The Shape of Posterior Corneal Surface in Normal, Post-LASIK, and Post–epi-LASIK Eyes

Lin Zhang and Yan Wang

PURPOSE. To evaluate the shape of the posterior corneal surface in eyes with normal myopia or myopic astigmatism and the changes after LASIK and epi-LASIK.

METHODS. A total of 152 eyes were included in the study. The posterior corneal elevation was measured with Scheimpflug imaging (Pentacam; Oculus, Wetzlar, Germany), before LASIK or epi-LASIK and at 1 and 6 months after surgery, along the four optical zones (center and 2-, 4-, and 6-mm diameters) as a function of the meridian.

RESULTS. In normal eyes, the heights were lower in the vertical meridian than in the horizontal meridian and were also lower in the superior hemisphere than in the inferior hemisphere. In post-LASIK eyes, almost all regions protruded 1 month after surgery, except for the 6-mm diameter, which exhibited a slight but not significant (P = 0.703) backward displacement. The various elevations returned to original levels 6 months after LASIK. In the post–epi-LASIK group, there was a significant backward displacement in the center and 2-mm regions after surgery. Moreover, there was no shift at the 4-mm diameter, and the 6-mm diameter showed a progressive forward shift.

CONCLUSIONS. The shape of the normal posterior corneal surface exhibited obvious regional disparities and radial asymmetry. The displacement after LASIK was observed as time-dependent changes that protruded at an early stage but then returned to original levels 6 months after surgery. On the other hand, the displacement after epi-LASIK appeared as region-dependent changes that could be divided into central and peripheral parts that displayed backward and forward shift trends, respectively.

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In recent years, the evolution of modern corneal refractive surgery has refocused attention on the biological properties of the cornea, because an adequate understanding of the corneal shape and its natural variations is important for designing and evaluating corneal refractive surgeries as well as in detecting such corneal diseases as keratoconus at an early stage. It is well known that the radius is not constant over the corneal surface, as the peripheral cornea is aspheric, and the radius of curvature changes from the center to the limbus and does so at different semimeridians.1,2 Thus, more accurate data on the shape of the cornea are needed. Traditionally, only the topography of the anterior corneal surface has been described.3 Accurate data on the shape of the posterior surface of the cornea have been rather insufficient, despite the considerable contribution of the posterior surface to total corneal power.4–10 The posterior corneal surface compensates for 31%11 of the anterior corneal surface astigmatism and has a significant effect on the spherical aberration of the cornea.12 On the other hand, there are two main disadvantages in describing the posterior corneal surface by using existing studies. First, early investigations of corneal topography were confined to gross estimates of the corneal curvature, which has limitations in reconstructing the corneal surface.13 The axial curvature (global or sagittal curvature) is a referenced parameter that has been used to measure the curvature at a certain point on the corneal surface in the axial direction relative to the center. As a result, the same shape can have many different curvatures based on which axis is used to make the measurement. Instantaneous curvature data (local or tangential curvature) are highly sensitive to local changes in shape.14 The curvature is usually not measured directly and must be calculated from axial power by taking a derivative, and so the values may exaggerate the noise. Also, the data do not allow direct visualization of the overall corneal location.15 The shape of the posterior surface can also be expressed in micrometers as the elevation of the actual surface relative to a chosen reference surface (best-fit-sphere [BFS]). The BFS has led to a better understanding of the surface created from the x, y, and z coordinates of the usual representation of data in a 3-D world.16 Furthermore, data measured in elevation are of particular value in corneal excimer laser surgeries, where the outcome is determined by the depth of tissue removed. The second disadvantage has to do with the regional selection, because most previous studies focused on the central cornea or gave a small number of meridians. As a result, information may have been lost during the calculations.

After the widespread acceptance of surgical correction of refractive errors,17–20 there have been increasing reports of central posterior corneal ectasia after surgery. However, to the best of our knowledge, most published reports that showed posterior elevation increases were based on topography measurements (Orbscan II; Bausch & Lomb, Tampa, FL) and the accuracy of assessing the posterior corneal measurement has been questioned.20–22 Recently a Scheimpflug imaging–based commercial device, the Pentacam (Oculus GmbH, Wetzlar, Germany) has become available. This system allows for calculation of posterior corneal elevation without mathematical reconstruction.23 The earlier studies with Pentacam have shown no significant changes in the posterior surface of the cornea after refractive surgery.24–31 The results of posterior corneal elevation changes with Pentacam are summarized in Table 1.

In this study, we presented measurements of the topography by using Pentacam and created a detailed reference database that can be used to determine the shape of the posterior corneal surface in normal myopia and myopic astigmatism. Furthermore, we retrospectively studied the data on posterior
TABLE 1. Published Posterior Corneal Elevation Changes after Refractive Surgery with Pentacam\(^*\)

<table>
<thead>
<tr>
<th>Source</th>
<th>n</th>
<th>Surgery</th>
<th>Mean ± SD (µm)</th>
<th>Range (µm)</th>
<th>Follow-up Period</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ciolino and Belin(^{24})</td>
<td>103</td>
<td>LASIK</td>
<td>2.64 ± 4.95</td>
<td>−12 to +14</td>
<td>4−8 weeks</td>
</tr>
<tr>
<td></td>
<td>18</td>
<td>PRK</td>
<td>0.88 ± 4.64</td>
<td>−7 to +10</td>
<td>4−8 weeks</td>
</tr>
<tr>
<td>Ciolino et al.(^{25})</td>
<td>102</td>
<td>LASIK</td>
<td>0.47 ± 3.48</td>
<td>−7 to +10</td>
<td>13.6 mo (8.8−19.3 mo)</td>
</tr>
<tr>
<td>Hashemi and Mehravaran(^{26})</td>
<td>46</td>
<td>LASIK</td>
<td>0.87 ± 6.18</td>
<td>−21 to +13</td>
<td>6 weeks</td>
</tr>
<tr>
<td>Vicente et al.(^{28})</td>
<td>10</td>
<td>LASIK</td>
<td>2 ± 4</td>
<td>−9 to +24</td>
<td>11 wk (4−22)</td>
</tr>
<tr>
<td></td>
<td>24</td>
<td>Enhancement</td>
<td>5 ± 6</td>
<td></td>
<td>11 wk (4−22)</td>
</tr>
<tr>
<td>Pérez-Escudero et al.(^{29})</td>
<td>27</td>
<td>LASIK</td>
<td>&lt;8</td>
<td></td>
<td>1.3, 10.8, and 33.4 d</td>
</tr>
<tr>
<td>Ha et al.(^{30})</td>
<td>19</td>
<td>PRK</td>
<td>4.60 ± 4.43</td>
<td></td>
<td>1–3 mo</td>
</tr>
<tr>
<td></td>
<td>17</td>
<td>PRK, LASIK</td>
<td>4.55 ± 4.01</td>
<td></td>
<td>5–13 mo</td>
</tr>
<tr>
<td>Sun et al.(^{31})</td>
<td>30</td>
<td>PRK, LASIK</td>
<td>0.47 ± 4.25</td>
<td>−8 to +9</td>
<td>2.21 ± 1.12 mo</td>
</tr>
</tbody>
</table>

* Oculus GmbH, Wetzlar, Germany.

The posterior corneal elevation was defined by the maximum forward protrusion of the posterior cornea above the BFS in the central 3.0- to 4.0-mm zone of topography. An ectatic change, the forward protrusion of the posterior corneal surface is indicated by a positive number.

corneal elevation changes after LASIK and epi-LASIK and evaluated the changes along four optical zones (center and 2-, 4-, and 6-mm diameters).

METHODS

Subjects

A total of 78 subjects (152 eyes) were recruited at the Tianjin eye hospital, Tianjin Medical University. Experimental protocols were approved by an Institutional Review Board and complied with the tenets of the Declaration of Helsinki. Informed consent was obtained from each subject after a thorough discussion of the benefits and known risks of the procedure. One hundred fifty-two eyes, 75 right and 77 left eyes, had either normal myopia or myopic astigmatism before surgery. Twelve subjects (23 eyes) were recruited for the epi-LASIK group. These subjects had an average age of 25 ± 5 years and an average spherical equivalent (MRSE) of −1.32 D. All surgical procedures were performed with topical anesthesia. An excimer laser treatment was performed in the usual manner with the same nomogram and laser system as was used in LASIK, but with an additional eye-tracking device. A bandage contact lens was placed on the surgically treated eye.

After surgery, topical ofloxacin 0.3% combined with 0.1% fluorometholone was applied four times daily for 1 month and then tapered over 4 months in the epi-LASIK group. In the LASIK group, it was applied four times daily for 1 week and then tapered over 1 month.

Pentacam Scheimpflug Imaging

All patients were imaged with the Pentacam (software ver. 1.17\(^{27}\), Oculus GmbH) in both eyes before surgery, as well as at 1 and 6 months after LASIK or epi-LASIK. The Pentacam is a rotating Scheimpflug camera that measures 25,000 true elevation points to compute the corneal topography. Some studies have explored the reliability of this device in measuring the anterior segment.\(^{32−35}\) According to the manufacturer, this device provides quantitative information about the posterior cornea, as it automatically compensates for the optical and geometric distortion of the system. Furthermore, validation of the accuracy of this system in measuring the posterior cornea has been shown previously.\(^{36}\) Patients were asked to blink twice and then look at the fixation device. Image acquisition was a 1-second scan of 25 rotational Scheimpflug images through the corneal sighting point, which is the point where the ray of light from the fovea to the fixation device crosses the cornea. All measurements were performed just after a blink, to minimize the effect of tear film alteration on the data. Acceptable maps had at least 10.0 mm of corneal coverage with no extrapolated data in the central 9.0-mm zone. Extrapolated data are indicated by black dots on the color topographic map.

Data Collection and Analysis

In this study, data on corneal posterior elevation were obtained from the Pentacam software. The reference BFS was determined by the

### Table 2. The Measured Parameters in the Normal, LASIK, and Epi-LASIK Groups

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Normal (n = 152)</th>
<th>Range</th>
<th>Mean ± SD</th>
<th>Range</th>
<th>Mean ± SD</th>
<th>Range</th>
<th>Mean ± SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>SE, D</td>
<td>7.75 to 0.00</td>
<td>−4.49 ± 1.26</td>
<td>−7.75 to −2.25</td>
<td>−4.73 ± 1.17</td>
<td>−6.75 to 0.00</td>
<td>−4.22 ± 1.32</td>
<td></td>
</tr>
<tr>
<td>CE, D</td>
<td>−3.00 to 0.00</td>
<td>−0.69 ± 0.61</td>
<td>−3.00 to 0.00</td>
<td>−0.60 ± 0.63</td>
<td>−3.00 to 0.00</td>
<td>−0.78 ± 0.58</td>
<td></td>
</tr>
<tr>
<td>MBSE, D</td>
<td>−9.00 to −1.50</td>
<td>−4.84 ± 1.30</td>
<td>−9.00 to −2.38</td>
<td>−5.03 ± 1.30</td>
<td>−7.25 to −1.50</td>
<td>−4.65 ± 1.27</td>
<td></td>
</tr>
<tr>
<td>CCT, µm</td>
<td>481 to 621</td>
<td>538.60 ± 29.70</td>
<td>481 to 621</td>
<td>555.56 ± 24.74</td>
<td>481 to 593</td>
<td>520.25 ± 24</td>
<td></td>
</tr>
<tr>
<td>AD, µm</td>
<td>22 to 98</td>
<td>68.04 ± 13.67</td>
<td>40 to 98</td>
<td>72.22 ± 13.56</td>
<td>22 to 86</td>
<td>63.52 ± 12.36</td>
<td></td>
</tr>
<tr>
<td>RBT, µm</td>
<td>—</td>
<td>—</td>
<td>277 to 445</td>
<td>373.34 ± 29.58</td>
<td>403 to 545</td>
<td>456.73 ± 26.17</td>
<td></td>
</tr>
</tbody>
</table>

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central 8.0-mm zone of the preoperative cornea (i.e., the BFS for both
preoperative and postoperative maps were identical and were deter-
moved from the preoperative data), so that it was the same across all
examinations. The corneal posterior elevation and changes were ob-
tained at the center, paracenter (4 points, 1 mm from the center, at
45°, 135°, 225°, and 315° semimeridians), midperiphery (8 points, 2
mm from the center at 0°, 45°, 90°, 135°, 180°, 225°, 270°, and 315°
semimeridians), and peripheral regions (14 points 3 mm from the
center at 15°, 45°, 60°, 90°, 120°, 135°, 165°, 195°, 225°, 245°, 270°,
295°, 315°, and 345° semimeridians). In all mathematical analyses, we
set 0° at a point on the right and moved counterclockwise in both eyes.
All these points were divided symmetrically into superior and inferior
hemispheres by the 0° to 180° meridian, with the exception of the
center values. Changes in the posterior surface were determined by
subtracting the preoperative elevation data from the postoperative
elevation data (difference map). The difference in elevation was deter-
moved to be the displacement of the posterior corneal surface. An
ectatic change (forward protrusion of the posterior corneal surface)
would result in a positive number.

**Statistical Analysis**

Descriptive statistical results included the mean, standard deviation,
and minimum and maximum values. The normality of all data samples
was checked with the Kolmogorov-Smirnov test. Parametric statistics
were then applied subsequently. The Student *t*-test for paired data was
used to compare data from the right and left eyes as well as from
superior and inferior hemispheres in different optical zones (center and
2-, 4-, and 6-mm diameters). Mauchly’s test of sphericity was used
before comparing the preoperative corneal posterior elevations with
those at 1 and 6 months after surgery. However, because
\( P < 0.05 \), we used the paired-sample *t*-test to perform these comparisons. For biva-
rate correlation analysis, the Pearson correlation coefficient was used
in all right eyes because of the bilateral symmetry. \( P < 0.05 \) was
considered statistically significant (SPSS, ver. 13.0 for Windows; SPSS,
Chicago, IL).

**RESULTS**

**Normal Myopia and Myopic Astigmatism**

Figure 1 shows the variations in posterior corneal elevations in
various optical zones (center and 2-, 4-, and 6-mm diameters) in

<table>
<thead>
<tr>
<th>District</th>
<th>Mean ± SD (μm)</th>
<th>Range (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Center</td>
<td>1.09 ± 2.56</td>
<td>−4.00–8.00</td>
</tr>
<tr>
<td>2 mm</td>
<td>1.79 ± 3.09</td>
<td>−7.00–11.00</td>
</tr>
<tr>
<td>4 mm</td>
<td>0.41 ± 8.92</td>
<td>−40.00–22.00</td>
</tr>
<tr>
<td>6 mm</td>
<td>−3.82 ± 15.44</td>
<td>−55.00–88.00</td>
</tr>
</tbody>
</table>
both normal myopia and myopic astigmatism as a function of the meridian. The height data on 2-mm diameter rarely deviated from the BFS, and it was slightly lower in the superior than in the inferior hemisphere. From the midperipheral and peripheral elevation distributions, the geometric trend began to change and appeared to have two dips lower than the BFS (the first one occurred at 90° and the second at 270°). Furthermore, the posterior elevation was below the BFS along the vertical meridian but was raised off the BFS along the horizontal meridian (4 mm, vertical, 8.78 ± 8.90 μm; horizontal, 8.07 ± 4.70 μm; t = 25.840, P = 0.000; 6 mm, vertical −22.27 ± 11.38 μm; horizontal 9.69 ± 9.50 μm; t = 31.262, P = 0.000).

In addition, a general trend was observed by comparing between the superior and inferior hemispheres in various optical zones (2-, 4-, and 6-mm diameters). The height of the superior hemisphere was significantly lower than that of the inferior hemisphere on the basis of the deviation from the BFS (2 mm, superior 0.80 ± 2.83 μm, inferior 2.78 ± 3.01 μm; t = −7.609, P = 0.000; 4 mm, superior −2.42 ± 10.00 μm, inferior 3.25 ± 6.57 μm; t = −15.188, P = 0.000; 6 mm, superior −16.82 μm, inferior −0.42 ± 13.06 μm; t = −24.563, P = 0.000). In fact, the geometric characteristic became more obvious as the distance increased from the center. Furthermore, there were no significant differences between the right and left eyes on normal posterior corneal elevations in the various optical zones (center, P = 0.162; 2 mm, P = 0.507; 4 mm, P = 0.071; 6 mm, P = 0.280).

Figures 2 and 3 show the mean and SD for the posterior corneal elevation as a function of optical zone (center and 2-, 4-, and 6-mm diameters) in eyes with normal myopia or myopic astigmatism. As shown in Figure 2, the normal posterior corneal elevation was above the BFS in the central zone, but below it in the peripheral region. The value (as well as the degree of deviation from the BFS) gradually increased to 2 mm from the center and then declined toward the 4-mm diameter (to the point of being negative in the periphery; Fig. 3). The most significant variance occurred in the 6-mm diameter optical zone, where the average standard deviation (±SD) was ±15.44 μm (range, −55.00 to −88.00 μm). The quantitative values of normal posterior corneal elevations in the various optical zones (center and 2, 4, and 6 mm) are displayed in Table 3.

### Laser In Situ Keratomileusis

As seen in Figure 4, the posterior elevation in the various optical zones (center and 2, 4, and 6 mm) essentially showed similar values before LASIK, as well as at 1 and 6 months after surgery as a function of the meridian. Meanwhile, the degree of posterior elevation, when displayed as a function of the optical zones (center and 2, 4, and 6 mm) before surgery as well as at 1 and 6 months after surgery, showed some changes after the procedure. Except for the 6-mm optical zone, where it exhibited a slight but not significant (P = 0.731) backward displacement, the posterior elevation in almost all points protruded slightly 1 month after surgery (Fig. 5; Table 4). Significant differences were found in the paracentral (2 mm, P = 0.044) and midperipheral (4 mm, P = 0.002) areas between the preoperative period and 1 month after surgery. However, the
the period of observation (4 mm, riphenral posterior corneal elevation did not change throughout the pre- and postoperative periods (center, posterior elevation in the center and paracentral areas between the meridians). However, it returned to its original level 6 months after LASIK.

The posterior elevation of the corneal surface in every position eventually returned to the original levels, and no significant differences were found in the posterior elevation in any position between the preoperative period and 6 months after LASIK (center, $P = 0.351$; 2 mm, $P = 0.485$; 4 mm, $P = 0.157$; 6 mm, $P = 0.110$).

Epi-LASIK

The posterior surface in various optical zones (center and 2, 4, and 6 mm) was constant as a function of the meridian, even after epi-LASIK (Fig. 6). However, the posterior elevations (Fig. 7, Table 5), as a function of location (center and 2, 4, and 6 mm), showed significant backward displacement of the posterior elevation in the center and paracentral areas between the pre- and postoperative periods (center, $P = 0.008$, $P = 0.000$; 2 mm, $P = 0.011$, $P = 0.000$). Meanwhile, the level of midperipheral posterior corneal elevation did not change throughout the period of observation (4 mm, $P = 0.370$, $P = 0.076$), and the periphery showed a distinct progressive forward shift (6 mm, $P = 0.018$, $P = 0.011$).

Correlations

The Pearson correlation test showed no significant correlation between the changes in the posterior corneal surface data and the MRSE, central corneal thickness (CCT), ablation depth (AD), and residual bed thickness (RBT) at 1 and 6 months after surgery.

DISCUSSION

In recent attempts to measure the posterior corneal surface, the radius of curvature has been extensively measured on the basis of size and location by using various techniques such as Purkinje imagery, pachymetry, and Scheimpflug photography. However, in this study we initially described the posterior corneal shape by using another parameter—elevation—which is independent of the axis or orientation and the reference surface. It is therefore more accurate in corneal surface reconstruction. Moreover, we initially tested our posterior surface separately at various diameters including 0, 2, 4, and 6 mm. From the database of the corneal posterior shapes that we have set up, four characteristics emerged: (1) the shape of the posterior surface exhibited more toricity and complexity than previously assumed, since the elevation was not constant over the corneal surface (neither along the diameters nor the meridians) but instead had some discernible regularity. In fact, Dunne et al. also found that the posterior surface exhibited more toricity than the anterior surface, and Dubbelman et al. recently reported that the radius of curvature for both corneal surfaces could be well fitted by using the $\cos^2$ function, which is periodic. (2) The height data appeared to be different between the vertical meridian and the horizontal meridian. This result was not surprising, given that the difference may be related to the higher incidence of with-the-rule astigmatism in young adults in whom an average cornea is mostly steeper in the vertical meridian by approximately 0.5 D compared with the horizontal meridian. In addition, some previous studies have demonstrated a difference in the vertical and horizontal corneal radii of individual subjects. Hirji and Larke and Rüfer et al. found that the peripheral cornea was thicker vertically than horizontally, which could explain the discrepancy to some extent. (3) The elevation of the superior hemisphere was significantly lower when compared with that of the inferior hemisphere, a trend that was more obvious in the peripheral cornea. To explain this phenomenon, Kasprzak and Pierścionek proposed a model of the gravitational sag of the cornea and showed that the upper eyelid may have a certain degree of influence. It was intriguing that this geometry characteristic appeared to share similar regional specificity with the inherent cohesive weakness found by Smolek, who noted that the mean cohesive strength in the

**Table 4. Posterior Elevations in Various Optical Zones after LASIK**

<table>
<thead>
<tr>
<th>District</th>
<th>Preop</th>
<th>1 mo</th>
<th>6 mo</th>
<th>$P$ (Preop-1 mo)</th>
<th>$P$ (Preop-6 mo)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Center</td>
<td>0.90 ± 2.53</td>
<td>1.92 ± 4.20</td>
<td>0.33 ± 4.48</td>
<td>0.094</td>
<td>0.351</td>
</tr>
<tr>
<td>2 mm</td>
<td>1.73 ± 1.60</td>
<td>2.69 ± 3.22</td>
<td>1.40 ± 3.71</td>
<td>0.044*</td>
<td>0.485</td>
</tr>
<tr>
<td>4 mm</td>
<td>0.54 ± 1.34</td>
<td>1.39 ± 1.82</td>
<td>0.92 ± 4.47</td>
<td>0.002*</td>
<td>0.157</td>
</tr>
<tr>
<td>6 mm</td>
<td>−3.70 ± 2.56</td>
<td>−3.86 ± 3.17</td>
<td>−2.91 ± 3.36</td>
<td>0.731</td>
<td>0.110</td>
</tr>
</tbody>
</table>

Data are expressed as mean micrometers ± SD.

* Analyzed by $t$-test for paired samples ($P < 0.05$).
inferior periphery was significantly less than the strength in the superior periphery. Since the ultimate determinants for corneal shape were the structural elements of the tissue itself and the magnitude and direction of forces distributed within the load-bearing structures, the unequal cohesive strength distribution is likely to have played a role to some extent. (4) There was the same tendency in the posterior corneal surfaces of the right and left eyes with regard to different evaluated diameters and meridians. Bilateral symmetry occurred in almost all the eyes, which may indicate that the Pentacam is a reliable technique for the posterior corneal surface and, consequently, for elevation measurements.

In the postoperative groups, we compared the mean changes in posterior corneal elevation changes after LASIK and epi-LASIK along four optical zones. Although the slight forward displacements in posterior corneal elevation at the 2- and 4-mm diameters (2 mm, 1.73 ± 1.60 µm; 4 mm, 0.54 ± 1.34 µm) 1 month after LASIK were statistically significant ($P = 0.044; P = 0.002$), the values were within the manufacturer’s reported range of error (±5 µm) for the Pentacam and were therefore below the sensitivity of the instrument. Moreover, the changes after LASIK and epi-LASIK are all within the measurement noise of the device. Ciolino and Belin26 studied posterior corneal changes after LASIK and photorefractive keratectomy (PRK) with a Pentacam and found no posterior corneal ectasia in either group, which was consistent with our results.

In this study, we showed a systematic and characteristic response of the posterior surface to LASIK that was related to the biomechanical and wound-healing responses as a function of time and space. In most areas, the posterior corneal elevation exhibited forward protrusion 1 month after surgery, but this occurrence tended to be stable and returned to its original level 6 months after surgery. Such time-dependent changes agree with the findings of Pérez-Escudero et al.,30 who detected a change in the radius of curvature and asphericity of

**Figure 6.** Posterior elevation in the various optical zones (center and 2, 4, and 6 mm) in the preoperative period and 1 and 6 months after epi-LASIK as a function of the meridian. The posterior surface in various optical zones (center, and 2, 4, and 6 mm) was constant as a function of the meridian, despite epi-LASIK.

**Figure 7.** Posterior elevation in the various optical zones (center and 2, 4, and 6 mm) in the preoperative period and 1 and 6 months after epi-LASIK as a function of the various optical zones. Triangle: preoperative value; square: 1 month after surgery; circle: 6 months after surgery.
the posterior corneal surface at the first day after surgery, but noted that the changes disappeared on a timescale of days to weeks. We suspect that these postsurgical changes may be relevant to the process of wound healing after LASIK, since previous studies have shown that LASIK corneal wounds remain in the active wound-healing stage for up to the first 6 months after surgery and then enter the wound-remodeling stage.\textsuperscript{43,44} LASIK produced circumferential severing of corneal lamellae resulting in a forward herniation at a very early stage after surgery, but in the wound-remodeling stage, chronic biomechanical changes and complete fibrotic and primitive wound healing would improve the corneal transparency and wound strength. Thus, changes in the posterior corneal elevation at a region with a 6-mm diameter showed a backward shift at the beginning and then a forward displacement 6 months after surgery. Other studies have accounted for this by demonstrating that fibrotic wound repair after LASIK was restricted to a narrow band peripheral to the corneal flap edge,\textsuperscript{45} causing disordered morphology and deflection of the optical paths. LASIK thus represents a particularly complex situation that could lead to time-dependent changes in areas surrounding the cornea as well as in the underlying flap.

An interesting finding from this study was that epi-LASIK had posterior elevation changes with a progressive backward shift at all follow-up time points in both the central and para-centric regions. However, a 4-mm diameter ring positioned between the central part and the periphery marked the division of the posterior elevation after epi-LASIK into two parts, creating a boundary between the backward shift and the forward shift. The cause of this feature is unclear to us. The phenomenon may be related to the hyperopic shift model, as demonstrated by Dupps and Roberts\textsuperscript{46} during photo-therapeutic keratectomy (PTK), in which a depth-dependent ablation flattening was observed in the donor. Because of the swelling and thickening of the peripheral stromal surface immediately after surgery, flattening of the optical surface occurs, resulting in hyperopic shift. On the other hand, there may be some noise in the actual measurement or during the wound-healing responses that may constitute a measurement bias. In particular, keratocyte apoptosis, keratocyte proliferation, and myofibroblast generation over the central cornea in epi-LASIK could all amplify the wound-healing response and possibly account for variations in measurement accuracy.

Moreover, there was no significant correlation between the elevation changes and residual bed thickness. It is likely that the changes became more obvious when current acceptable standards were not followed (RBT < 250 μm).\textsuperscript{17} Our study was limited, in that no patient had an estimated RBT below 270 μm, and the deepest AD was 98 μm in the LASIK group.

Along with the findings of this study, more experimental data on corneal optical and biomechanical properties and more accurate models of corneal biomechanics should be studied to provide better explanations of the changes in corneal shape as a response to LASIK and advanced surface ablation procedures.

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**References**


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