Visual Psychophysics and Physiological Optics

Anterior Corneal, Posterior Corneal, and Lenticular Contributions to Ocular Aberrations

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Submitted: June 5, 2016
Accepted: August 16, 2016
Citation: Atchison DA, Suheimat M, Mathur A, Lister LJ, Rozema J. Anterior corneal, posterior corneal, and lenticular contributions to ocular aberrations. Invest Ophthalmol Vis Sci. 2016;57:5263–5270. DOI: 10.1167/iovs.16-20067

PURPOSE. To determine the corneal surfaces and lens contributions to ocular aberrations.

METHODS. There were 61 healthy participants with ages ranging from 20 to 55 years and refractions −8.25 diopters (D) to +3.25 D. Anterior and posterior corneal topographies were obtained with an Oculus Pentacam, and ocular aberrations were obtained with an iTrace aberrometer. Raytracing through models of corneas provided total corneal and surface component aberrations for 5-mm-diameter pupils. Lenticular contributions were given as differences between ocular and corneal aberrations. Theoretical raytracing investigated influence of object distance on aberrations.

RESULTS. Apart from defocus, the highest aberration coefficients were horizontal astigmatism, horizontal coma, and spherical aberration. Most correlations between lenticular and ocular parameters were positive and significant, with compensation of total corneal aberrations by lenticular aberrations for 5/12 coefficients. Anterior corneal aberrations were approximately three times higher than posterior corneal aberrations and usually had opposite signs. Corneal topographic centers were displaced from aberrometer pupil centers by 0.32 ± 0.19 mm nasally and 0.02 ± 0.16 mm inferiorly; disregarding corneal decentration relative to pupil center was significant for oblique astigmatism, horizontal coma, and horizontal trefoil. An object at infinity, rather than at the image in the anterior cornea, gave incorrect aberration estimates of the posterior cornea.

CONCLUSIONS. Corneal and lenticular aberration magnitudes are similar, and aberrations of the anterior corneal surface are approximately three times those of the posterior surface. Corneal decentration relative to pupil center has significant effects on oblique astigmatism, horizontal coma, and horizontal trefoil. When estimating component aberrations, it is important to use correct object/image conjugates and heights at surfaces.

Keywords: aberrations, cornea, iTrace, lens, Pentacam

Studies of component contributions to ocular aberrations have determined ocular and anterior corneal aberrations, and then obtained internal aberration contributions as their differences.1–7 They did not distinguish between the contributions to the internal aberrations from the posterior cornea and the lens. Three studies used a Scheimpflug-based instrument (Oculus Pentacam; Oculus, Wetzlar, Germany) to determine anterior corneal and posterior corneal component aberrations according to the instrument’s software (Anand S, et al. IOVS 2008;49:ARVO E-Abstract 1031.).5,9 The results of these studies suggested that posterior corneal aberrations are much higher than anterior corneal aberrations. This is unexpected given the small refractive index difference between aqueous and cornea. Meanwhile, other studies have found much higher aberrations at the anterior surface than at the posterior surface using different instruments, including, the scanning slit Bausch & Lomb (Houston, TX, USA) Orbscan,10,11 a laboratory Scheimpflug imager,12,13 the Pentacam,14 and anterior segment optical coherence tomography (SS-1000; Tomey, Nagoya, Japan).15 These studies used different analyses including Fourier decomposition of the surfaces,10 raytracing through surfaces,12,13,15 and comparing the surface shapes with ideal (aberration-free) shapes.11,14 A potential problem with the latter approaches arises if the object for the posterior cornea is set at infinity rather than that corresponding to refraction by the anterior cornea, as the choice of object position affects aberration estimates.

Accurate assessments of component contributions to ocular aberrations can be provided only by correcting the reference position of a corneal topographer to that of an aberrometer2 or by using a combined topographer/aberrometer with a single reference position.16 Chen and Yoon11 re-referenced their data from the corneal topographic center, the corneal intersection of the line between fixation point and the center of curvature of the anterior cornea, to the corresponding pupil center. Most of the above studies comparing anterior and posterior corneal components did not make this correction, but this is reasonable, as they were making comparisons only within the cornea.

In this study, we determined anterior corneal, posterior corneal, and lenticular contributions to ocular aberrations of normal eyes by a raytracing procedure. We hypothesized that results would be inaccurate if the decentration of corneal data relative to the pupil was ignored, and that results would be inaccurate if the optical conjugates for surfaces were not correct.
Component Contributions to Ocular Aberrations

METHODS

Participants

Participants were 61 adults aged 41 ± 9 years (range, 20-55 years) for which we had Pentacam topography and iTrace (Tracey Technologies, Houston, TX, USA) aberrometry data. They were West-European Caucasians recruited from the personnel of the Antwerp University Hospital and people of the nearby suburban town of Edegem. Exclusion criteria were prior ocular pathology or surgery, an IOP higher than 22 mm Hg, and wearing rigid contact lenses less than 1 month before testing. Five right eyes and five left eyes were excluded because of poor-quality images or because pupil size with aberrometry was less than 5.0 mm. For the remainder, mean right eye spherical equivalent refraction was \(-1.53 \pm 2.50\) diopters (D) (range, \(-8.25\) to \(+3.25\) D) and mean left eye spherical equivalent refraction was \(-1.27 \pm 2.60\) D (\(-9.25\) to \(+3.25\) D) as determined by Nidek (Gamagori, Japan) ARK-700 autorefractometer. Participants were not cyclopleged for any of the measurements. This study complied with the tenets of the Declaration of Helsinki, it was approved by the Antwerp University Hospital Ethical Committee and all participants gave written informed consent prior to the measurements.

Determination of Corneal Surface and Lens Aberrations

The four steps to determine corneal surface and lens aberrations are described below.

1. Corneal data decentration relative to the pupil center obtained with aberrometry

This step was needed because corneal topographic data are not referenced to pupil center, and pupil sizes, and consequently pupil centers, are different under the conditions at which the corneal topography and ocular aberrations are obtained. The anterior eye images for the iTrace and Pentacam were analyzed using an adaptation of our method. This involved using the corneal limbus center as a common reference point for the two images.

ImageJ (http://imagej.nih.gov/ij/) provided in the public domain by the National Institutes of Health, Bethesda, MD, USA) was used to measure limbal diameters in pixels for Pentacam (Oculus) and iTrace (Tracey Technologies) cameras. The iTrace instrument provides horizontal limbal diameter and a good quality image was used to give a pixel-to-millimeter conversion. For the Pentacam, a scale in millimeters on an image was used to provide the conversion. Draggable ellipses were manually fitted to the limbus and the pupil for the contrast-enhanced iTrace and Pentacam images using a program written in Matlab (The Mathworks, Natick, MA, USA), to estimate pupil and limbus centers for the images from the two instruments. Previously we found mean absolute repeatability of pupil center relative to limbal center to be \(\leq 0.05\) mm. Elevation files exported from the Pentacam had information about the Pentacam pupil center relative to the corneal topographic center.

The Pentacam corneal topographic center relative to the iTrace pupil center, or corneal decentration for short, was determined as (Fig. 1):

\[
\text{Corneal decentration} = \left(\text{Limbus center} - \text{iTrace pupil center}\right) + \left(\text{Pentacam pupil center} - \text{limbus center}\right) + \left(\text{Pentacam corneal topographic center} - \text{Pentacam pupil center}\right)
\]

where each of the differences in brackets has horizontal and vertical projections. In vector form, this can be given as follows:

\[
\text{C}_{\text{ip}} = \text{C}_{\text{L}} + \text{C}_{\text{Pt}} + \text{C}_{\text{Pt}} - \text{C}_{\text{ip}}.
\]

where \(C\) indicates center, \(ip\) indicates iTrace pupil, \(Pt\) indicates Pentacam topographic, \(L\) indicates limbus, and \(Pp\) indicates Pentacam pupil. The corneal decentration was nearly always nasal, with corresponding positive horizontal values for right eyes and negative horizontal values for left eyes. In approximately half of the eyes, it was upward (positive vertical values).

2. Produce GridSag files and other files for use in raytracing

The elevation files contained several items of information, including anterior and posterior corneal elevation coordinates, central cornea thickness (CCT), anterior surface maximum and minimum vertex radii of curvature and their meridians, and anterior chamber depth (ACD). The elevation data were saved in a file in GridSag format. This file contains a set of \(141 \times 141\) xyz surface coordinate points across a 7-mm diameter. The corneal decentration, as determined in the previous step, and other biometric information, were saved in another data file. If the fixation target is not at infinity, decentration of the anterior corneal surface means that there is a corneal tilt relative to the line of sight. However, as the Pentacam target was set at infinity or the far point of the eye, it was considered that this would have negligible effect and no tilt was incorporated.

3. Determine anterior and total corneal aberration components

Using into-the-eye ray tracing, corneal aberration coefficients up to sixth order were estimated with Zemax optical design software (Zemax LLC, Kirkland, WA, USA), taking into account the corneal decentration. A macro was written in Zemax programming language to read the GridSag.dat files and convert them to 7-mm diameter “grid sag” surfaces. This macro read the other data file mentioned above to introduce the corneal decentration. The entrance pupil position \(EP\) is the image position of the aperture stop in the cornea, relative to the anterior cornea. It was calculated in the macro using a single surface cornea as

\[
\frac{1}{EP} = \frac{1.3375}{R} - \frac{0.3375}{R^2},
\]

where \(R\) is the mean of the maximum and minimum anterior
vertex radii of curvature and

\[ l' = CCT + ACD. \]

The corneal system was generated with the macro and consisted initially of an object at infinity, a 5.0-mm diameter stop to coincide with the entrance pupil, the anterior cornea surface at \(-EP\) from the stop and with decentration relative to the line of sight. Raytracing was done from infinity through the stop and anterior cornea with the refractive index of the aqueous set to 1.336, and raytracing and Zernike aberrations were again determined. The mean residual RMS fitting errors for both one surface (anterior corneal contribution) and two surfaces (the total corneal contribution) were 0.089 ± 0.005 μm. The output of the macro consisted of aberration coefficients estimated for the ocular aberrations. To allow for mirror symmetry between right and left eyes, the signs of left eye ocular aberration coefficients \( C_{2n} \) were changed when the \( m \) and \( n \) indices were either negative and even, respectively, or positive and odd, respectively; for example, \( C_2^2, C_4^1 \). For anterior corneal and total corneal aberration coefficients, the magnitudes were divided by 0.555 to convert from waves to micrometers and the order was changed to match the ophthalmic optics standard for aberrations, and signs were altered for left eye coefficients, as described for the ocular aberrations. Other aberration coefficients were calculated as follows:

\[
\text{posterior corneal coefficient} = \text{total cornea coefficient} - \text{anterior cornea coefficient}
\]

\[
\text{lenticular coefficient} = \text{ocular coefficient} - \text{total cornea coefficient}
\]

Mean sphere \( SE \), horizontal astigmatism \( J_{60} \) and oblique astigmatism \( J_{45} \) were calculated from second to sixth orders. Root mean square aberrations were determined from second to sixth order coefficients \( \text{RMS}_{\text{TOT}} \), without defocus \( \text{RMS}_{\text{NoDef}} \) and without second order coefficients \( \text{RMS}_{\text{No2}} \).

### Statistical Analysis

Comparisons of fellow eye corneal decentrations were by orthogonal regression analysis. As both right and left corneal decentrations were normally distributed according to the Kolmogorov-Smirnov test \((P = 0.18 \text{ and } 0.20)\), Pearson correlations were used. Comparisons of the aberration coefficients of components were done by linear regression rather than orthogonal regression because one set of coefficients was usually dependent on the other. For example, in the comparison of lenticular and corneal parameters, the lenticular parameter had been already determined as the difference between ocular and corneal parameters. Because of the large symmetry between fellow eyes, including both eyes in the analyses would exaggerate the correlations. For this reason, left eye data were used only to determine the symmetry in corneal decentration. As many of the 18 parameters were not normally distributed according to the Kolmogorov-Smirnov test \((P < 0.05)\) and multiple comparisons were made, correlations were assessed by Spearman \( \rho \) with significance set at \( P < 0.05/18 = 0.0028 \).

Several correlations were made for right eye ocular and lenticular aberration coefficients.

### Results

#### Comparison of Corneal Decentrations Between Fellow Eyes

Figure 2 shows corneal decentrations for fellow eyes of 52 participants. Slopes of correlations between fellow eyes were close to \(-1\) and \(+1\) in the horizontal and vertical directions, respectively. Correlation was strong in the horizontal direction \((R^2 = 0.47)\). Although correlation was much lower in the vertical direction \((R^2 = 0.10)\), the slope was significantly different from zero. Mean decentrations in the horizontal direction for right eyes and left eyes were \(+0.32 \pm 0.17\) mm and \(-0.32 \pm 0.20\) mm, respectively; corresponding decentrations in the vertical direction were \(-0.01 \pm 0.18\) mm and \(-0.03 \pm 0.19\) mm, respectively. The mean absolute centra...
for right and left eyes were 0.38 ± 0.15 mm and 0.39 ± 0.17 mm, respectively.

**Contributions of Cornea and Lens to Ocular Aberrations**

Table 1 shows Zernike aberration coefficients of ocular aberrations and their total corneal, anterior corneal, posterior corneal, and lenticular contributions for 56 right eyes. Coefficients are given for the second to fourth orders, but the RMS aberrations are for second to sixth orders. Horizontal astigmatism ($J_0$) and oblique astigmatism ($J_{45}$) are included. The last four columns indicate correlations. Note the large mean defocus coefficient $C_0^0$ and the large spherical equivalent refraction $SE$ for the lens; these arise because our procedure minimizes the defocus associated with the cornea, and so the lenticular defocus closely matches that of the eye.

Across the components, disregarding defocus, the highest mean aberration coefficients were $C_3^2$, $C_2^1$, and $C_0^0$ (coefficients for horizontal astigmatism, horizontal coma, and spherical aberration, respectively). The signs of mean coefficients for ocular and total corneal aberrations were usually the same (8/12 coefficients). All but two correlations between the total corneal and ocular parameters were positive, although only six were significant ($C_2^2$, $C_3^1$, $C_4^0$, $J_0$, and $J_{45}$). All correlations between lenticular and ocular parameters were positive and all but those for the astigmatisms $C_2^2$ and $C_3^1$ were significant. Some correlations of the ocular with lenticular and total corneal parameters are shown in Figure 3.

The means of total corneal and lenticular aberrations had opposite signs usually (9/12) and similar magnitudes. There appeared to be genuine compensation of total corneal aberrations by lenticular aberrations (i.e., the ocular and total corneal coefficients had the same sign, but the latter were of higher magnitude) for 5/12 coefficients. There were negative relationships between all the lens and total corneal coefficients, with only those of the fourth-order coefficient, except for $C_0^0$, being significant. Although it may seem intuitive that the regression lines of the corneal and lenticular aberrations shown in Figure 3 should stack up to a 1:1 relationship with the total aberrations, this is not the case due to lenticular compensation of the corneal aberrations.

**Comparisons of Anterior and Posterior Corneal Contributions**

The total cornea was significantly correlated with the anterior cornea for all parameters, but with the posterior cornea only for astigmatic coefficients and oblique tetrafoil coefficient $C_4^1$ (correlations not shown in Table 1).

The mean anterior cornea and posterior cornea coefficients had opposite signs for 8/12 cases. Of the coefficients for which the total cornea had absolute values greater than 0.05 μm, the compensations of the anterior cornea by the posterior cornea were 39% for horizontal astigmatism $C_2^2$, 28% for horizontal coma $C_3^1$, and 43% for spherical aberration $C_4^0$. $RMS_{cornea}$ and $RMS_{lens}$ values in Table 1 show that anterior corneal aberrations were approximately three times higher than posterior corneal aberrations, and taking ratios of total cornea RMS/ anterior cornea RMS gives compensations of the anterior cornea by the posterior cornea of 17% and 10%, respectively.

All but one correlation of anterior cornea and posterior cornea aberration coefficients were negative, and those for the astigmatisms and the coma were significant. Some correlations of the anterior and posterior corneal parameters are shown in Figure 4.
Aberration Coefficients Versus Other Parameters

The correlations of right eye lenticular coefficients with coefficients of left eyes, corneal decentrations, age, spherical refraction, mean anterior corneal radius of curvature, and ACD were analyzed. The only significance found was between right and left eyes for \( C_{0}^{2} \) and \( C_{0}^{4} \). A similar analysis for right eye ocular coefficients showed right/left eye significances for \( C_{0}^{2}, C_{x}^{-2}, C_{x}^{2}, C_{x}^{-1}, \) and \( C_{y}^{0} \), as well as a significant positive correlation between \( C_{r}^{0} \) and spherical refraction.

Influence of Corneal Decentration

Systematic effects of corneal decentration on determination of aberration coefficients occurred for oblique astigmatism \( C_{z}^{2} \), horizontal coma \( C_{y}^{1} \), horizontal trefoil \( C_{x}^{1} \), oblique trefoil \( C_{xx}^{4} \), and secondary astigmatism \( C_{xx}^{3} \), where ignoring corneal decentration changed the respective means of the first three of these coefficients for the total cornea by \(-0.023 \pm 0.062 \mu m, +0.071 \pm 0.056 \mu m, \) and \(-0.027 \pm 0.038 \mu m \) (Wilcoxon
test, $P \leq 0.002$). The corresponding effects for the lens were the opposites of these corneal effects.

**Theoretical Analysis**

In the introduction, we mentioned that previous studies have determined posterior corneal aberrations in different ways. To consider some of these variables, we use corneal model variants based on the Atchison myopic eye models. The anterior cornea had radius of curvature $R = 7.72$ mm and asphericity $Q = -0.15$. The posterior cornea, 0.55 mm behind the anterior surface, had $R = 6.4$ mm and $Q = -0.275$. The stop was 3.15 mm behind the posterior cornea. With corneal and aqueous indices of 1.376 and 1.3374, the entrance pupil was 3.135 mm behind the anterior cornea; the entrance pupil was set as the stop and given a 5-mm diameter. Nasal decentration of the corneal surfaces was either 0 or $+0.3$ mm (corresponding to nasal decentration in a right eye). The total cornea was converted into an anterior cornea by changing the aqueous index to 1.376, and the total cornea was converted into a
posterior cornea by changing the air index to 1.576. Table 2 shows results with the model variants.

For a distance object, the total cornea has a spherical aberration of +0.12 μm, and, when the cornea is decentered, horizontal coma of −0.09 μm. Astigmatism induced by decenteration is small in comparison with the coma. If the object is set to 100 mm before the eye, corresponding to the far point of a 10 D myopic eye, horizontal coma, horizontal trefoil, and spherical aberration increase by 18%, 25%, and 32%, respectively (compare models 3 and 4 with models 1 and 2, respectively). There is an approximately linear relationship between each aberration coefficient and refraction. Usually when the aberrations of the cornea are determined, the object distance is not taken into account. This is relevant for Hartmann-Shack based aberrometers, for which aberrations are relative to the object conjugate of the retina (far point if the eye is relaxed). However, the iTrace is a laser raytracing instrument for which the object is always at infinity, and so raytracing from infinity as used in our raytracing is appropriate in this situation.

When the anterior cornea is considered in isolation, the changes noted for the total cornea are approximately duplicated. In this model, the anterior corneal aberrations are 3% to 6% higher than the corresponding aberrations for the total cornea (compare models 5 and 6 with models 1 and 2, respectively, and compare models 7 and 8 with models 3 and 4, respectively). The closeness is because in this model the posterior corneal aberrations are small.

If raytracing is done with a distant object for the posterior cornea, it seems that the posterior corneal aberrations are appreciable and are approximately −40% those of the anterior cornea (compare models 9 and 10 with models 5 and 6, respectively). This approach is wrong because the appropriate object position is 27.9 mm behind the posterior cornea (28.4 mm behind the anterior cornea). With the correct object distance, the aberrations of the posterior cornea are very small at −5% to −17% those of the anterior cornea (compare models 11 and 12 with models 3 and 4, respectively). However, height at the posterior cornea is now greater than occurs in the total cornea model; when the aperture stop is reduced to correct for this, the values are −3% to −14% (models 13 and 14). The posterior corneal aberrations are now similar to the differences between aberrations of the anterior eye and the total cornea, thus validating our approach of determining the posterior corneal aberrations as the differences between total cornea and anterior corneal aberrations. It should be noted that the posterior corneal aberrations of the model are much lower than the means found in this study, which is partly a consequence of the surface asphericity chosen for the posterior cornea.

**Table 2. Model Variations and Their Aberrations**

<table>
<thead>
<tr>
<th>Model</th>
<th>Object Distance From Anterior Cornea, mm&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Corneal Decentration, mm</th>
<th>Horizontal Astigmatism, μm</th>
<th>Horizontal Coma, μm</th>
<th>Spherical Aberration, μm</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Total cornea</td>
<td>Infinity</td>
<td>−</td>
<td>−</td>
<td>−</td>
<td>+0.115</td>
</tr>
<tr>
<td>2 Total cornea</td>
<td>Infinity</td>
<td>+0.3</td>
<td>+0.019</td>
<td>−0.089</td>
<td>+0.116</td>
</tr>
<tr>
<td>3 Total cornea</td>
<td>−100</td>
<td>−</td>
<td>−</td>
<td>−</td>
<td>+0.153</td>
</tr>
<tr>
<td>4 Total cornea</td>
<td>−100</td>
<td>+0.3</td>
<td>+0.022</td>
<td>−0.111</td>
<td>+0.153</td>
</tr>
<tr>
<td>5 Anterior cornea</td>
<td>Infinity</td>
<td>−</td>
<td>−</td>
<td>−</td>
<td>+0.119</td>
</tr>
<tr>
<td>6 Anterior cornea</td>
<td>Infinity</td>
<td>+0.3</td>
<td>+0.020</td>
<td>−0.092</td>
<td>+0.120</td>
</tr>
<tr>
<td>7 Anterior cornea</td>
<td>−100</td>
<td>−</td>
<td>−</td>
<td>−</td>
<td>+0.161</td>
</tr>
<tr>
<td>8 Anterior cornea</td>
<td>−100</td>
<td>+0.3</td>
<td>+0.023</td>
<td>−0.117</td>
<td>+0.162</td>
</tr>
<tr>
<td>9 Posterior cornea</td>
<td>Infinity</td>
<td>−</td>
<td>−</td>
<td>−</td>
<td>−0.046</td>
</tr>
<tr>
<td>10 Posterior cornea</td>
<td>Infinity</td>
<td>+0.3</td>
<td>−0.008</td>
<td>+0.035</td>
<td>−0.046</td>
</tr>
<tr>
<td>11 Posterior cornea</td>
<td>+28.43</td>
<td>−</td>
<td>−</td>
<td>−</td>
<td>−0.006</td>
</tr>
<tr>
<td>12 Posterior cornea</td>
<td>+28.43</td>
<td>+0.3</td>
<td>−0.003</td>
<td>+0.010</td>
<td>−0.006</td>
</tr>
<tr>
<td>13 Posterior cornea†</td>
<td>+28.43</td>
<td>−</td>
<td>−</td>
<td>−</td>
<td>−0.004</td>
</tr>
<tr>
<td>14 Posterior cornea†</td>
<td>+28.43</td>
<td>+0.3</td>
<td>−0.003</td>
<td>+0.007</td>
<td>−0.004</td>
</tr>
</tbody>
</table>

<sup>a</sup> Positive/negative distance for object behind/in front of the cornea.

† Stop diameter changed from 5.0 mm to 4.512 mm so that the marginal ray height at posterior cornea reduced from 2.697 mm to 2.444 mm to match that occurring for total cornea with object at infinity.

**DISCUSSION**

Based on corneal topography and wave aberration measurements, this study separated ocular aberrations into those occurring at different refracting components of the eye. Disregarding defocus, highest aberration coefficients occurred for horizontal astigmatism, horizontal coma, and spherical aberration. Signs of coefficients for ocular and total corneal aberration were usually the same (8/12 coefficients), with correlations being significant in six cases. All correlations between lenticular and ocular parameters were positive, with all but those for the horizontal and oblique astigmatisms being significant. Total corneal and lenticular aberrations usually had opposite signs (9/12 coefficients) and similar magnitude, consistent with previous studies. There was genuine compensation of total corneal aberrations by lenticular aberrations for 5/12 coefficients. Anterior corneal aberrations were approximately three times larger than posterior corneal aberrations and usually had opposite signs.

We considered the compensation of the anterior cornea by the posterior cornea in people without disorders in previous studies. This is made difficult by the different ways that compensation was determined, the pupil sizes used, and the raytracing involved (see Introduction). Oshika et al. found a 30% overall compensation, with various measures showing 14% to 46% compensation. Chen and Yoon found mean compensations of 21% for astigmatism, 6% for coma, and 18% for spherical aberration. Yamaguchi et al. wrote that compensation for higher-order aberrations was approximately 10%, Dubbelman et al. found approximately 4% compensation for coma, and Sicam et al. reported variable compensation of 10% to −26% for spherical aberration. In our study, the mean compensations of the anterior cornea by the posterior cornea were approximately one-third for the major higher-order aberrations of horizontal astigmatism, horizontal coma, and spherical aberrations, and the RMS values of the posterior cornea were also approximately one-third of those of the anterior cornea. When using RMS to determine the compen-
sation, the total corneal RMS should be compared with the anterior cornea; when this is done for RMS for all aberrations and RMS for higher-order aberrations, the mean compensations were smaller than one-third at 17% and 10%. The compensation of the power of the anterior surface by the posterior surface was similar to these values at approximately 12%. A caveat with all of this is that we do not know the details of how posterior corneal topography is determined by the Pentacam.

Corneal topographic centers were displaced from aberrometer pupil centers by 0.32 ± 0.19 mm nasally and 0.02 ± 0.16 mm inferiorly. Disregarding the effect of corneal decentration on aberration coefficients had significant influences on oblique astigmatism, horizontal coma, and horizontal trefoil. This supports our first hypothesis that results will be inaccurate if the decentration of corneal data relative to the pupil is ignored. Absolute decentration was 0.38 ± 0.16 mm, similar to the 0.38 ± 0.10 mm reported by Mandell et al.22 However, the decentrations of Mandell et al.22 were referenced to the pupil center for the corneal topographer, whereas our decentrations used the pupil center of the aberrometer. As aberrometers operate at lower illuminances than topographers, the pupil size would be larger and the pupil center would be in a more temporal position for the aberrometer than for the corneal topographer (Figure 1),17 and so the values of Mandell et al.22 are effectively larger than ours. A finite distance for the corneal topographer (Figure 1),17 and so the values of phers, the pupil size would be larger and the pupil center
corneal surface (Table 2).

The theoretical investigation showed the importance of selecting the correct object distance when determining aberrations of ocular components. It gives support to our second hypothesis that posterior corneal aberrations will be inaccurate if the optical conjugates for the posterior corneal surface are not correct. The appropriate object distance for the total cornea or the anterior cornea is infinity if the aberrometer is calibrated for distance, as is the case for the iTrace used in this study, but it is that of the retinal conjugate (the far point for an eye with relaxed accommodation) for Hartmann-Shack aberrometers. The appropriate object position for the poste-
rior cornea by itself is the image position in the anterior cornea. An object at infinity will give considerable overesti-
mates of the (negative) spherical aberration of the posterior corneal surface (Table 2).

CONCLUSIONS
The most important aberration coefficients at a 5-mm pupil for the components of the eye are horizontal astigmatism, horizontal coma, and spherical aberration. Magnitudes of corneal and lenticular aberrations are of similar magnitudes, and anterior corneal aberrations are approximately three times higher than posterior corneal aberrations. Corneal decentra-
tions relative to the pupil center have significant effects on horizontal coma and horizontal trefoil. When estimating the aberrations of ocular components by raytracing or other means, it is important to have the correct object/image conjugates and heights at the surface.

Acknowledgments
Supported by a research grant by the Flemish government agency for Innovation by Science and Technology (Grant IWT/110684) and by Australian Research Council Discovery Grant DP140101480.

Disclosure: D.A. Atchison, None; M. Suheimat, None; A. Mathur, None; L.J. Lister, None; J. Rozema, None

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