Change in corneal shape and corneal wave-front aberrations with accommodation

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This study investigated the change in corneal curvature and corneal wave-front aberrations with accommodation. The corneal curvature of the right eyes of 12 young adults was measured using a corneal topography system, while subjects fixated far (4.0 m) and near (0.2 m) targets with their left eyes. Convergence was controlled. Both the mean corneal radius at the vertex and the shape parameter significantly increased from the far to the near viewing condition. No significant change in root mean square of wave-front aberrations with accommodation was observed for the group, but there was individual variation in the change of wave-front aberration. A significant mean change for the group in both x-axis coma and spherical aberration was found. The change in corneal surface with accommodation suggests an increase in peripheral curvature with flattening at the vertex.

Keywords: accommodation, corneal shape, wave-front aberration, Zernike aberration, corneal topography

Introduction

When a normal eye is relaxed, objects in the distance are imaged on the retinal plane by the ocular system, mainly the cornea and the crystalline lens, while near objects are out of focus and form blurred images on the retina. To bring near objects into focus on the retina, the eye accommodates by changing the refractive power of the lens via the action of the ciliary muscle. The primary change during accommodation is in the shape of the lens, but change in corneal shape also may occur as a result of the action of the extrinsic muscles or the anterior insertions of the ciliary muscle (Bannon, 1946). The question of whether changes in corneal curvature occur with changes in viewing distance has long been debated, with several previous studies (Bannon, 1971; Fairmaid, 1959; Lopping & Weale, 1965; Mandell & Helen, 1968) failing to observe a change in corneal shape during accommodation when convergence was controlled. Using the technology available to them more than 30 years ago, these investigators reached their conclusions based on radii measurements of only a small, central region of their subjects' corneas (Bannon, 1971; Fairmaid, 1959; Lopping & Weale, 1965) or on an early imprecise placido disk system (Mandell & Helen, 1968). When convergence was allowed, the radius of the accommodated corneal surface was found to increase (or decrease in curvature), with a greater increase of the radius in the primary (or horizontal) meridian than in the secondary (or vertical) meridian (Bannon, 1971; Fairmaid, 1959; Lopping & Weale, 1965; Mandell & Helen, 1968). This asymmetric change in the corneal radius was claimed to cause an accommodative corneal astigmatism. The flattening in the cornea for the accommodating and converging eye was attributed to the extraocular tension produced by the recti during convergence (Fairmaid, 1959).

In a recent study using a modified keratometer with convergence controlled, Pierscionek and colleagues (Pierscionek, Popiolek-Masajada, & Kasprzak, 2001) found an increase in central corneal curvature in at least one principal meridian when focus changed from distant to near targets. They explained the change in corneal curvature by the movement of the ciliary muscle, which exerts its intraocular force on the cornea via the anterior sclera.

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During accommodation, not only is the refractive power of the eye changed, but also the aberration of the eye. The changed aberrations include astigmatism (Denieul 1982; Fletcher, 1952; Millodot & Thibault 1985; Mutti, Enlow, & Mitchell, 2001; Tsukamoto, Nakajima, Nishino, Hara, Uozato, & Saishin 2000; Ukai & Ichihashi, 1991), spherical aberration (Atchison, Collins, Wildsoet, Christensen, & Waterworth 1995; He, Burns, & Marcos, 2000; Ivanoff, 1956; Jenkins, 1963; Koomen, Tousey, & Scolnik, 1949; Van den Brink, 1962) and high-order wave-front aberrations (comas and others) (Atchison, et al.1995; He, et al. 2000; He, Marcos, Webb, & Burns, 1998; Howland & Buettner, 1989). Given the recent finding on the change in corneal shape with accommodation (Pierscionek, et al. 2001), it is interesting to know if corneal aberration is also changed, because it will help us understand to what extent the change in aberrations of the accommodated eye is caused by either the cornea or the lens. This result will also provide useful information for customizing aberration correction using techniques such as laser surgery and contact lenses.

In this work, we report measurement, using a highly sensitive corneal topography system, and analysis of changes in corneal curvature and corneal aberrations for 12 subjects when viewing far and near targets with convergence controlled. Significant changes in corneal shape and some Zernike aberrations with accommodation were found.

Methods

Twelve subjects participated in this study. They ranged in age from 23 to 32 years (mean age = 26.2 years). Refraction was tested by noncycloplegic distance retinoscopy. The spherical equivalent ranged from 0 to –3.00 D (mean = –0.85 D), with astigmatism less than or equal to 0.25 D (mean = 0.02 D). All subjects had corrected decimal visual acuity of 1.0 (20/20) or better, no prior history of ocular surgery, normal binocular function, and a relatively large interpupillary distance (over 6 cm). The large interpupillary distance was required to allow enough space to adjust the reflective mirror in front of the left eye.

The research followed the tenets of the Declaration of Helsinki, and was approved by the New England College of Optometry Institutional Review Board. Informed consent was obtained from the subject after verbal and written explanation of the nature and possible consequences of the study.

Corneal topography was measured for the right eye while the left eye fixated the stimulating target via a mirror. A diagram of the instrumentation is shown in Figure 1, where the position of the subject's eyes (S) relative to the corneal topography system (CTS) and the stimulating targets (T1 and T2) is shown.

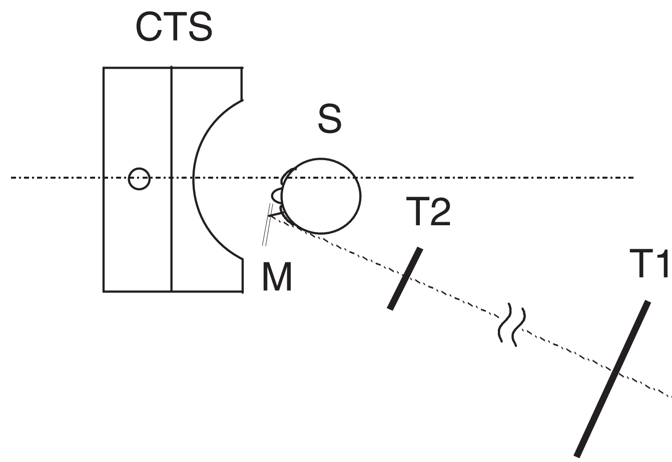

Figure 1. Diagram of the position of the subject's eyes (S) relative to the corneal topography system (CTS) and the stimulating targets (T1 for far and T2 for near). M is the mirror.

The corneal topography system was the Humphrey Atlas Eclipse Corneal Topographer System Model 995 (Zeiss Humphrey System, Dublin, CA), which is a placido-based videokeratographer with 22 rings, and the luminance as measured by the Minolta LS-100 photometer is 0.95 cd/m^2. The infrared illumination provides greater comfort for the subject. A red spot inside the system was used as the fixation point for the right eye.

The Atlas system was calibrated with spherical model surfaces provided by the company. To make the system precisely measure the human cornea, which is aspherical, we recalibrated it with six aspherical model surfaces made by Sterling International Technologies, Inc. (Tampa, FL). A detailed description of the calibration procedure is given elsewhere (He, Held, Thorn, & Gwiazda, in press). When calibrated, the Atlas system was capable of detecting a change in corneal height as small as 0.5 micron (Guirao & Artal, 2000; Salmon & Thibos, 2002).

As shown in Figure 1, the left eye fixated the letters on the backlit LogMar ETDRS Visual Acuity Chart "2000," Chart "2" (Precision Vision, La Salle, IL) (T1) or a miniature version of the chart (T2) via a mirror (M). The fixation targets T1 and T2 were placed at a distance of 4.00 m and 0.20 m, respectively, from the left eye and served as the distance and near accommodative stimulus. The mirror (M) was mounted on a straight mount so that the angle of the mirror was adjustable. By adjusting the mirror angle, the experimenter was able to move the fixation target for the left eye and superimpose it on the red fixation spot for the right eye without changing the alignment of the subject's right eye.

With his or her chin on the chin rest and forehead against the forehead rest of the topographer, the subject was asked to look at the red fixation spot inside the system with the right eye. First, several measurements were taken without any stimulus for accommodation (e.g., no fixation target was given for the left eye to look at). Then the mirror was moved into position in front of the left eye and turned so that the subject could view the target at 4.0 m. Fine angle adjustment was performed in such a way that the right eye's image of the red fixation spot was superimposed on a letter centered on a row of the left eye's image of the visual acuity chart. The subject was asked to fixate the letter on which the image of the red spot was superimposed. One practice measurement was then taken for the distant viewing condition, followed by five reliable measurements.

After the measurements for the distant viewing condition were completed, the near target was moved into the view of the subject's left eye. Again, by adjusting the mirror, a letter in the left eye was superimposed on the red spot in the right eye. One practice and five reliable measurements were then taken for the near viewing condition. A complete session took approximately 45 min.

Data Analysis

To analyze corneal aberrations, we used data interface software provided by Humphrey to export the corneal curvature and corneal height data that were derived using an arc step method in the system (Campbell, 1997). With the Atlas system, some resulting height data are almost always missed in a corneal area of 11 mm in diameter. The missing data make it difficult to precisely estimate aberrations for the measured corneal area. Therefore, we have treated a measurement without any missing data in a 7-mm diameter area as a complete data set. The corneal area covers approximately 14 Placido rings, but the number varies from 13 to 15 depending on eye size.

For each completed measurement, the corneal heights were used to analyze the wave-front aberrations for the anterior corneal surface. To calculate the corneal aberrations, a reasonable reference surface is required. We used a conic surface, which is aberration-free for an object at infinity from the eye, as the reference surface.

The conic surface (Hr) is described by:

$$Hr = (1/p)\ \{Rc - [Rc^2 - p\ (x^2 + y^2)]^{1/2}\} \qquad (1)$$

where p and Rc are the shape parameter and the apical radius at the vertex, respectively, and x and y represent the coordinates with the origin at the vertex.

The Rc for the aberration-free surface was approximated with the average radius derived from corneal curvature for the first inner ring in the corneal measurement. The shape parameter (p) for an aberration-free conic surface is determined by:

$$p = 1 - 1/n^2, \qquad (2)$$

where n is the refractive index of the cornea ($n = 1.376$), and thus is a constant equal to 0.47184.

Given the reference surface as described in Equation 1, wave-front aberrations for the anterior corneal surface were derived by subtracting the corneal height from the reference surface. If the corneal height from the corneal topography system and the reference surface are mathematically described as $Hc(x,y)$ and $Hr(x,y)$, respectively, the anterior corneal wave-front aberration would be determined as following:

$$Wc(x,y) = (n - 1)\ [Hc(x,y) - Hr(x,y)] \qquad (3)$$

Equation 3 provides a description of the wave-front aberrations for the anterior cornea, from which we have derived 35 Zernike coefficients that indicate the amount of individual Zernike aberrations, using the Gram-Schmidt procedure (Schwiegerling, Greivenkamp, & Miller, 1995; Guirao & Artal, 2000; Salmon & Thibos, 2002). The Zernike polynomials are those recommended by the Vision Science and Its Application (VSIA) Standards Taskforce team (Thibos, Applegate, Schwiegerling, Webb, & VSIA Standards Taskforce Members, 2000).

Results

Figure 2 shows the change in radius, derived from corneal curvature for the first inner ring in the corneal measurement, with accommodation (near radius – far radius) for the 12 eyes. The change in radius varied from subject to subject, ranging from -0.020 mm to 0.096 mm. The mean corneal radii at the vertex for the 12 right eyes for the far and near viewing distances were 7.748 ± 0.254 mm and 7.774 ± 0.277 mm, respectively. Eight of the 12 eyes had an increase in radius. A paired t test yielded a significant mean increase in the radius from far to near

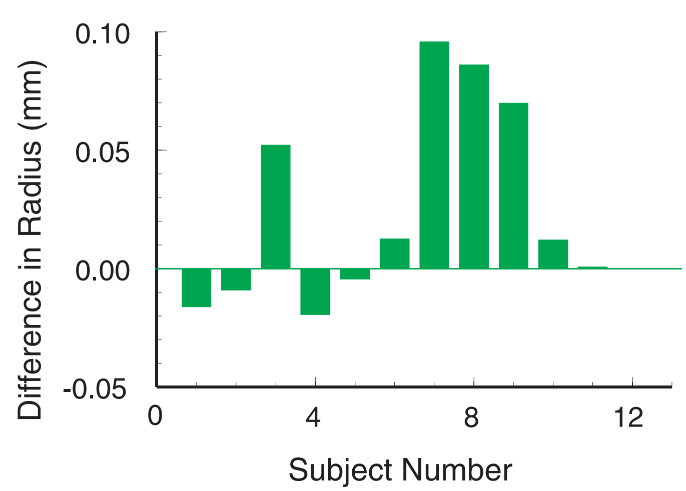

Figure 2. Change in corneal radii at the vertex (near – far) for the 12 right eyes when fixation for the left eyes was changed from far to near. Eyes are plotted in order of the size of the corneal radius at the far viewing condition.

(mean difference = 0.026 ± 0.041 mm; paired $t = 2.21$, $p < .025$).

Changes in shape parameters, derived by best-fitting the corneal height data to Equation 1, for both the whole tested corneal area (about 11 mm in diameter) and a 7-mm diameter area for the 12 eyes, are illustrated in Figure 3a and 3b, respectively. The change in shape parameter (y-axis) is plotted against the eye number (x-axis). For the whole tested corneal area (11 mm), the mean shape parameters for the far and the near conditions were 0.766 ± 0.078 and 0.790 ± 0.057, respectively. Ten out of the 12 eyes had an increase in the shape parameter from far to near, with the change in shape parameter ranging from -0.058 to 0.104. The mean change in shape parameter with accommodation was significant (mean difference = 0.024 ± 0.039; paired $t = 2.12$, $p = .029$).

For the 7-mm corneal area (Figure 3 b), the mean shape parameters were 0.819 ± 0.114 and 0.861 $\pm$ 0.101 for far and near, respectively, and the mean change from far to near approached significance (mean difference = 0.043 ± 0.091; paired $t = 1.63$, $p = .065$). The change in shape parameter ranged from –0.080 to 0.278. Relative to the mean shape parameters for the 11-mm corneal area, the mean shape parameters for the 7-mm corneal area at both the far and the near viewing condition were significantly greater (mean difference = 0.053 ± 0.054; paired $t = 3.36$, $p = .003$ for far; and mean difference = 0.072 ± 0.077; paired $t = 3.25$, $p = .004$ for near). But, the change in shape parameter from far to near for the 7-mm corneal area was not significantly different from that for the 11-mm area (mean difference = 0.019 ± 0.058; paired $t = 1.15$, *ns*).

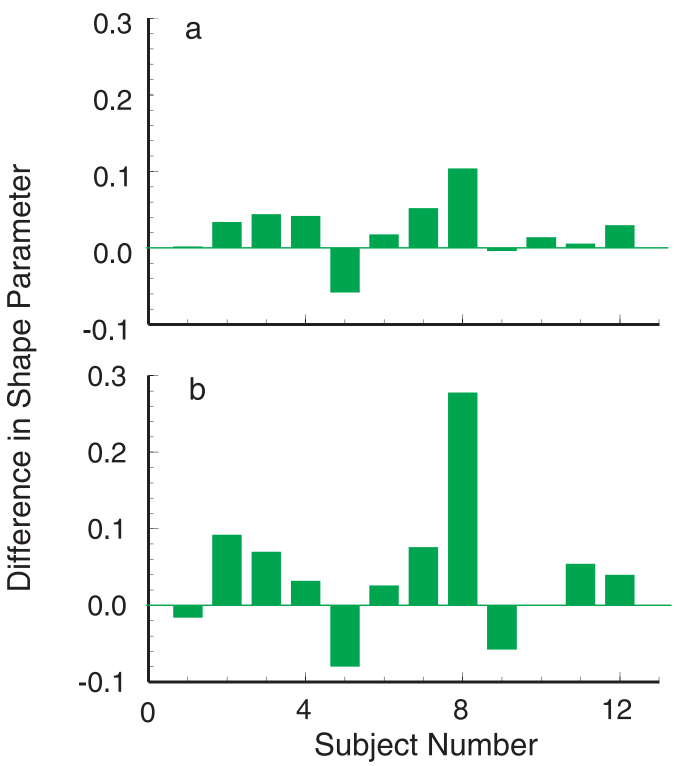

Figure 3. Change in shape parameters (near – far) for an 11-mm diameter corneal area (a) and a 7-mm diameter area (b) for the 12 eyes plotted in the same order as in Figure 2.

Figure 4 illustrates the wave-front aberration maps and the corresponding Zernike aberrations for two eyes under far (left panel) and near (middle panel) viewing conditions. The x-axis and y-axis indicate normalized pupil location, whereas the z-axis represents wave-front error (µm). The right panels show comparisons of Zernike aberrations (2nd to 5th orders only) between the far (cross) and the near (empty circle) viewing conditions. The x-axis is the number of the Zernike function, and the y-axis represents the coefficient value for each Zernike aberration. For the eye shown in Figure 4a, the root mean square (RMS) value for the far viewing distance (1.16 µm) was almost the same as that for the near one (1.19 µm), and the shapes of the wave-front aberrations were almost identical. Similarly, the Zernike coefficients for the far viewing condition matched those for the near condition very well.

The corneal wave-front aberrations for the far viewing condition for the eye shown in Figure 4b, however, were different from those in the near condition. The RMS value for the near condition was 1.39 µm, significantly greater than 1.08 µm for the far condition ($t = 3.77$, $p < .01$). The Zernike coefficients for Z3, Z5, and Z8 for the far condition were significantly different from those for the near condition ($t = 3.49$, $p < .02$ for Z3; $t = 2.84$, $p < .025$ for Z5 and $t = 2.63$, $p < .05$ for Z8, respectively).

Differences in RMS values of the corneal wave-front aberrations for the 12 subjects between far and near are shown in Figure 5, where the difference in RMS value (y-axis) is plotted against the subject number (x-axis) arranged as in the previous figures. Differences in RMS values for total wave-front aberrations including astigmatism are shown in Figure 5a, and the differences in RMS values for wave-front aberrations with astigmatism removed are illustrated in Figure 5b. For the 12 subjects, mean RMS values were 1.11 ± 0.32 µm for far and 1.14 ± 0.29 µm for near. A paired *t* test showed no significant difference in the change in RMS values from far to near (mean difference = 0.03 $\pm$ 0.12 µm; paired $t = 0.85$, *ns*). However, 3 of the 12 subjects were found to have a significant difference in RMS values for total wave-front aberrations between the far and near viewing conditions (difference = 0.310 µm; $t = 3.77$, $p < .01$, for subject 4; difference = 0.179 µm; $t = 3.38$, $p < .02$, for subject 5; and difference = 0.115 µm; $t = 2.14$, $p < .05$, for subject 11). While the RMS value at far viewing was greater than that at near viewing for subject 11, subjects 4 and 5 had RMS values greater at near than at far.

With astigmatisms removed, only one subject (4) was found to have a significant difference in RMS values between the far and near conditions (difference = 0.108 µm; $t = 2.20$, $p < .05$). The mean RMS values for the 12 subjects for the far (0.69 ± 0.09 µm) and the near (0.71 ±

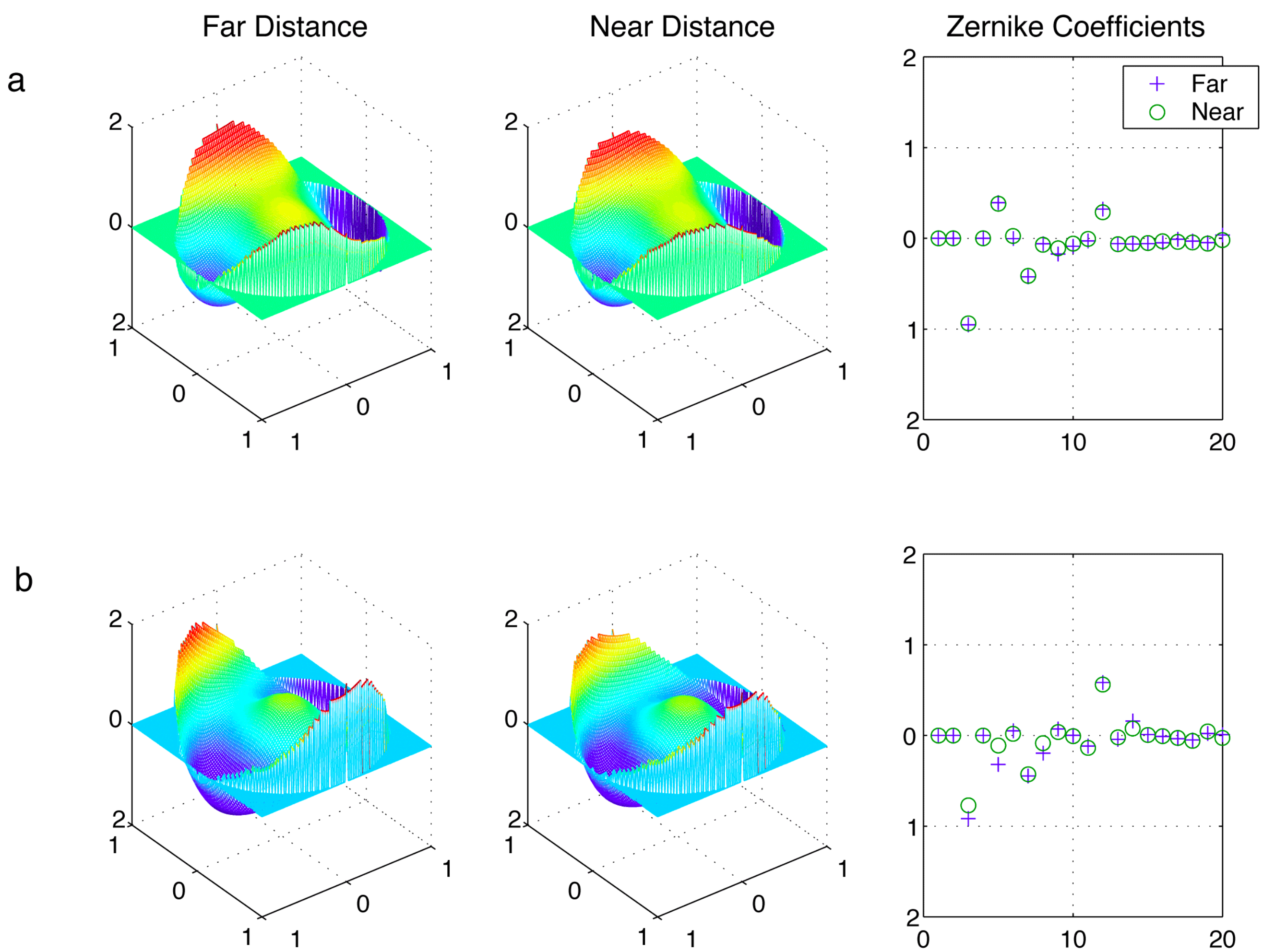

Figure 4. Wave-front aberration maps (left and middle panels for far and near, respectively) and Zernike aberrations (right panels) for one eye with the same wave-front aberrations for far and near (a) and another eye with different aberrations for far and near (b). The wave-front errors were plotted against normalized pupil location for a 7-mm diameter area. The right panels show comparisons of Zernike aberrations (2^{nd} to 5^{th} orders only) between the far (cross) and the near (empty circle) viewing conditions. The x-axis is the number of the Zernike function and the y-axis represents the coefficient value for each Zernike aberration.

0.09 μm) viewing conditions were similar, and there was no significant change in the RMS values (mean difference = 0.02 ± 0.06; paired $t = 0.94$, *ns*), as shown in Figure 5b.

Mean Zernike coefficients of the 2nd and 3rd orders and spherical aberration for far and near viewing conditions for the 12 subjects are listed in Table 1, where the paired *t* test values for the change in Zernike coefficients with accommodation are also listed. For the 2nd order Zernike aberrations (Z3 and Z5 astigmatisms), there was no significant change in the coefficients from far to near. Among the four 3rd order aberrations (Z6-Z9), only one (Z8, x-axis coma) was found to have a significant change ($p < .007$; the significant level was corrected from the level of $p = .05$ for multiple comparisons using the Bonferroni correction). In addition, corneal spherical aberration (Z12) was significantly changed when the eye's fixation changed from far to near ($p < .007$).

Discussion

We have measured corneal shape and corneal wave-front aberrations for 12 subjects when the eye was fixated first on a far and then on a near target. For the group, both corneal radius at the vertex and the shape parameter were significantly increased from far to near for the 11-mm cornea. The change in shape parameter for the 7-mm corneal area was in the same direction as for the 11-mm cornea, but did not reach significance. The radius at the vertex was found to increase 0.26 mm at near, which corresponds to a 0.16 D decrease in the corneal refractive power. Such a small radius change may explain why this had not been observed in several previous studies (Bannon, 1971; Fairmaid, 1959; Lopping & Weale, 1965; Mandell & Helen, 1968), possibly because their techniques were not sensitive enough.

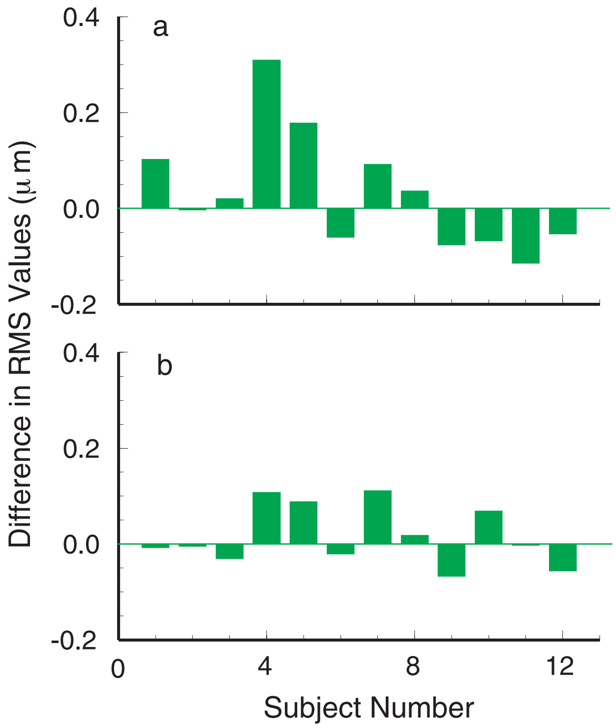

Figure 5. Change in root mean square values (near – far) of the total corneal wave-front aberrations (a) and the wave-front aberrations with astigmatism removed (b) of a 7-mm diameter area for the 12 subjects.

Pierscionek et al. (2001) observed a change in central corneal curvature in at least one principal meridian with accommodation. However, they found an increase in corneal curvature, which is opposite to the direction of corneal change observed in this study and in several previous studies where convergence was allowed (Bannon, 1971; Fairmaid, 1959; Lopping & Weale, 1965; Mandell & Helen, 1968).

An increase in the vertex radius means the corneal surface is flatter at the vertex. The flattening of the vertex radius with accommodation in our subjects was found to accompany an increase in the shape parameter (Figure 2). Figures 6a and 6b illustrate what might be happening to the cornea with accommodation. Figure 6a shows a diagram of the corneal sections when the eye is fixated at far (solid line) and near (dotted line). To emphasize the change in the cornea at near, which is too small to show in Figure 6a with the scale of mm, the dotted curve of the near condition was exaggerated. The vertex area for the accommodated cornea is flatter and the shape is more curved at the peripheral corneal zone, resulting in an increase in the shape parameter. Figure 6b shows the difference in corneal section between far and near (far – near). It can be seen that the difference is very small, only 2 µm at the maximum.

It is not clear how accommodation causes the cornea to change in this way. Fairmaid (1959) proposed the action of the recti muscle as the cause of corneal change and the induction of corneal astigmatism for eyes that are converged. This explanation, however, does not account for a general increase in the radius, and the extraocular factor does not explain the change in corneal shape with accommodation in this current study. The contraction of the ciliary muscle may be the cause of corneal change in an accommodated eye (Pierscionek, et al. 2001). As the ciliary muscle contracts, the eyeball may change toward a more oval shape, and thus make the peripheral corneal area steeper. As an alternative explanation, pressure of the aqueous humor may increase due to the shape change and forward movement of the lens, and this may act on the corneal surface and flatten the central corneal area.

In this study, no significant change in corneal astigmatism with accommodation was found, consistent with previous studies (Bannon, 1971; Fairmaid, 1959; Lopping & Weale, 1965; Mandell & Helen, 1968). This result supports the theoretical position that accommodative astigmatisms are caused by the lens (Denieul 1982; Fletcher, 1952; Millodot & Thibault 1985).

The corneal x-axis coma and spherical aberration were significantly changed for the accommodated eyes of our subjects, but the changes were very small, about 0.02 to 0.03 µm. The changes observed in the whole eye are much larger (about 0.5 µm) (Atchison, et al. 1995; He, et al. 1998; He, et al. 2000; Howland & Buettner, 1989; Ivanoff, 1956; Jenkins, 1963; Van den Brink, 1962). This differential effect for the cornea and the whole eye

Table 1. Mean Normalized Coefficient Values of the Corneal Zernike Aberrations of a 7-mm Area for Far and Near Viewing Conditions for 12 Subjects and the Paired *t* Test Values.

	Z3	Z5	Z6	Z7	Z8	Z9	Z12
Far	-0.009 ± 0.469	-0.616 ± 0.523	-0.003 ± 0.178	-0.133 ± 0.227	-0.152 ± 0.260	0.024 ± 0.136	0.482 ± 0.103
Near	-0.008 ± 0.481	-0.632 ± 0.520	0.007 ± 0.155	-0.155 ± 0.215	-0.066 ± 0.251	0.013 ± 0.134	0.512 ± 0.098
Near-Far	0.001 ± 0.088	-0.016 ± 0.141	0.010 ± 0.081	-0.022 ± 0.070	0.086 ± 0.100	-0.011 ± 0.046	0.030 ± 0.029
Paired *t*	0.02	-0.40	0.44	-1.08	2.96*	-0.83	3.55*

Data are expressed as means ± SD. The star symbol indicates a significant difference at $p < .007$, the level corrected for multiple comparison using the Bonferroni correction.

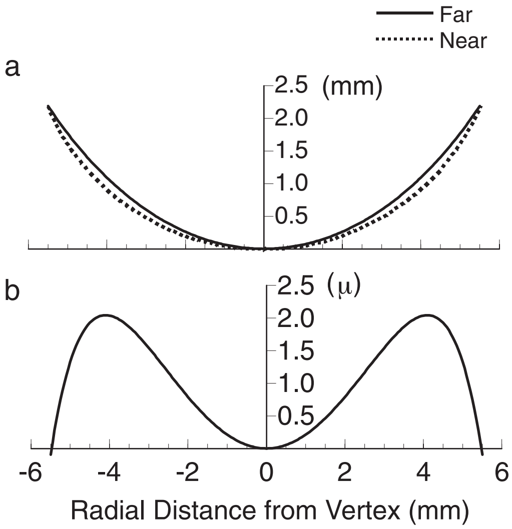

Figure 6. Diagram of the corneal sections for far (solid line) and near (dotted line) viewing conditions (a) and the difference in corneal section between far and near (b).

suggests that the change in Zernike aberrations for the whole eye can be attributed mainly to the lens.

A significant change in total corneal wave-front aberrations with accommodation was not observed for the group of 12 subjects, but individual variation was found. For example, subjects 4, 5, and 11 showed significant changes in RMS of wave-front aberration during accommodation (Figure 5). While the corneal wave-front aberrations were almost the same for some subjects when the eye was accommodated, they were changed for others (e.g., the subject shown in Figure 4b). Wave-front aberrations in the whole eye were found to change with accommodation for almost every subject in a previous study (He, et al. 2000). The stability of the corneal wave-front aberrations during accommodation for 9 of 12 subjects in the current study indicates that the change in wave-front aberrations in the whole eye during accommodation is caused by the lens for most individuals. However, the contribution from the cornea cannot be overlooked because three subjects showed a change.

Tear film fluctuations cannot account for our results. The effect of tear film fluctuations on corneal topography measurements was carefully examined by Guirao and Artal, (2000), who failed to find any significant effect. Eye movements may introduce noise in corneal topography measurements. However, the influence theoretically can be reduced by taking repeated measurements. Given that five measurements were taken for our subjects, we do not expect there to be a significant effect of eye movements on our estimates.

Because we could not monitor accommodation during data collection, the inter-subject differences could have been due, in part, to differences in the amount of accommodation used by each subject. This is unlikely because the subjects reported that they saw clear letters. However, if this were the case, it would suggest that some subjects might have greater accommodative effects on their corneas than we have shown. Further study with accurate measurement of the accommodative response may aid understanding of the causes of individual variation in corneal change with accommodation.

In summary, we found a statistically significant increase in both the mean corneal radius at the vertex and the shape parameter when fixation was changed from the far to the near viewing condition, although the changes were small. However, no significant change in RMS of wave-front aberrations with accommodation was observed for the group, but there was individual variation in the change of wave-front aberration. A significant mean change for the group in both x-axis coma and spherical aberration was found.

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