Evaluating Corneal Displacement Using High-Speed Photography at the Early and Late Phases of Noncontact Tonometry

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Purpose. We investigated the extent of corneal displacement and factors associated with the measurement of IOP during the early and late phases of noncontact tonometry.

Methods. One eye in each of 61 healthy volunteers was studied. In each case, the cornea was photographed in profile using a high-speed camera during noncontact tonometry. The extent of displacement at the corneal center, and at the midperipheral corneal areas at 13.2 and 30.0 ms after the application of an air puff was recorded. For each measurement point, multiple regression analyses were performed against age, sex, axial length, corneal curvature, IOP, and central corneal thickness (CCT) to determine the independent predictors of corneal displacement. Multiple comparison tests were used to determine whether the displacement differences were associated with age or sex.

Results. Our results showed that the factors most associated with corneal displacement were the IOP (P < 0.001) and CCT (P = 0.02) at the corneal center at 13.2 ms, the CCT (P = 0.041) at the corneal midperiphery at 13.2 ms, age (P < 0.01) at the corneal center at 30.0 ms, and age (P = 0.04) and IOP (P = 0.04) at the corneal midperiphery at 30.0 ms. Young females had the smallest amounts of corneal displacement at all measurement points, and elderly females had largest amounts of displacement at the late phase of tonometry.

Conclusions. The amount of corneal displacement is affected by an individual’s IOP, age, and CCT. Our findings indicated that the corneas of females may be more susceptible to aging than those of males.

Keywords: noncontact tonometer, high-speed camera, ocular rigidity, ocular bioproperty intraocular pressure

The ability to measure IOP accurately is important for the management of patients with glaucoma.1 The Goldmann applanation tonometer is accepted as the gold standard instrument for measuring IOP, and the accuracy of the measurements is based on the Imbert-Fick law. This law assumes a very thin central corneal thickness (CCT), an even corneal curvature, a lack of ocular rigidity, that is, the corneal tissue is completely elastic, and negligible tear film surface tension. Unfortunately, these assumptions are not applicable to the living eye; therefore, determining the true IOP is difficult.

Ocular rigidity is a general term used to describe the eye’s resistance to being deformed and is the primary factor that influences the ability to measure the true IOP. Friendenwald et al. investigated ocular rigidity in enucleated eyes and reported that increases in the intraocular volume are proportional to the logarithm of the IOP.2 The slope of the regression line between the IOP and the injected volume of saline solution is the coefficient of rigidity.2 Other investigators have attempted to measure ocular rigidity in living human eyes using different procedures with manometers and tonometers.3–12 In general, these studies have shown that elderly, nonmyopic males with thicker CCTs have higher ocular rigidity than young, myopic females with thin CCTs and keratoconic subjects.3–12 Kempf et al. reported a new method of evaluating ocular rigidity noninvasively using a high-speed camera to observe corneal displacement during noncontact tonometry.8,9 They reported that the degree of corneal displacement during tonometry can be one of the indicators of corneal rigidity, and the degree of corneal displacement is more pronounced during the late recovery phase, that is, a slower elastic return to the initial position after compression. They showed that the corneas of young subjects simply deformed, and returned to the initial position and shape during tonometry. The corneas of young subjects returned to the initial shape first, then returned to the initial position. Kiuchi et al. used a similar method to measure the central corneal displacement at the early phase.
and reported that older males with low IOPs exhibit significantly greater displacement.\textsuperscript{10} Unfortunately, Kiuchi et al. did not measure the central corneal displacement at the late phase or whether different regions of the cornea exhibit different degrees of displacement.

Therefore, the aim of our study was to investigate the extent of corneal displacement in the central and midperipheral cornea at the early and late phases using a noncontact tonometer, and to determine the demographic factors that affect the extent of corneal displacement.

**METHODS**

The procedures used in our study were approved by the Institutional Review Board of Hiroshima University and conformed to the tenets of the Declaration of Helsinki. Informed consent for the measurements was obtained from all subjects. The subjects consisted of 61 healthy volunteers (34 males and 27 females) recruited between January 2005 and March 2007. Only the left eye of each subject was examined. Subjects with a history of ocular surgery or with any type of eye disease, other than mild cataracts and refractive errors, were excluded. The images reported by Kiuchi et al.\textsuperscript{10} were reanalyzed for this report.

A complete ophthalmic examination, including phthalmoscopy, was performed on all subjects before obtaining the measurements. The CCT was measured with a specular microscope (SP-2000p; Topcon Corporation, Tokyo, Japan), and the corneal curvature and axial length were measured with the IOLMaster (Carl Zeiss Meditec, Jena, Germany). Before beginning the measurements, we confirmed that our noncontact tonometer (CT-80A; Topcon Corporation) would consistently apply an air puff to each subject’s cornea with the same pressure distribution.\textsuperscript{9,10}

During tonometry, the cornea was photographed in profile with a high-speed camera oriented perpendicular to the geometrical axis of the eye (Fig. 1). At 15 minutes after photographing the cornea, we measured the IOP three times with a Goldmann applanation tonometer, and the average was taken as the standard IOP.

**High-Speed Camera**

A high-speed digital still camera (Phantom V7.1; Vision Research, Wayne, NJ) with a field of 512 × 1024 pixels was used to photograph the corneal profile at 5000 frames/s (1 frame/0.2 ms).

The cornea was illuminated by two infrared light sources to assure high optical quality images would be photographed at this high frame rate. The high-speed camera shutter was synchronized to the noncontact tonometer switch such that the photographic system would begin to photograph the cornea from the onset of the air puff for 40.0 ms.

To examine the corneal surface in detail, the photographed images were processed based on a threshold value to obtain a binary image using an original software program that uses the Microsoft Visual Studio 2008 (Microsoft, Redmond, WA), and its precision of resolution was 14 μm/pixel.\textsuperscript{13} With the edge of the cornea delineated, the corneal surface was fitted to circles of different radii using the least squares method. This made it possible for us to find the center coordinate of the extrapolated circle and the radius of curvature of the corneal surface. The coordinate of the top of the corneal edge was defined as the point of intersection of the corneal edge with the geometric x-axis extending from the center coordinate of the cornea. Figure 2 shows continuous photographs from the beginning of the air puff to corneal inversion, and also the associated recovery phenomena.

The amount of corneal displacement from the initial position was computed from the edge of the cornea frame-by-frame.\textsuperscript{8,9} The corneal midperiphery points were determined by the distance of 0.4 × individual radius of the corneal curvature from the corneal center. We confirmed that this area does not undergo any deformation after receiving the air puff from the tonometer.

Therefore, the amount of displacement at our midperipheral area is considered to be the whole cornea backward movement during tonometry. These upper and lower positions are referred to as the corneal midperiphery. Data from the corneal midperiphery were taken as the average of the upper and lower points (Fig. 3).

We also evaluated the distance (d3, the difference between the central corneal displacement [d1] and the midperiphery corneal displacement [d2]), because this parameter was considered to indicate the real backward movement of the central cornea.

The effect of distortion due to the optical system of the camera on the amount of displacement has been reported previously by Kaneko et al.\textsuperscript{14} They reported that the tonometer automatically aligns the nozzle for the air jet within a range of 0.25 mm around the tip of the cornea, and a shift in the vertical direction has hardly any influence on the measurement, since the curvature radius of the cornea (R = 7.2–8.0 mm) is large in comparison to such a shift (Δy = 0.25 mm) and the impact of the shift on the imparted force scales (with cos[Δy/R] ≈ 0.995). If the camera is not positioned exactly perpendicular to the air jet direction, then the deformation is underestimated systematically, and there are large deformations at approximately 300 μm, so the systematic, relative estimated error is reported to be approximately 14% per degree.\textsuperscript{14}

**Determination of the Corneal Displacement**

**Evaluation Time Points**

After the cornea is displaced by an air puff, it becomes concave at its center. This is called the inversion phase. Our system was not able to observe the degree of corneal indentation because the camera was perpendicular to the corneal axis. During the preliminary examination, we measured the relationship between the peak time of flattening of the surface, as measured by the optical sensor, and the IOP. The peak time of flattening of the surface was correlated strongly with the IOP. When the IOP was 9 mm Hg, its peak time was 13.2 ms.\textsuperscript{13} In this study, the lowest IOP in all our subjects was 9 mm Hg. Therefore, we defined 13.2 ms after the onset of the air puff as the length of the measurement time. The deformation of the cornea into a concave shape had not yet occurred at this time. Therefore, we measured the displacement of the cornea on the image at 13.2 ms after the air puff.

All of our subjects recovered from this concave inversion period 30.0 ms after the onset of the air puff. Therefore, we measured the displacement of the corneal on the image 30.0 ms after the air puff. The average of the results of five trials was used for the statistical analyses. This study had an 82% and 91% power to identify a 15 μm difference in the mean corneal displacement between males and females, and also between younger and older subjects, respectively.

**Statistical Analyses**

The statistical analyses were performed using the JMP software program, version 6.0.3 (SAS Institute, Inc., Cary, NC). The data are expressed as the mean ± SD. P values of <0.05 were considered statistically significant. Appropriate t-tests were...
used to evaluate demographic data, and sex and age differences at the four measurement points. The relationships between the amount of corneal displacement, and the IOP, CCT, radius of corneal curvature, and axial length were evaluated using Pearson’s correlation coefficients at the six positions. The significant factors identified by the Pearson’s correlation coefficients were used for the multiple regression analysis to evaluate the independent predictors of corneal displacement at each point. The $\beta \pm \text{SEM}$ partial regression coefficients were adjusted for the compared parameters. The subjects were divided by age into two groups, those 50 years of age and younger (33 eyes, 22.0 $\pm$ 1.5 years), and those older than 50 years (28 eyes, 68.5 $\pm$ 7.9 years), because the age distribution showed peaks for those subjects in their 20s and 60s.

To investigate the trends associated with sex and age in detail, a two-way ANOVA and a post hoc analysis (Tukey-Kramer) were used to compare differences in corneal displacement among the six measurements, and the demographic data among the age- and sex-divided groups: younger males, younger females, older males, and older females.

**Figure 1.** Diagram of the experimental setup (A, B). The optical axis of the camera was perpendicular to the visual axis. The tonometer was placed along the visual axis. The camera shutter and tonometer switch were synchronized (B).

**Figure 2.** Continuous photographs from the beginning of the air puff to corneal inversion, and also the associated recovery phenomena as shown by a high-speed camera. The photograph at 20.0 ms shows the parameters used in this study.
RESULTS

Comparisons of Demographics

The demographic data for our subjects are shown in Table 1. There were no significant differences between CCT and IOP among any of the four groups. A post hoc analysis found significant differences in the axial length between the younger and older males, younger males and older females, older males and younger females, and older males and older females. A post hoc analysis also found differences in corneal curvature between the younger and older males, and between the younger males and older females.

Comparisons of Four Corneal Measurement Points

The Pearson’s correlation coefficients for each parameter are shown in Table 2. At the early phase (13.2 ms after the air puff), there were significant correlations between the amount of central corneal displacement, d3, and the IOP, and between the amount of central corneal displacement, midperiphery corneal displacement, and the CCT. The amount of central, midperiphery corneal displacement, and d3 at the late phase (30.0 ms after the air puff) was correlated significantly with the corneal curvature and axial length. The degree of midperiphery corneal displacement was correlated significantly with the IOP.

Student’s t-test showed no significant differences in the amount of corneal displacement between the males and females for any of the four points and d3. However, t-tests showed significant differences in the amount of central corneal displacement and d3 between the younger and older subjects at 13.2 and 30.0 ms, and in the amount of midperiphery corneal displacement at 30.0 ms only (Table 3). The older group exhibited larger amounts of corneal displacement than the younger group.

Figure 3. Corneal displacement is defined as the distance between the initial and deformed corneal surfaces along a line parallel to the geometric axis of the eye. It was measured at 13.2 ms and 30.0 ms after application of an air puff.

Table 1. Patient Demographics

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Average</th>
<th>Range</th>
<th>Younger</th>
<th>Older</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age, y</td>
<td>43.3 (24.0)</td>
<td>20–86</td>
<td>22.1 (1.7)</td>
<td>21.8 (1.4)</td>
<td>70.7 (7.9)</td>
</tr>
<tr>
<td>N</td>
<td>61</td>
<td>18</td>
<td>15</td>
<td>16</td>
<td>12</td>
</tr>
<tr>
<td>CC, mm</td>
<td>7.74 (0.27)</td>
<td>7.21–8.55</td>
<td>7.94 (0.25)</td>
<td>7.74 (0.27)</td>
<td>7.67 (0.21)</td>
</tr>
<tr>
<td>Axial length, mm</td>
<td>24.81 (1.81)</td>
<td>22–29.11</td>
<td>26.19 (1.26)</td>
<td>25.53 (1.49)</td>
<td>25.96 (1.35)</td>
</tr>
<tr>
<td>IOP, mm Hg</td>
<td>14.46 (2.3)</td>
<td>9–19</td>
<td>14.60 (1.9)</td>
<td>14.93 (2.19)</td>
<td>14.25 (2.82)</td>
</tr>
<tr>
<td>CCT, µm</td>
<td>533.02 (33.47)</td>
<td>459–629</td>
<td>542.50 (37.82)</td>
<td>532.93 (26.58)</td>
<td>532.25 (35.41)</td>
</tr>
</tbody>
</table>

Significant differences were determined by the post hoc analysis. CC, corneal curvature.

* Significant difference for younger and older males in CC and in axial length.
† Significant difference for younger males and older females in CC and axial length.
‡ Significant difference for older males and younger females in axial length.
§ Significant difference for older males and older females in axial length.
Evaluation of Corneal Displacement

**Table 2.** Coefficients of Correlation and *P* Values for Each Factor, and Corneal Displacement Pairing by Location

<table>
<thead>
<tr>
<th>13.2 ms</th>
<th>30.0 ms</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Corneal Center (d1)</strong></td>
<td><strong>Corneal Mid-Periphery (d2)</strong></td>
</tr>
<tr>
<td>CC</td>
<td>−0.19; 0.148</td>
</tr>
<tr>
<td>Axial length</td>
<td>−0.14; 0.254</td>
</tr>
<tr>
<td>IOP</td>
<td>−0.53; &lt;0.001*</td>
</tr>
<tr>
<td>CCT</td>
<td>−0.35; 0.005*</td>
</tr>
</tbody>
</table>

* Statistically significant values.

**Independent Predictors of Corneal Displacement**

A multiple regression analysis showed that IOP (β = −3.41 ± 0.75, 95% confidence interval [CI] −4.91 to −1.90, *P* < 0.001) and CCT (β = −0.13 ± 0.1, 95% CI −0.23 to −0.02, *P* = 0.02) were predictive factors of corneal center displacement at 13.2 ms. CCT (β = −0.08 ± 0.04, 95% CI −0.15 to −0.00, *P* = 0.04) was a predictive factor of midperiphery corneal displacement at 13.2 ms. Age (β = 5.13 ± 16.48, CI 21.13–87.13, *P* < 0.01) was a predictive factor for the central corneal displacement at 30.0 ms. In addition, age (β = 30.19 ± 14.72, 95% CI 0.70–59.69, *P* = 0.04) and IOP (β = −4.92 ± 2.41, 95% CI −9.75 to −0.08, *P* = 0.04) were predictive factors for the midperiphery corneal displacement at 30.0 ms.

A multiple regression analysis showed that age (β = 7.38 ± 3.01, 95% CI 1.34–13.43, *P* = 0.018) and IOP (β = −2.76 ± 0.65, 95% CI −4.87 to −1.65, *P* < 0.001) were predictive factors of the amount of the d3 at 13.2 ms.

No predictive factor was found for the amount of the d3 at 30.0 ms.

The coefficients of the correlations between corneal displacement and these significant predictive factors are shown in Figures 4 and 5.

**Multiple Comparisons Between Sex and Age Groups by Location**

The average amount of corneal displacement at each of the four measurement points, and the amount of d3 as a function of sex and age are shown in Table 4.

Two-way unpaired ANOVA revealed that there was a significant difference in the corneal displacements in the sex × age groups (*P* < 0.001), and for the time points × measurement points (*P* < 0.001).

At 13.2 ms, the young females showed the smallest displacement at the corneal center and midperipheral cornea. However, there were no significant differences in the degree of displacement among the four groups for 13.2 ms after the air puff at the corneal center and the corneal midperiphery.

With respect to the amount of d3 at 13.2 ms, significant differences were observed between the younger females and older males, and between the younger and older males.

At 30.0 ms, the older females showed the largest amount of displacement at the corneal center and midperipheral cornea. At the corneal center, significant differences were observed between the older females and older males, older females and younger males, older and younger females, and younger and older males.

At 30.0 ms, the measurements of displacement at the midperipheral cornea indicated significant differences between the older females and older males, older females and younger males, and older and younger females.

With respect to the amount of d3 at 30.0 ms, significant differences were observed between the younger and older males, and between the younger and older females.

**DISCUSSION**

The multiple regression analyses showed that the amount of corneal displacement during tonometry using a noncontact tonometer is significantly associated with age, CCT, and IOP. The amounts of central corneal displacement (β = −5.41 ± 0.75, *P* < 0.001) measured after 13.2 ms and midperiphery corneal displacement (β = −4.92 ± 2.41, *P* = 0.04) measured after 30.0 ms were relatively lower than the amount of corneal movement in the eyes with high IOP, as has been reported previously. This means that eyes with higher IOP have higher ocular resistance against forces from outside the eyes and lower corneal displacements. If the IOP is elevated, a stronger force is needed to displace the cornea. This relationship is

**Table 3.** Corneal Displacements and *P* Values for Student’s *t*-Tests Comparing the Sex and Age Groups

<table>
<thead>
<tr>
<th>13.2 ms, μm</th>
<th>Female</th>
<th>Male</th>
<th><em>P</em> Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Younger</td>
<td>Older</td>
<td><em>P</em> Value</td>
<td></td>
</tr>
<tr>
<td>Corneal center, d1</td>
<td>24.3 (13.3)</td>
<td>33.4 (18.9)</td>
<td>0.032*</td>
</tr>
<tr>
<td>Corneal midperiphery, d2</td>
<td>2.6 (9.9)</td>
<td>2.7 (10.2)</td>
<td>0.965</td>
</tr>
<tr>
<td>Distance 3, d1–d2</td>
<td>21.7 (10.2)</td>
<td>30.7 (16.1)</td>
<td>0.010*</td>
</tr>
<tr>
<td>Male</td>
<td>Female</td>
<td><em>P</em> Value</td>
<td></td>
</tr>
<tr>
<td>Corneal center, d1</td>
<td>31.2 (17.7)</td>
<td>25.1 (14.9)</td>
<td>0.160</td>
</tr>
<tr>
<td>Corneal midperiphery, d2</td>
<td>3.5 (10.8)</td>
<td>1.6 (8.7)</td>
<td>0.456</td>
</tr>
<tr>
<td>Distance 3, d1–d2</td>
<td>27.6 (16.1)</td>
<td>23.6 (10.4)</td>
<td>0.265</td>
</tr>
</tbody>
</table>

* Statistically significant values.
reasonable and constitutes the biophysical principle of tonometry.

Earlier studies have shown that older corneas have higher ocular rigidity than younger corneas.\(^4,12\) In an experimental model that was not like the dynamic corneal deformation used in our study, Elsheikh et al. mounted corneas onto a custom-built pressure chamber and applied pressure to one side of the cornea.\(^12\) They measured the amount of displacement using a laser beam and reported that the degree of central corneal displacement was smaller in older corneas. They suggested that age-related, nonenzymatic cross-linkages among corneal proteins, which affect stromal collagen fibrils, could be responsible for the increase in rigidity that occurs with age. Malik et al. investigated the microstructure of corneas and determined that, with increasing age, there is a higher proportion of cross-sectional areas that become associated with corneal collagen and that the corneal stromal interfibrillar spacing diminishes.\(^15\)

Unexpectedly, in our study, the eyes of older individuals exhibited greater corneal displacement than those of younger

**Figure 4.** Relationship between the degree of corneal displacement and the CCT and IOP. Significant correlations were found between the degree of corneal displacement, and the CCT and IOP.
The supporting tissue of the central cornea must be sufficiently flexible to allow for such backward movement. Our result is compatible with the suggestion of Kempf et al. The whole eyeball might move backwards after receiving an air puff from the tonometer. In our results, when the IOP was higher, the midperiphery corneal displacement was smaller. The fact that eyes with a high IOP resist any backward movement suggests that the backward movement of the cornea induced by the air puff is not completely explainable by the backward movement of the entire eye. This is because soft eyes with a low IOP would absorb the pressure from the outside, and thereby show less backward movement. The degree of ocular rigidity is affected not only by corneal factors, but also by scleral factors. Albon et al. investigated the composition of human lamina cribrosa and found that, while the elastin content increased with age, the sulfated glycosaminoglycan and lipid content decreased. Changes in these scleral components then can change the rigidity of the sclera. Such changes may explain the larger amounts of corneal displacement observed in our older subjects.

The age influences the stiffness of the cornea and should be recognized even in application tonometry, which was consistent with the result of the t-test at the early phase. Spoerl et al. previously reported that the IOP should be corrected by the CCT and by an age-dependent correction factor; the effect of increasing the CCT to correct the IOP influences more strongly the results of older subjects than younger subjects. CCT has long been recognized to be a major factor associated with ocular or corneal rigidity, and has been shown to affect IOP measurements. Our multiple regression analysis findings showed that CCT influences the degree of corneal displacement in the early phase, which would support the idea that CCT can affect IOP measurements.

Our multiple regression analysis showed that sex is not a significant predictor for the amount of corneal displacement. When the measurements were obtained during the recovery phase, the degree of corneal displacement in the older females was the largest at the corneal center and midperipheral areas. The young females had the smallest values for both areas in the early and late phases. We suggest that this is because the cornea may be more susceptible to aging in females than in males; therefore, the difference between younger and older females would be larger than that for the same age groups for males. The average amount of displacement of the cornea in.

### Table 4. Corneal Displacements by Location, Sex, and Age Group

<table>
<thead>
<tr>
<th>Location</th>
<th>Average</th>
<th>Male</th>
<th>Female</th>
<th>Male</th>
<th>Female</th>
<th>Male</th>
<th>Female</th>
</tr>
</thead>
<tbody>
<tr>
<td>13.2 ms, μm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Corneal center, d1</td>
<td>28.5 (16.6)</td>
<td>27.4 (12.9)</td>
<td>20.6 (13.5)</td>
<td>35.4 (21.5)</td>
<td>30.8 (15.5)</td>
<td>31.2 (17.7)</td>
<td>25.1 (14.9)</td>
</tr>
<tr>
<td>Corneal midperiph., d2</td>
<td>2.6 (9.9)</td>
<td>5.8 (12.2)</td>
<td>-1.2 (3.5)</td>
<td>0.9 (8.8)</td>
<td>5.2 (11.8)</td>
<td>3.5 (10.8)</td>
<td>1.6 (8.7)</td>
</tr>
<tr>
<td>Distance 3 = d1 − d2</td>
<td>25.8 (13.9)</td>
<td>21.6 (9.6)†</td>
<td>21.9 (11.2)*</td>
<td>34.5 (19.5)*</td>
<td>25.6 (8.8)</td>
<td>27.6 (16.1)</td>
<td>23.5 (10.2)</td>
</tr>
<tr>
<td>30.0 ms, μm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Corneal center, d1</td>
<td>55.2 (60.3)</td>
<td>23.7 (25.1)†‡</td>
<td>15.9 (17.3)‡</td>
<td>70.9 (55.2)§</td>
<td>120.3 (75.0)†‡</td>
<td>45.9 (47.8)</td>
<td>62.3 (73.0)</td>
</tr>
<tr>
<td>Corneal midperiph., d2</td>
<td>35.1 (50.3)</td>
<td>17.1 (26.3)‡</td>
<td>6.8 (12.3)‡</td>
<td>40.3 (48.4)*</td>
<td>90.6 (66.0)*†‡</td>
<td>28.0 (39.4)</td>
<td>44.0 (61.0)</td>
</tr>
<tr>
<td>Distance 3 = d1 − d2</td>
<td>18.1 (24.9)</td>
<td>6.6 (10.4)†‡</td>
<td>9.2 (9.0)</td>
<td>30.5 (32.0)*</td>
<td>29.7 (50.8)*</td>
<td>17.9 (26.5)</td>
<td>18.5 (23.5)</td>
</tr>
</tbody>
</table>

The values are the (mean ± SD). Significant differences were determined in the post hoc analyses.

* Significant difference for younger females and older males with respect to the amount of d3 at 13.2 ms, for older males and older females at the corneal center at 30.0 ms, for older males and older females at the corneal midperiphery at 30.0 ms, and for younger males and older females with respect to the amount of d3 at 30.0 ms.

† Significant difference for younger and older males with respect to the amount of d3 at 13.2 ms.

‡ Significant difference for younger and older females at the corneal center at 30.0 ms.

§ Significant difference for younger females and older males with respect to the amount of d3 at 13.2 ms.

| Distance 3 = d1 − d2 | 25.8 (13.9) | 21.6 (9.6)† | 21.9 (11.2)* | 34.5 (19.5)* | 25.6 (8.8) | 27.6 (16.1) | 23.5 (10.2) |

The age influences the stiffness of the cornea and should be recognized even in application tonometry, which was consistent with the result of the t-test at the early phase. Spoerl et al. previously reported that the IOP should be corrected by the CCT and by an age-dependent correction factor; the effect of increasing the CCT to correct the IOP influences more strongly the results of older subjects than younger subjects. CCT has long been recognized to be a major factor associated with ocular or corneal rigidity, and has been shown to affect IOP measurements. Our multiple regression analysis findings showed that CCT influences the degree of corneal displacement in the early phase, which would support the idea that CCT can affect IOP measurements.

Our multiple regression analysis showed that sex is not a significant predictor for the amount of corneal displacement. When the measurements were obtained during the recovery phase, the degree of corneal displacement in the older females was the largest at the corneal center and midperipheral areas. The young females had the smallest values for both areas in the early and late phases. We suggest that this is because the cornea may be more susceptible to aging in females than in males; therefore, the difference between younger and older females would be larger than that for the same age groups for males. The average amount of displacement of the cornea in.

### Figure 5. Box plots of the amounts of corneal displacement in the different age groups. A significant difference was found by the t-test between younger and older subjects in the amount of d3 at 13.2 ms, and in the central and midperiphery corneal displacement at 30.0 ms.
the young and older females was similar to that observed in the males. Therefore, any sex differences that may have been significant predictors would have been difficult to detect using Student’s t-test and a multiple regression analysis.

The question, then, is what causes this sex difference? One explanation may be differences in the levels of sex hormones, as androgen, estrogen, and progestrone receptors have been identified in the human cornea, conjunctiva, and lacrimal glands.22 Corneal structure and rigidity have been found to exhibit sexual dimorphism, and this difference has been attributed in part to the effects of sex hormones.23,24 The mean age of the older females (65.7 ± 7.3) was older than the usual age of menopause. Hormonal changes may have caused greater changes in corneal displacement in this group. The differences in the radius of the corneal curvature and the axial length between the sexes might have had some effect on this result. However, our results showed that sex did not influence the IOP measurements in the early phase; therefore, it is not necessary to consider the sex of the patient as a factor affecting the IOP readings.

Displacement of the central cornea is characterized by applanation of the central cornea and backward movement of the entire cornea. Central corneal displacement minus midperipheral corneal displacement indicates the real amount of corneal flattening (d3). The value of d3 is influenced by age, but not sex. This means that an aging effect in central corneal movement is prominent and a sex effect appears in whole corneal backward movement.

Another useful instrument to investigate the ocular rigidity using dynamic corneal deformation is the Ocular Response Analyzer (ORA; Reichert Ophthalmic Instruments, Depew, NY). The ORA is a more advanced version of a noncontact applanation tonometer, and provides new biomechanical parameters: the corneal hysteresis (CH) and the corneal resistance factor (CRF). The CH is believed to reflect the damping properties of the cornea compatible with a shock absorber, which is influenced by the viscosity of the ground substance (reflecting the glycosylation of proteoglycans and glycosaminoglycans), and the CRF is believed to indicate the total resistance of the cornea to deformation.25

The facts that the CH and the CRF were decreased significantly with age26 were compatible with our results showing that aging decreased the viscosity of the eyeball and the resistance to outer pressure, which caused a larger corneal displacement in older subjects at the 30.0 ms time point. Furthermore, the fact that the thicker CCT causes higher CH and CRF values, while the axial length and sex have no significant effects on the CH and CRF also supports our results.26

Our study is associated with some limitations. First, our data were acquired from a relatively small sample, which partly was due to the difficulty in photographing the superior and inferior cornea due to the narrow eyelids and eye lashes. Second, the factors that were found to be associated significantly with ocular rigidity overlap and are not truly independent. For example, IOP values are correlated with axial length and CCT.5,7 This weak point may be due to the fact that we cannot measure the true IOP using our noninvasive method. Third, the factors of age and sex are not biomechanical properties. Therefore, they may not be appropriate to explain the biomechanical behavior. However, they can be surrogates for biomechanical properties. The biochemical changes may be able to explain the corneal displacement directly. However, we do not have any arms in our system to evaluate the biochemical properties in the living human eye noninvasively.

In conclusion, we measured the amount of corneal displacement by photographing the corneal profile with a high-speed camera during noncontact tonometry. We analyzed the amount of corneal displacement at the center and midperiphery of the corneal surface in the early inversion and late recovery phases. During the former phase, the IOP levels and CCT significantly affected the degree of corneal displacement, while during the latter phase, the IOP levels and age had significant effects on the degree of corneal displacement.

Among the different sex and age groups, the younger females exhibited the smallest displacement and the older females exhibited the largest displacement at the late phase. Therefore, corneal rigidity may be more susceptible to aging in females than in males.

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