The contribution of the posterior surface to the coma aberration of the human cornea

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Scheimpflug imaging was used to measure in six meridians the shape of the anterior and posterior cornea of the right eye of 114 subjects, ranging in age from 18 to 65 years. Subsequently, a three-dimensional model of the shape of the whole cornea was reconstructed, from which the coma aberration of the anterior and whole cornea could be calculated. This made it possible to investigate the compensatory role of the posterior surface to the coma aberration of the anterior corneal surface with age. Results show that, on average, the posterior surface compensates approximately 3.5% of the coma of the anterior surface. The compensation tends to be larger for young subjects (6%) than for older subjects (0%). This small effect of the posterior cornea on the coma aberration makes it clear that for the coma aberration of the whole eye, only the anterior corneal surface and the crystalline lens play a role. Consequently, for the design of an intraocular lens that is able to correct for coma aberration, it would be sufficient to only take the anterior corneal surface into account.

Keywords: posterior cornea, Scheimpflug, coma, aberration, aging


Introduction

Usually, corneal aberration is determined solely from measurements of the anterior corneal surface. Nevertheless, according to recent studies using Scheimpflug imaging, the contribution of the posterior surface cannot be neglected. For example, the posterior corneal surface compensates for 31% of the anterior corneal surface astigmatism, which is larger than could be expected based on the astigmatism of the anterior surface alone (Dubbelman, Sicam, & Van der Heijde, 2006). Furthermore, the posterior corneal surface appears to have a significant effect on the spherical aberration of the cornea (Sicam, Dubbelman, & Van der Heijde, 2006). This effect (10% reduction to 26% addition) is age dependent and is related to the asphericity of both anterior and posterior corneal surfaces.

Currently, not much is known about the contribution of the posterior surface to corneal coma aberration. Barbero, Marcos, and Merayo-Llories (2002) reported aberration measurements for an aphakic eye. Their results show that the vertical coma aberration of the anterior corneal surface is compensated partially (about 20%) by the posterior surface, whereas the lateral coma became larger because of the contribution of the posterior surface.

More knowledge of the coma aberration of the posterior corneal surface is needed to be able to distinguish between the aberrations of the cornea and those of the crystalline lens (Artal, Benito, & Taberner, 2006; He, Gwiazda, Thorn, & Held, 2003; Smith, Cox, Calver, & Garner, 2001). At this moment, the aberrations of the anterior corneal surface and those of the whole eye are measured. Then, subtracting the aberrations of the anterior surface of those of the whole eye gives the aberrations of the internal optics, that is, lens and posterior corneal surface. Information on the coma of the posterior surface could make it possible to further distinguish between the contribution of the posterior corneal surface and that of the lens. Furthermore, attempts have been made to replace the crystalline lens by an intraocular lens (IOL), which also corrects for higher order aberrations. Traditionally, IOLs were only designed to correct spherical refractive error (Ridley, 1952/2003). After that, toric IOLs were introduced to correct corneal astigmatism (Shimizu, Misawa, & Suzuki, 1994). This was followed by an
aspheric IOL, which enabled correction for spherical aberration (Holladay, Piers, Koranyi, van der Mooren, & Norrby, 2002; Mester, Dillinger, & Anterist, 2003; Padmanaban, Rao, Jayasree, Chowdhry, & Roy, 2006). Recently, first attempts have been made to correct coma aberration (Tabernero, Piers, & Artal, 2007).

In this study, the compensatory role of the posterior surface to the coma aberration of the anterior corneal surface with age has been investigated. Using Scheimpflug imaging in six meridians, a three-dimensional (3D) model of the shape of the whole cornea was reconstructed. From this model, the coma aberration of the anterior and whole cornea was calculated, which made it possible to determine the contribution of the posterior corneal surface to the coma aberration of the whole cornea.

Methods

The sample population, the setup of the Scheimpflug camera, and the necessary correction of the Scheimpflug images have been described previously in detail (Dubbelman et al., 2006). Briefly, two series of Scheimpflug images were made in six meridians (90°, 60°, 30°, 0°, 150°, and 120°) of the right eye of 114 subjects (57 men, 57 women; age range = 18–65 years) who had not worn contact lenses in the previous 2 years. Images were obtained with the Topcon SL-45 Scheimpflug camera, the film of which was replaced by a CCD camera (St-9XE, SBIG Astronomical Instruments) with a dynamic range of 16 bits of gray values (512 × 512 pixels; pixel size, 20 × 20 μm; magnification, ×1). The Scheimpflug images were corrected for distortion due to the geometry of the Scheimpflug imaging system and the refraction of the anterior corneal surface (Dubbelman, Van der Heijde, & Weeber, 2005). For each of the six meridians, the anterior and posterior surfaces of the cornea were fitted to the following function, which is used in various forms (Atchison & Smith, 2000):

\[ y = \frac{c(x - x_0)^2}{1 + \sqrt{1 - kc(x - x_0)^2}} + y_0, \]

where \( c \) is the curvature (inverse radius \( r \)) at the vertex \((x_0, y_0)\) and \( k \) is the conic constant, which indicates the asphericity of the surface (e.g., hyperbola: \( k < 0 \); parabola: \( k = 0 \); circle: \( k = 1 \)). The y-axis is the axis of revolution of both the conic axis and the optical axis of the cornea. By combining the Scheimpflug images in six meridians, it is possible to determine the astigmatism (Dubbelman et al., 2006) and spherical aberration (Sicam et al., 2006) of the anterior and posterior cornea. Nevertheless, the coma aberration cannot be obtained using Equation 1, which, therefore, has to be expanded to

\[ y = \frac{c(x - x_0)^2}{1 + \sqrt{1 - kc(x - x_0)^2}} + f(x - x_0) + m(x - x_0)^3 + y_0, \]

where \( f \) describes corneal tilt and \( m \) describes coma. The mathematical formulation is analogous to the primary Seidel aberrations (Atchison & Smith, 2000). For each of the six meridians, Equation 2 was fitted to a 7.5-mm corneal zone as in Dubbelman et al. (2006). The 3D corneal profile is reconstructed by applying the following fit functions to the measured values of the shape parameters from all six meridians:

\[ r(\theta) = r_1 + \Delta r \cos^2(\theta - \alpha) \]

\[ k(\theta) = k_1 + \Delta k \cos^2(\theta - \beta) \]

\[ m(\theta) = m_1 + \Delta m \cos(\theta - \gamma), \]

where \( \alpha, \beta, \) and \( \gamma \) are the angles of the meridian where \( r, k, \) and \( m \) are maximal. For the 3D modeling of the corneal surfaces, the measured tilt \( r \) of the corneal shape appeared to have no influence on the coma aberration and was, therefore, not taken into account.

After the 3D model of the anterior and posterior surfaces of the cornea has been reconstructed, meridian ray tracing was applied to find the coma aberration. Rays are traced from the corneal focal point to the posterior surface. This focal point is determined by calculating an effective refractive index for each individual cornea (Olsen, 1986). A second reference point (the focal point of the anterior corneal surface) is used to trace points from the posterior surface back to the anterior surface. The corneal wave aberration is then defined as the difference in optical path length of the traced rays compared to the path going through the principal ray (Guirao & Artal, 2000). The third-order coma aberration is indicated by Zernike coefficients \( Z_3^1 \) (vertical coma) and \( Z_3^{-1} \) (horizontal coma) for this wave aberration (Thibos, Applegate, Schwiegerling, & Webb, 2002). In our study, the corneal wave aberration was calculated for a 6-mm pupil size. Using similar principles, the contribution of the anterior
surface to the coma wave aberration was also calculated, which allows to determine how the posterior corneal surface influences the coma of the anterior surface.

**Results**

**Coma and corneal shape**

Figure 1 shows an example of the coma coefficient $m$ of Equation 2 of the anterior and posterior corneal surface as a function of meridian. The meridional variation of $m$ of both corneal surfaces could be well fitted using the cos function (Equation 5). The average $r^2$ was .66 and .61 for the anterior and posterior corneal surface, respectively. Because the goodness of fit varied among subjects, a weighted linear regression was performed, and the weighted mean, weighted standard deviation, and weighted standard error of the mean are presented (Bevington, 1969). Figure 2 shows the age dependence of the meridional variation of $m$ ($\Delta m$) of the anterior and posterior corneal surface. For clarity, the data are also grouped in four bins ($\pm SEM$) of equal age range between 18 and 65 years, which shows the trend more clearly. The weighted linear regression was applied to all subjects. The $\Delta m$ of both the anterior and the posterior corneal surface changes significantly with age ($p < .00001$) but in the opposite direction. The $\Delta m$ of the anterior surface increases, whereas that of the posterior surface decreases with age. Figure 3 shows the ratio of the $\Delta m$ of the posterior corneal and that of the anterior corneal surface, which significantly changes with age. At the age of 20, the $\Delta m$ of the posterior corneal surface is almost twice that of the anterior surface. With age, the difference becomes smaller.

There was a small but significant difference ($p < .001$) between the axes of the coma of both surfaces. For the anterior surface, the average axis $\gamma$ ($\pm SD$) was $54^\circ \pm 21^\circ$, whereas it was $64.5^\circ \pm 21^\circ$ for the posterior surface. The mean of the paired difference in axis ($\pm SD$) was $13^\circ \pm 16^\circ$, which makes it clear that the coma axes of both surfaces are almost equal.

**Coma aberration**

Using the radius, conic constant, and coma of both corneal surfaces, it is possible to find the relative

![Figure 1](jov.arvojournals.org) Typical example for a 44-year-old male of the coma of the anterior and posterior corneal surface as a function of meridian. The solid line represents Equation 5 fitted through the 12 data points of the anterior surface: $m = -1 \pm 0.8 \times 10^{-4} + 7 \pm 1 \times 10^{-4} \times \cos (\theta - 72\pm3.6)$, $r^2 = .82$. The dashed line was fitted to the data of the posterior surface: $m = -2 \pm 2 \times 10^{-4} + 15 \pm 3 \times 10^{-4} \times \cos (\theta - 78\pm5)$, $r^2 = .73$. The data points after 150$^\circ$ have also been plotted to illustrate the periodicity of Equation 5, although they were not included in the fit.
contribution of the posterior surface to the coma aberration of the whole cornea. Figure 4a shows the coma aberration of the anterior surface of the cornea as a function of age. There was a significant change with age ($p < .01$). Figure 4b shows the age dependence of the coma aberration of the whole cornea, that is, both the anterior and posterior corneal surfaces. The difference between the aberration of the anterior and whole cornea is hardly visible, which indicates the small effect of the posterior cornea on the coma aberration. Figure 5 shows the ratio between the coma of the whole cornea and that of the anterior surface as a function of age. A ratio smaller than 1 indicates that the posterior surface reduces the coma aberration of the anterior surface; a value of 1 indicates no change, and a value above 1 indicates that the posterior surface has an additive effect to the coma of the anterior corneal surface. It can be seen that the compensation of the posterior corneal surface is small. Average compensation ($\pm SD$) is $3\% \pm 3.5\%$. Furthermore, because of the propagation of the uncertainties, the error in the ratio becomes large and no significant change with age can be determined. Nevertheless, a trend can be seen. For young subjects, the posterior surface compensates approximately 6% of the coma of the anterior surface, but this compensation disappears completely with age.

Discussion

The aim of the study was to measure the relative contribution of the posterior corneal surface to the coma aberration of the cornea as a function of age. The

Figure 2. The meridional variation of the $m$ ($\Delta m$) of the anterior and posterior corneal surface as a function of age. The weighted linear regression showed a significant age dependence for both surfaces. (a) Anterior surface: $\Delta m = 4.5 (\pm 0.4) \times 10^{-4} + 3.2 (\pm 1.0) \times 10^{-6} \times Age; n = 114; r = .18; p < .01$. (b) Posterior surface: $\Delta m = 1.3 (\pm 0.6) \times 10^{-3} - 1.05 (\pm 0.1) \times 10^{-5} \times Age; n = 114; r = -.37; p < .00001$. 

The refractive power of the whole cornea is due to the variation in the refractive indices of air (1.0), cornea (1.376), and the aqueous (1.336; Atchison & Smith, 2000). Because the difference in the indices of refraction at the anterior interface is 10 times larger than that of the posterior interface, it could be expected that the contribution of the posterior surface to the corneal aberration is small. However, from Dubbelman et al. (2006) and Sicam et al. (2006), it appeared that the posterior surface does make a considerable contribution to the astigmatism and spherical aberration of the whole cornea. The results of the present study show, however, that this does not hold true for the coma aberration. Firstly, the shape of both corneal surfaces was measured, and it was found that the meridional variation of the coma coefficient ($D_m$) of both the anterior and posterior surfaces significantly changes with age. At the age of 20, the $D_m$ is almost two times larger than that of the anterior surface, whereas it becomes almost equal to that of the anterior surface at the age of 65. Then, the results on the shape of the corneal surfaces were used to calculate the coma aberration, and it was found that the contribution of the posterior surface is almost negligible. At the age of 20, the posterior surface compensates approximately 6% of the coma of the anterior surface. This compensation decreases with age and disappears at the age of 60. This means that the dynamics of the refraction is different for coma aberration compared to astigmatism and spherical aberration. Calculations show that when $D_m$ is almost the same for both the anterior and posterior surfaces, the posterior corneal surface does not contribute to the coma aberration of the whole cornea. This can be explained by the fact that after refraction of the anterior corneal surface, the wave front that approaches the posterior corneal surface has the same form as the coma shape feature of the posterior surface. As a result, there will be no change in the coma aberration at the posterior corneal surface. This is particularly true for older subjects: At the age of 60, the $D_m$ of the posterior surface is equal to that of the anterior, which, therefore, results in minimal compensation of the corneal coma aberration by that of the posterior surface. This makes it clear that the contribution of the coma aberration of the posterior corneal surface is, thus, almost negligible and that the coma aberration that remains when the coma aberration of the anterior corneal surface has been subtracted to that of the whole eye is due to the crystalline lens. For the design of an IOL that is able to correct for coma aberration, it is sufficient to only take into account the anterior corneal surface.

The compensatory role of the posterior corneal surface has not yet been measured earlier. Measurements of the coma aberration of the anterior corneal surface have been performed before, which allows a comparison with the present study. The age-dependent increase in the coma aberration of the anterior surface is in agreement with the studies of Amano et al. (2004), Guirao, Redondo, and Artal (2000), Oshika, Klyce, Applegate, and Howland (1999), and Wang, Dai, Koch, and Nathoo (2003). Only Fujikado et al. (2004) did not find a significant increase of the corneal coma aberration with age, but this might be explained by the smaller number of subjects and also by the inclusion of very young subjects (ages 4–9 years). For the coma aberration of the anterior surface, we found a high intersubject variability. This is also in agreement with...
with the studies mentioned above, which indicates that the coma aberration differs considerably between subjects and that large groups are needed to determine age-related trends. In the present study, the anterior coma aberration was determined for a pupil with a 6-mm zone, and an increase of 0.15 μm was found between the age of 25 and 65. For the same pupil size and age interval, Amano et al. and Wang et al. found an increase of 0.12 and 0.09 μm, respectively, which does not differ significantly from our results. There was yet a significant difference in the absolute value of the anterior coma aberration. For a 6-mm pupil, the coma aberration found in the present study was approximately twice the value found by Amano et al. and Wang et al. in these studies, a corneal topographer was used to measure the shape of the anterior corneal surface. The origin of this difference is not clear. Because the trend with age is similar, the difference in absolute value could indicate a systematic error in one method or in both methods. Scheimpflug imaging and cornea topography agreed well for the radius and asphericity of the anterior corneal surface (Dubbelman et al., 2006). This also holds true for the absolute value of the spherical aberration (Sicam et al., 2006). In the present study, the shape of the 7.5-mm zone of the cornea was measured, and subsequently, the aberrations were calculated for the 6-mm zone. It could be that Placido-based videokeratographs have a problem to accurately capture data from the periphery of the cornea (Oshika et al., 1999; Tripoli, Cohen, Obla, Coggins, & Holmgren, 1996). It could also be that this error increases because the coma aberration is

Figure 4. Coma aberration of the anterior corneal surface (a) and the whole cornea (b) as a function of age. The weighted linear regression showed a significant change with age for both surfaces. (a) Anterior coma aberration = 0.53 (+0.05) + 0.0037 (±0.001) * Age; n = 114; r = .18; p < .01. (b) Corneal coma aberration = 0.49 (+0.06) + 0.0046 (+0.0015) * Age; n = 114; r = .22; p < .01.
due to a non-rotation-symmetric feature of the corneal shape (Sicam et al., 2006). Furthermore, it must be noted that in the present study, Scheimpflug images were not made along the line of sight but along the optical axis. On average, the fixation target was horizontally displaced 4.5° nasally from the slit beam and vertically 2° upward (Dubbelman et al., 2006). Calculations have made it clear that this does not change the radius and asphericity of both corneal surfaces significantly. Nevertheless, a calculation to determine the influence on the coma aberration is not straightforward because the coma shape feature is non-rotational. It could be that this influences the absolute value of the coma aberration. Nevertheless, it will not change the ratio between the coma shape feature of the anterior and posterior corneal surfaces, which was the primary aim of the present study.

Figure 5. Ratio of the coma aberration of the whole cornea and that of the anterior corneal as a function of age. The linear regression was not significant = 0.9 (±0.1) + 0.0017 (±0.002) * Age; n = 114; r = .46; p = .49. The secondary right axis shows the percentage that the posterior surface compensates the coma aberration of the anterior surface (Comawhole/Comaanterior – 1).

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