eyelid morphology or pressure could result in ATR astigmatism. Further research is required to investigate a larger population of subjects with ATR and OBL corneal cylinder axes.

A number of our results support the notion that sustained mechanical pressure from the eyelids leads to corneal astigmatism. We expect that corneal characteristics such as stromal collagen architecture and corneal rigidity interact with eyelid parameters such as eyelid angles and eyelid tension and lead to the cornea's characteristic astigmatic shape. One would expect that in this model, the angle of the eyelids would be correlated with the axis of astigmatism (as was found in our study). Such a model also leads to the expectation that the magnitude of corneal astigmatism would be related to eyelid factors, yet this was generally not found to be the case in our subjects. It is most likely that multiple factors such as eyelid tension, eyelid position, and corneal physiological characteristics (such as stromal collagen orientation and corneal rigidity) all play a role in determining the magnitude of astigmatism.

Another possible reason for the associations found in this study could be a "correlated growth model " of astigmatism development. In this model, corneal and eyelid parameters would all be primarily inherited characteristics (and we would assume that pressure from the eyelids has negligible effect on the cornea). For noncausal associations to exist between eyelid parameters and corneal shape, correlations in the normal growth of these structures would have to occur (presumably because of a similar genetic influence on these ocular components). The finding that the corneal best sphere correlated significantly with the horizontal palpebral fissure width tends to support this correlated growth model. Some recent studies with animals suggest that corneal astigmatism can develop in response to imposed astigmatic defocus.[56] It is therefore also possible that the development of corneal astigmatism in humans may, at least in part, involve a visual feedback mechanism. Thus, short-term changes in corneal astigmatism as a result of eyelid forces[9,42] may lead to astigmatic defocus and to subsequent compensatory meridional growth of the cornea that result in correlations between corneal astigmatism and eyelid morphology.

None of the possible models of astigmatism development that we have discussed exactly match our experimental results. It appears that the most likely explanation of our results may be a combination of correlated growth and eyelid morphology. Two factors likely to be important for further understanding of astigmatism development are the influences of upper and lower eyelid tension and the biomechanics of the cornea.

In summary, we have shown that a number of parameters relating to the morphology of the palpebral fissure are significantly correlated with parameters relating to the shape of the cornea in young, healthy subjects. Although the significant correlations found between eyelid morphology and corneal astigmatism tend to support a model of corneal astigmatism development in which eyelid pressure is involved, they do not prove causation.

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