The Contribution of the Posterior Surface to the Corneal Aberrations in Eyes after Keratoplasty

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PURPOSE. To investigate the contribution of posterior corneal surfaces to higher-order aberrations (HOAs) of the cornea, optical quality, and visual acuity after keratoplasty.

METHODS. Corneal topography of anterior and posterior surfaces and pachymetry were conducted using anterior segment optical coherence tomography (AS-OCT) in 40 eyes (10 eyes after penetrating keratoplasty [PK], 10 eyes after deep anterior lamellar keratoplasty [DALK], 10 eyes after Descemet’s stripping automated endothelial keratoplasty [DSAEK], and 10 normal eyes). Anterior, posterior, and total corneal HOAs were calculated using ray-tracing and decomposition into Zernike polynomials and were evaluated as root mean square values. Modulation transfer functions (MTFs) were also evaluated.

RESULTS. Topography maps of the anterior and posterior surfaces showed reverse patterns in the normal, PK, and DALK eyes, but not in DSAEK eyes. In the normal, PK, and DALK eyes, the total corneal HOAs were significantly smaller (10%) than were the HOAs of the anterior surface (P < 0.01), whereas there was no significant difference between total and anterior HOAs in the DSAEK eyes (P = 0.483). In the normal, PK, and DALK eyes, the MTFs of the total cornea were slightly better than those of the anterior surface. In the DSAEK eyes, the MTFs of the total cornea were lower than those of the anterior surface. Visual acuity was significantly correlated with total and anterior surface HOAs (P < 0.05).

CONCLUSIONS. Posterior surfaces compensate for anterior aberrations in normal, PK, and DALK eyes. In DSAEK eyes, the posterior surface increased total corneal HOAs and had a negative influence on MTFs. (Invest Ophthalmol Vis Sci. 2011;52:6222–6229) DOI:10.1167/iovs.11-7647

With the advances in surgical techniques and instruments, lamellar keratoplasty has become less invasive and more sophisticated by removing only the pathologic parts and retaining healthy portions of the patient’s cornea.

Anterior lamellar keratoplasty (ALK) has an advantage over conventional penetrating keratoplasty (PK), in that it retains the patient’s endothelial cells, which decreases endothelial graft rejection.1–3 Descemet’s stripping automated endothelial keratoplasty (DSAEK) offers rapid visual recovery and has less irregular astigmatism and superior biomechanical properties and integrity.1–6 Although the number of lamellar surgeries has increased in corneal transplantation, the postoperative visual acuities are sometimes poor, despite the success of surgery.7 Lamellar opacity has been reported to be one of the reasons for poor improvement in visual acuity.8 We previously reported that visual acuity after DSAEK correlated significantly with the irregular astigmatism of the anterior surface, but not with that of the posterior surface.9 The previous reports evaluated spherical power, astigmatism, and irregular components of the anterior and posterior surfaces separately and demonstrated that anterior and posterior corneal surfaces compensate for each other in normal and keratoconic eyes, and in eyes after keratoplasty.9–16 We hypothesized that these lamellar keratoplasties, that is, ALK with only anterior surface replacement and DSAEK with only posterior surface replacement, can degrade the optical quality of the eye due to the lack of physiological parallelism of the anterior and posterior surfaces. However, the effect of the disruption of this parallelism on the HOAs of the whole cornea remains unknown because of the difficulty in calculating it. One question is, to what extent does the posterior surface compensation contribute to the total corneal HOAs in eyes after corneal transplantation. Moreover, it has been difficult to measure HOAs of the whole eye after keratoplasty with conventional aberrometers, such as Shack-Hartmann wavefront sensors, due to the highly irregular cornea.17–19 In this study, we investigated the influence of corneal posterior surface on optical quality of the total cornea and visual acuity in normal eyes and eyes after PK, deep ALK (DALK), and DSAEK using a ray tracing method in combination with AS-OCT.

METHODS

Subjects

This prospective study included 10 normal eyes and 30 consecutive eyes of 30 patients who underwent PK (n = 10 eyes), DALK (n = 10), and DSAEK (n = 10) at Tokyo Dental College. Only one eye of each subject was used. The detailed characteristics are shown in Table 1. None of the normal control eyes had ocular disorders except for refractive errors. The indications for PK included corneal stromal opacity (n = 6 eyes), keratoconus (n = 2), and bullous keratopathy (n = 2). The indications for DALK included corneal stromal opacity (n = 7 eyes), lattice dystrophy (n = 2), and keratoconus (n = 1). DSAEK was performed for the treatment of bullous keratopathy in 10 eyes of the DSAEK group. Although postoperative logarithm of minimal angle resolution (logMAR)
tended to be better after DSAEK than after PK and DALK, there were no statistically significant differences between the groups (Kruskal-Wallis test, \( P = 0.5227 \)). All surgeries were performed in standard ways by one experienced surgeon (JS) from August 2009 to July 2010. The exclusion criteria included corneal scar or opacity in the graft, persistent epithelial defect, severe dry eye or ocular cicatricial diseases, graft rejection, pterygium, previous glaucoma surgery, and retinal diseases. The research complied with the Declaration of Helsinki. The institutional Review Board of Tokyo Dental College approved this study. Informed consent was obtained from all participants after the purpose of the study was explained to them.

Keratoplasty Surgery

We performed keratoplasty (PK, DALK, and DSAEK) according to our standard techniques, as previously published.\(^9\)\(^,\)\(^18\)\(^,\)\(^19\) They are explained briefly here.

PK was performed under retrobulbar anesthesia. The donor button was cut with a Barron punch trephine (diameter, 7.75 mm in all eyes). The recipient bed was 7.5 mm in all cases. A Hesse-Barron suction trephine was used to cut a partial-depth, circular incision in the cornea, centered at the geometric center of the cornea. Excision of the recipient corneal button was completed with curved corneal scissors. The graft was sutured in place with a single-running 10-0 nylon suture with 24 bites in all eyes.

DALK was performed with the double-bubble technique, in eyes under retrobulbar anesthesia.\(^1\(^8\)\(^,\)\(^19\) After a superficial 7.5 mm-diameter trephination with Hesse-Barron suction trephine, superficial keratectomy was performed. After injection of air into the anterior chamber, air was injected into the deep stroma using a 27-gauge needle, creating a large bubble in the supra-Descent membrane space. After removing the residual deep stroma, the 7.75-mm graft was sutured in place with a single-running 10-0 nylon suture with 24 bites in all eyes.

DSAEK was performed through a 5.0-mm cleomeoscleral temporal incision after administering sub-Tenon’s anesthesia. Descemet stripping was performed for a diameter of 8.0 mm, and the recipient’s endothelium and Descemet’s membrane were carefully removed with forceps. A precut donor was trephinated at a size of 8.0 mm and was gently inserted into the anterior chamber using forceps and a Busin glide spatula. Air was carefully injected into the anterior chamber to unfold the graft. Ten minutes after the air injection, most of the air was replaced with balanced salt solution (BSS; Alcon, Fort Worth, TX).

Corneal Topography Using OCT

The participants’ eyes were examined using three-dimensional AS-OCT (SS-1000, CASIA: Tomey, Nagoya, Japan) 6 months after keratoplasty. In all the PK and DALK eyes, the AS-OCT data were obtained before suture removal. Thirty-two rotating OCT scans were taken to reconstruct a three-dimensional model of the entire corneal configuration. All subjects were examined at least twice to confirm the reproducibility of the obtained data. Examination-quality data were accessed with a built-in program, and the results with serious errors were excluded. The CASIA system corrects distortion in the AS-OCT images based on the refraction of the anterior surface to show various color-coded maps of the anterior segment configurations, including corneal heights and pachymetric data. After this correction, the anterior and posterior corneal heights and pachymetric data, for an area up to a diameter of 10.2 mm, were exported to spreadsheet software (Excel 2007; Microsoft, Inc., Redmond, WA). The corneal height data, \( CH(r_r, \theta_j) \), and pachymetric data, \( CT(r_r, \theta_j) \), consisted of 256 \( \times \) 32 points in polar coordinates (1 \( \leq r \leq 256, 1 \leq j \leq 32 \)) for an area of a diameter of 10.2 mm. Surface parallelism index (SPI) was proposed as an index to represent the surface parallelism of the anterior and posterior surfaces within a diameter of 6 mm (1 \( \leq r \leq 154 \)), defined as follows:

\[
SPI = \frac{154}{\sum_{i=1}^{154} CV(r_r)}
\]

with standard deviation

\[
SD(r_r) = \sqrt{\frac{1}{31} \sum_{i=1}^{32} (CT(r_r, \theta_j) - CT(r_r))^2}
\]

\[
CV(r_r) = \frac{SD(r_r)}{CT(r_r)}
\]

where \( CT(r_r) \) is the mean corneal thickness in circle of radius \( r_r \) and \( CV(r_r) \) is the coefficient of variation in the circle of radius \( r_r \).

Ray-Tracing Analysis

The anterior and posterior surfaces were reconstructed as a three-dimensional model from the corneal height data, \( CH(r_r, \theta_j) \), using the damped least-squares method up to the 10th order. We checked that a 10th-order approximation represented a good description of the surfaces. The RMS residual errors in the fitting of the anterior and posterior surfaces were 0.4 \( \pm \) 0.02 and 0.6 \( \pm \) 0.06 \( \mu \)m in normal eyes, 1.6 \( \pm \) 0.87 and 4.0 \( \pm \) 2.7 \( \mu \)m in PK eyes, 0.9 \( \pm \) 1.9 and 1.5 \( \pm \) 3.3 \( \mu \)m in DALK eyes, and 1.0 \( \pm \) 1.5 and 2.8 \( \pm \) 1.5 \( \mu \)m in DSAEK eyes. This fitting error was less than 1% of the total RMS values in all eyes and as low as the accuracy of the corneal topography devices in the AS-OCT system.

The anterior, posterior, and total corneal aberrations at diameters of 4 and 6 mm were calculated separately with ray-tracing software (CodeV; Optical Research Associates, Pasadena, CA). Ray aberrations were obtained by virtual ray tracing using a grid of 100 \( \times \) 100 sample points on the corneal surface.

The refractive indices of the cornea and aqueous humor in the software were set to 1.376 and 1.336, respectively.

The wavefront aberration was expanded with normalized Zernike polynomials up to the 14th order. For each pair of the standard Zernike terms for coma, trefoil, tetrafoil, and secondary astigmatism, a combined value for the magnitude was calculated as the RMS.
Total HOAs were defined as the RMS of the 3rd to 14th Zernike coefficients. The ratios $T/A_{HOA}$ and $P/A_{HOA}$ were defined as shown below and compared between the four groups:

$$T/A_{HOA} = \frac{\text{HOA of total cornea}}{\text{HOA of anterior surface}}$$

$$P/A_{HOA} = \frac{\text{HOA of posterior surface}}{\text{HOA of anterior surface}}$$

where T is total, A is anterior, and P is posterior. From the measured wavefront aberrations of anterior and total corneal surfaces, the MTF was calculated for spatial frequencies between 0 and 30 cyc/deg.

Statistical Analysis

Data were analyzed using statistical analysis software (SSRI Co. Ltd., Tokyo, Japan). The paired t-test was used to compare the aberrations between the anterior, posterior, and total corneal surfaces in each group. The Mann-Whitney rank sum test and the Kruskal-Wallis test were used to compare the SPI, postoperative logMAR, and aberrations between the groups. Spearman’s rank correlation analysis was used to evaluate the correlation between logMAR, SPI, keratometric values, and anterior, posterior, and total corneal aberrations. $P < 0.05$ was considered statistically significant.

RESULTS

Figure 1 shows the representative color maps of the anterior, posterior, and total corneal wavefront aberrations in the four groups. In the normal, PK, and DALK eyes, color maps of the anterior surfaces showed a reverse pattern with respect to those of the posterior surfaces, which indicated that the two surfaces had similar shapes, whereas in the DSAEK eyes, the anterior and posterior surfaces had obviously different color patterns in the wavefront color maps. SPIs of the normal, PK, DALK, and DSAEK eyes were $0.018 \pm 0.006$, $0.016 \pm 0.01$, $0.030 \pm 0.018$, and $0.045 \pm 0.019$, respectively ($P = 0.0005$, Kruskal-Wallis test). SPIs of the DSAEK eyes were significantly larger than those of the normal and PK eyes (Fig. 2, $P = 0.0082$ and $P = 0.004$, respectively). SPI was significantly correlated with $P/A_{HOA}$ ($R = 0.5196$, $P = 0.001$).

Figure 3 shows the regular astigmatism of the four groups. The astigmatism of the total cornea was significantly lower than that of
From the viewpoint of parallelism of the anterior and posterior surfaces, we evaluated the detailed optical properties of the cornea after three representative types of keratoplasty: PK, involving replacement of both anterior and posterior surfaces; DALK, involving replacement of the anterior surface; and DSAEK, involving replacement of the posterior surface. We demonstrated that disruption of parallelism in DSAEK caused a loss in the ability of the posterior surface to compensate for aberrations in the anterior surface, compared with PK and DALK. We also demonstrated that visual acuity after keratoplasty correlated significantly with HOAs of the anterior surface and total cornea, but not with those of the posterior surface.

The wavefront aberrations of the anterior and posterior surfaces have been reported by several authors. Chen et al.11 evaluated wavefront aberrations in keratoconic eyes and demonstrated that 14% to 24% of the anterior corneal coma was compensated for by the posterior cornea by comparing the coma of the anterior and posterior surfaces. Oshika et al.12 reported that the regular or irregular astigmatism of the posterior surface was approximately 30% of that of the anterior surface, by comparing the amounts of astigmatism in both surfaces. Nakagawa et al.13 calculated wavefront aberrations by multiplying the surface elevation data by the difference in refractive indices on the anterior and posterior surfaces using a rotating Scheimpflug image (Pentacam; Oculus, Wetzlar, Germany) in keratoconic and normal eyes. Muftuoglu et al.14 reported the wavefront aberrations of the anterior and posterior surfaces in eyes after PK and DSAEK using ray tracing from the height data. When considering the total aberration of the cornea, we think the generally accepted equation (total corneal aberration) = (anterior aberration) + (posterior aberration) is not correct for the following reasons: (1) Axial decentration or tilt of the two surfaces can cause other aberrations, as has been reported in intraocular lens decentration21,22; (2) the lines of rays entering the posterior surface are not actually parallel; and (3) the corneal thickness has an influence on the calculation. According to our data, there were some differences between the simple additive equation and ray-tracing results. Further study is necessary to substantiate the reason for this difference, as well as the effect of analysis diameter and corneal thickness and the effects of each Zernike coefficient, such as coma or spherical aberration, on this difference in normal eyes and those with corneal diseases.

### Table 2. Correlation of Astigmatism between an Autokeratometer, AS-OCT and the Ray Tracing in Eyes after Keratoplasty

<table>
<thead>
<tr>
<th>Ray Tracing</th>
<th>Anterior Surface</th>
<th>Total Cornea</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>4 mm</td>
<td>6 mm</td>
</tr>
<tr>
<td>Autokeratometer</td>
<td>0.6729 (0.0001)</td>
<td>0.6428 (0.0003)</td>
</tr>
<tr>
<td>AS-OCT</td>
<td>0.8324 (&lt;0.0001)</td>
<td>0.9367 (&lt;0.0001)</td>
</tr>
</tbody>
</table>

*n* = 30. Data are expressed as Spearman’s correlation coefficient *r* (*P*).
First of all, we calculated the wavefront aberrations of the total cornea, in addition to those of the anterior and posterior corneal surfaces with ray-tracing software (CodeV; Optical Research Associates) in combination with high-resolution AS-OCT. To our knowledge, this is the first report on the HOAs of the total cornea in pathologic eyes. Dubbelman et al. first investigated the contribution of the posterior surface to the coma aberration in normal eyes using ray tracing in three-dimensional reconstructed surfaces from Scheimpflug images of six meridians and demonstrated that the posterior surface

**Table 3. Measurement Results in Each Group**

<table>
<thead>
<tr>
<th></th>
<th>Normal</th>
<th>PK</th>
<th>DALK</th>
<th>DSAEK</th>
</tr>
</thead>
<tbody>
<tr>
<td>T/AHOA</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4 mm</td>
<td>0.96 ± 0.02</td>
<td>1.00 ± 0.07</td>
<td>1.01 ± 0.09</td>
<td>1.01 ± 0.16</td>
</tr>
<tr>
<td>6 mm</td>
<td>0.93 ± 0.02</td>
<td>0.92 ± 0.02</td>
<td>0.88 ± 0.09</td>
<td>1.04 ± 0.22</td>
</tr>
<tr>
<td>P/AHOA</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4 mm</td>
<td>0.17 ± 0.04</td>
<td>0.18 ± 0.10</td>
<td>0.27 ± 0.10</td>
<td>0.36 ± 0.25</td>
</tr>
<tr>
<td>6 mm</td>
<td>0.22 ± 0.03</td>
<td>0.14 ± 0.04</td>
<td>0.24 ± 0.06</td>
<td>0.45 ± 0.24</td>
</tr>
<tr>
<td>Correlation coefficient between anterior and total HOAs (6 mm)</td>
<td>0.9512 ($P &lt; 0.0001$)</td>
<td>0.9594 ($P = 0.0001$)</td>
<td>0.9483 ($P &lt; 0.0001$)</td>
<td>0.8061 ($P = 0.0049$)</td>
</tr>
<tr>
<td>Correlation coefficient between anterior and posterior HOAs (6 mm)</td>
<td>0.700 ($P = 0.181$)</td>
<td>0.8545 ($P = 0.0016$)</td>
<td>0.6485 ($P = 0.0425$)</td>
<td>0.1515 ($P = 0.6761$)</td>
</tr>
</tbody>
</table>
compensated for approximately 3.5% of the coma of the anterior surface in normal eyes.10 The present study demonstrated that the decrease in HOAs of the total cornea due to compensation by the posterior surface was −10%. Further studies will be necessary to evaluate the influence of factors such as corneal thickness and parallelism of both surfaces on the interaction of HOAs of the anterior and posterior surfaces.

Of interest to us is that the HOAs after keratoplasty, which we obtained from ray tracing in combination with high-resolution AS-OCT, correlated significantly with the actual visual acuity of the patients. The findings were in agreement with the results of MTF analysis in this study. We previously reported that visual acuity after DSAEK was dependent on the irregular astigmatism of the anterior surface, which may seem paradoxical.9 The results of our previous report are quite natural when we consider the difference of the refractive indices of the surfaces, but it has been quite difficult to calculate the actual HOAs of the total cornea. As shown in this study, total corneal aberration and optical function are mainly determined by the anterior surface, although there is some compensation by the posterior surface after PK and DALK, in which the two surfaces are maintained parallel and similar to each other. However, in some patients after DSAEK, with disruption of similarity and parallelism, the total HOAs were not compensated, but increased by as much as 20% compared with the HOAs of the anterior surfaces due to the posterior surfaces. It has been reported that, after DSAEK, some patients cannot regain sufficient visual acuity despite the clarity of the cornea. In this study, although there was no significant correlation between HOAs and the position of the DSAEK graft, which might be partly due to the sample size (data not shown), graft position, and nonuniform thickness had a detrimental effect on the HOAs of the total cornea in some patients. We believe that the calculation of the total, anterior, and posterior HOAs will provide valuable information in determining the cause of poor visual acuity after DSAEK. We also propose that this methodology be applied to investigating the efficacy of new technologies or surgical methods, such as DSAEK using thin grafts, Descemet’s membrane endothelial keratoplasty (DMEK), astigmatism calculation in toric intraocular lenses, and femtosecond-laser-assisted keratoplasty.

A few limitations of this study are the small sample of eyes (n = 40), the younger age of the normal eyes, and the lack of evaluation of reproducibility. We obtained AS-OCT data from

| Table 4. Correlation between Visual Acuity and logMAR in Eyes after Keratoplasty |
|-----------------------------------|-----------------|-----------------|
| HOAs                             | 4 mm Zone       | 6 mm Zone       |
| Total cornea                     | 0.3717 (0.0471) | 0.4956 (0.0309) |
| Anterior                         | 0.4022 (0.0305) | 0.5038 (0.0279) |
| Posterior                        | 0.2264 (0.2376) | 0.2678 (0.2677) |

Data are expressed as Spearman’s correlation coefficient r (P).
normal young volunteer subjects. Dubbelman et al.\textsuperscript{10} reported that age has a small effect on the compensation by the posterior surface. It has been reported that AS-OCT has good reproducibility and predictability.\textsuperscript{23,24} We also confirmed the accuracy of the surface detection in high-resolution AS-OCT images of all eyes. Another potential limitation is that all corneas in this study were transparent and clear, which might contribute to the significant correlation between visual acuity and HOAs. The results of this study were obtained purely from the corneal three-dimensional models reconstructed from the AS-OCT height data. In some actual eyes after lamellar keratopasty, corneal scarring or opacity can induce light scattering and degrade optical quality. We believe that future studies taking into consideration both HOAs and corneal haze data will open up new horizons in the evaluation of corneal optics. Another limitation of this study is the lack of evaluation of contrast sensitivity function. We found significant correlation between HOAs and visual acuity and MTFs in normal eyes and after each kind of keratoplasty. Further study including contrast sensitivity and HOAs measured by ray tracing will provide invaluable information for clinicians and patients regarding the quality of vision after keratoplasty.

In conclusion, we applied ray tracing in combination with high-resolution AS-OCT to evaluate eyes after corneal transplantation and demonstrated that the posterior surfaces compensated for the HOAs of the anterior surface in normal, PK, and DALK eyes, whereas in some DSAEK eyes, the posterior surfaces had a detrimental effect of up to 20% on the HOAs of the total cornea. Analysis of the influence of the posterior surface on the total corneal aberrations will add to our knowledge on the optical characteristics of the cornea as a whole.

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References


