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The shape of the anterior and posterior surface of the aging human cornea

M. Dubbelman [a,*], V.A.D.P. Sicam [a,b], G.L. Van der Heijde [a]

[a] Department of Physics and Medical Technology, VU University Medical Center, P.O. Box 7057, 1007 MB Amsterdam, The Netherlands
[b] Netherlands Ophthalmic Research Institute, 1005 AZ Amsterdam, The Netherlands

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Abstract

Purpose: To determine the shape and astigmatism of the posterior corneal surface in a healthy population with age, using Scheimpflug photography corrected for distortion due to the geometry of the Scheimpflug imaging system and the refraction of the anterior corneal surface.

Methods: Scheimpflug imaging was used to measure in six meridians the cornea of the right eye of 114 subjects, ranging in age from 18 to 65 years.

Results: The average radius of the anterior corneal surface was 7.79 ± 0.27 (SD) mm and the average radius of the posterior corneal surface was 6.53 ± 0.25 (SD) mm. Both surfaces were found to be flatter horizontally than vertically. The cylindrical component of the posterior surface of 0.33 mm is twice that of the anterior surface (0.16 mm).

The asphericity of both the anterior and the posterior surface was independent of the radius of curvature at the vertex, refractive error and gender. In contrast with that of the anterior corneal surface, the asphericity of the posterior corneal surface varied significantly between meridians. With age, the asphericity of both the anterior and the posterior corneal surface changes significantly, which results in a slight peripheral thinning of the cornea.

Conclusion: On average, the astigmatism of the posterior corneal surface (−0.305 D) compensates the astigmatism of the anterior corneal surface (0.99 D) with 31%. The results show that the effective refractive index is 1.329, which is lower than values commonly used. There is no correlation between the asphericity of the anterior and the posterior corneal surface. As a result, the shape of the anterior corneal surface provides no definitive basis for knowing the asphericity of the posterior surface.

Keywords: Posterior cornea; Scheimpflug; Astigmatism; Asphericity; Schematic eye; Radius; Effective refractive index; Aging

1. Introduction

Although the anterior corneal surface has been frequently described in the literature, accurate data on the shape of the posterior surface of the cornea is scarce. This is mainly because imaging of this surface must always be performed through the anterior surface of the cornea, which acts as a magnifying glass and distorts the perceived shape of the posterior cornea. During the past two decades, interest in the exact shape of the corneal surface has increased, especially due to new developments such as refractive surgery, for which a complete description of the whole cornea is required. More accurate data on the shape of the posterior surface could improve the optical modeling of the eye. The radius of the posterior corneal surface in the schematic eye of Gullstrand is 6.8 mm (Atchison & Smith, 2000), while in the schematic eye of Le Grand and El Hage (1980) and Liou and Brennan (1997), it is 6.5 and 6.4 mm, respectively. The asphericity of the posterior corneal surface is needed in order to model the higher order aberrations, but different values have been used due to the lack of accurate data. Kooijman (1983) used the same asphericity as that of the anterior corneal surface, while Lotmar

* Corresponding author. Tel.: +31 20 4441062; fax: +31 20 4444147.
E-mail address: m.dubbelman@vumc.nl (M. Dubbelman).

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(1971) and Navarro et al. (1985) assumed the posterior corneal surface to be spherical. Liou and Brennan (1997) entered the asphericity of the posterior corneal surface as a variable in the modeling of their schematic eye, which resulted in a shape factor '*p*' of 0.4 (*Q* value of −0.6). Furthermore, post-surgical refractive power after cataract surgery could be predicted more accurately if more was known about the posterior surface. In IOL calculations, the cornea is regarded as a single refractive surface with an effective refractive index, which varies from 1.332 to 1.3375, because there is usually no knowledge of corneal thickness and radius of the posterior corneal surface (Bennet & Rabbets, 1998). For this effective refractive index, it is assumed that there consists a fixed ratio between the radius of the anterior and posterior corneal surface. This is also the reason that the calculation of corneal power sometimes fails after previous refractive surgery of the cornea, because this ratio has been changed (Gimbel, Sun, & Kaye, 2000). Finally, it is important to know whether the shape of the cornea changes with age, because this could influence the stability of the corneal shape after refraction surgery.

The radius of curvature of the posterior cornea has most frequently been measured on the basis of the size and location of Purkinje images (Dunne, Royston, & Barnes, 1992; Garner, Owens, Yap, Frith, & Kinnear, 1997; Lam & Douthwaite, 2000; Royston, Dunne, & Barnes, 1990). Dunne et al. (1992) found that the posterior surface exhibited more toricity than the anterior surface. The asphericity of the posterior corneal surface cannot be measured using Purkinje imaging, so it was measured by combining videokeratoscopy with pachymetric thickness measurements (Lam & Douthwaite, 1997; Patel, Marshall, & Fitzke, 1993). Lam and Douthwaite (1997) found a significant relationship between anterior and posterior asphericity in the vertical meridian. Patel et al. (1993) measured the asphericity in the vertical and horizontal meridian and found some difference in asphericity. Nevertheless, this combination of videokeratoscopy with subsequent thickness measurements is quite sensitive to misalignment, and is rather time-consuming.

Scheimpflug photography has the advantage of being a non-contact technique whereby the anterior surface, the thickness profile, and the posterior surface are determined in one step (Brown, 1973). This eliminates alignment errors that may occur when combining videokeratoscopy and pachymetry, and accelerates the measurement procedure. However, standard Scheimpflug photography suffers from distortion of the images due to the geometry of the Scheimpflug imaging system and the refraction of the anterior corneal surface. To obtain an accurate measurement of the anterior and posterior corneal surfaces, we developed a method to correct for these two types of distortion (Dubbelman & Van der Heijde, 2001; Dubbelman, Van der Heijde, & Weeber, 2005). In an earlier study (Dubbelman, Weeber, Van der Heijde, & Völker-Dieben, 2002), this method was used to measure the age-dependency of the shape of the posterior corneal surface in the vertical meridian. In contrast with the radius, the asphericity appeared to be age-dependent. Nevertheless, only the vertical meridian was measured, and because of the reflections of the iris, especially in the older subjects, the Scheimpflug image was occasionally saturated in the periphery of the cornea.

In the present study, a CCD camera with a higher dynamic range and a higher resolution (25% higher than the camera used in our earlier study). Furthermore, a larger group of subjects was measured, and the shape of the corneal surface was investigated in six meridians instead of only the vertical meridian. This makes it possible to measure the change in radius, asphericity and thickness of the whole cornea as a function of age.

2. Methods

Scheimpflug images of the anterior eye segment were made of the right eye of 114 subjects, ranging from 18 to 65 years of age (average age ± SD: 39 ± 14 years). The group consisted of 57 females (average age: 38 ± 14 years) and 57 males (average age: 39.5 ± 15). The measurements were performed with the full understanding of the subjects and written consent was obtained from each subject. None of the subjects had suffered from diabetes mellitus, had undergone ocular surgery, or had worn contact lenses in the previous 2 years.

The radius and astigmatism of the anterior corneal surface and the ocular refractive error of the right eye were measured with a Topcon KR-3500 auto kerato-refractometer. The equivalent refractive error (ERE) varied between −6.88 and +3.5 D (average ± SD: −1.33 ± 2.18). No difference in refractive error was found between males and females, and there was no correlation between ERE and age.

Two series of Scheimpflug images were made in six meridians (90°, 60°, 30°, 0°, 150°,120°) and the time interval between each series varied from 1 to 3 min (2 × 6 images in total). 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 grey values (512 × 512 pixels, pixel size 20 × 20 μm, magnification: 1×). All measurements were performed between 10 a.m. and 4 p.m.

The Topcon SL-45 Scheimpflug camera is equipped with a fixation target (a green blinking LED). The intensity of the LED can be increased, which makes fixation less difficult for the subject and increases the reproducibility of the measurements. In order to correct for the angle between the optical and the visual axis (Dragomirescu, Hockwin, & Koch, 1980), the fixation target is displaced 5° nasally from the slitbeam, which is in accordance with the average value for the angle alpha. The visual axis is also downwards relative to the optical axis by 2–3° (Atchison & Smith, 2000). Because of the variation in the angle between subjects (3–8°), the Scheimpflug camera was adapted to make it possible to change the position of the fixation target between 1° and 8° in both the horizontal and the vertical direction. As a result, all Scheimpflug images were taken along the optical axis, which has the advantage that the shape of the cornea is maximally symmetric in all six meridians. The procedure for aligning the slit along the optical axis was as follows. First of all, the subject was asked to fixate on the target, which was in average position (H: 5°, V: 2.5°). The slit (low intensity) was positioned in a horizontal position, while the anterior eye segment was observed through the eye-piece. Using the crosshairs in the eye-piece, the cornea, the iris plane and the pupil center, the position of the fixation target was fine-tuned in order to align the slit along the optical axis. The same procedure was followed with the slit in the vertical position. After the adjustment of the fixation target, which had to be done only once at the beginning of the measurements, the slit was positioned perpendicularly to the apex of the cornea using an electronic-acoustical device, which uses the slit light reflected by the cornea to give an audible signal (Dragomirescu et al., 1980). Finally, an image was obtained with a Xenon flash-light and the Scheimpflug imaging system was rotated 30°, after which, if necessary, the slit was adjusted again in order to position it perpendicular to the apex of the cornea.

Ray tracing was used to correct each image for distortion due to the geometry of the Scheimpflug camera and the magnifying effect of the anterior surface. This method has been described extensively in an appendix of Dubbelman et al. (2005), and was validated by measuring an artificial eye with known dimensions (Dubbelman & Van der Heijde, 2001). A patterned grid of known geometry was used to calibrate the camera.

To describe the anterior and posterior corneal shape, it was assumed that the cornea was meridionally symmetric and could be described by the following conic of revolution (Malacara, 1988), which is used in various forms (Atchison & Smith, 2000; Kiely, Smith, & Carney, 1984):

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

where c is the curvature (inverse radius) at the vertex (x_0, y_0). The y-axis is the axis of revolution of both the conic and the optical axis of the cornea. The conic constant (k) indicates how rapidly a surface flattens ($k < 1$) or steepens ($k > 1$) with distance from the apex, and thus indicates the degree to which an aspherical surface differs from the equivalent spherical form. According to the value of k, the surface is a hyperboloid when $k < 0$, a paraboloid when $k = 0$, a prolate ellipsoid when $0 < k < 1$, a circle when $k = 1$ and an oblate spheroid when $k > 1$. Three other parameters that are commonly used to describe a conic are the Q value (where $k = Q + 1$), the shape factor 'p' (where $k = p$) and the eccentricity e (where $k = -e^2 + 1$). The conic of revolution was fitted to both corneal surfaces at an aperture of 7.5 mm, and for each meridian the radius at the vertex and the k value were determined. To determine the radius of both corneal surfaces as a function of meridian, a $\cos^2$ function

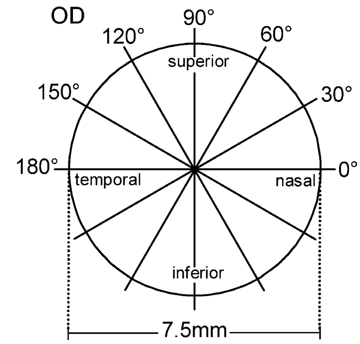

Fig. 1. Scheimpflug images were made at the indicated six meridians and analyzed at an aperture of 7.5 mm.

$$R(\theta) = R_1 - \Delta R\cos^2(\theta - \text{axis}).$$

was fitted to the radii of the six meridians in order to find either the maximal radius (R_1), the cylinder (ΔR) and the axis where the radius is minimal (Kiely, Smith, & Carney, 1982). The sign convention of the angle θ is shown in Fig. 1. In the first instance, it was assumed that the k value would exhibit similar periodic behaviour as the radius. Therefore, the $\cos^2$ function was also used to model the meridional variation of the k value.

3. Results

Fig. 2 shows the effect of correction of a Scheimpflug image. Note the change in the corneal thickness and the shape of the posterior surface.

3.1. Radius and astigmatism

Fig. 3 shows an example of the radius of curvature at the vertex (R) of the anterior and the posterior corneal surface

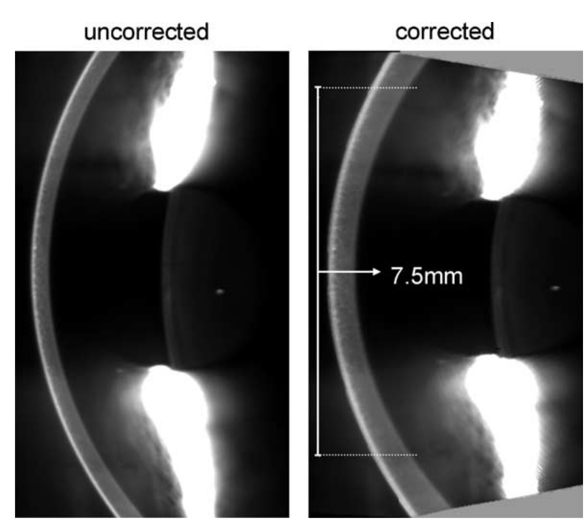

Fig. 2. Effect of correction of a Scheimpflug image. The aperture of 7.5 mm has been indicated in the corrected image.

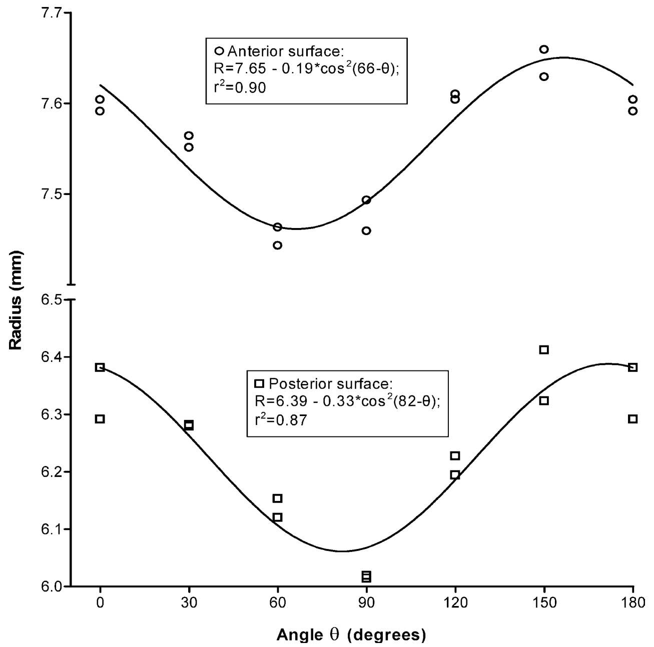

Fig. 3. Typical example for a 47-year-old female of the radius at the vertex of the anterior and the posterior corneal surface as a function of meridian. The solid line represents the $\cos^2$ function fitted through the 12 data points.

as a function of meridian, and Fig. 4 shows the variation in the k value in the same subject. The radius of curvature for both corneal surfaces could be well fitted using the $\cos^2$ function. To indicate that the function is periodic, the data points of 0° have also been plotted at 180°, but were included only once in the fit. The goodness of fit is less good for subjects with a small astigmatism. The average R squared ($r^2 \pm$ SD) for all subjects for the anterior and the posterior corneal surface was 0.84 ± 0.2 and 0.82 ± 0.15, respectively, but excluding subjects with astigmatism of the anterior corneal surface smaller than 0.5 diopter gave even better fits (0.91 ± 0.09 and 0.84 ± 0.15). The results of the radius for all subjects are summarized in Table 1, in which the whole group has also been sub-divided into males and females. The only statistical difference (unpaired t test) between genders was found for the radius of both the anterior and the posterior corneal surface (both $p < 0.01$). For all other parameters, including asphericity and trends with age, no gender difference could be observed.

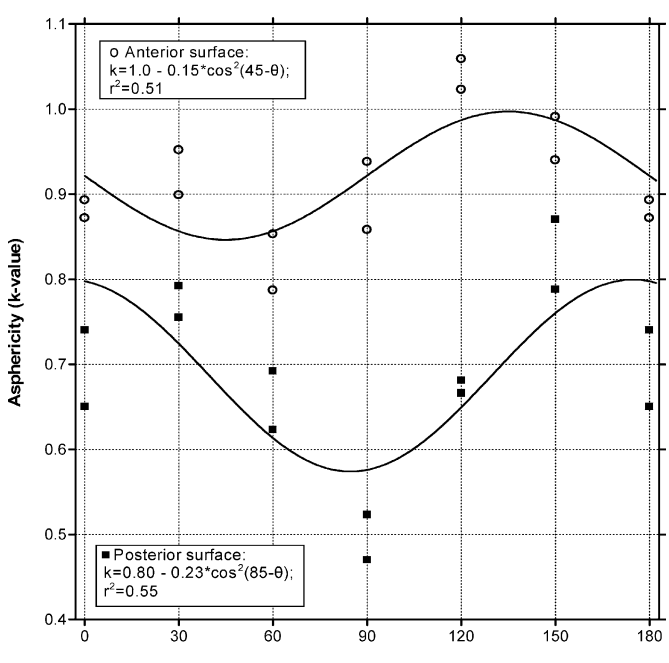

Fig. 4. Typical example of the variation of the k value as a function of meridian for the same subject as in Fig. 3. It can be seen that the $\cos^2$ function (solid line) is not an adequate model to describe the variation.

The mean central corneal thickness (±SD) was 0.579 ± 0.033 mm, which was not age-dependent ($r = 0.004$, $p = 0.97$). There was also no significant change with age in the mean radius of the anterior or the posterior corneal surface ($p = 0.97$ and $p = 0.26$, respectively). Both corneal surfaces were found to be flatter horizontally than vertically, and there was no significant difference between the axis of the two surfaces. Because the dioptric power of the anterior surface is positive while that of the posterior surface is negative, the astigmatism arising from the anterior surface is reduced by the astigmatism of the posterior surface. Furthermore, the cylindrical component in mm of the posterior surface was almost twice that of the anterior surface. The difference between the maximal and minimal radius of curvature of the posterior surface was thus significantly greater than that of the anterior surface.

There was a significant correlation between the mean radius ($R_1 + 0.5 * \Delta R$) of both corneal surfaces and the equivalent refractive error (ERE). The radius of curvature of both corneal surfaces tends to be smaller in myopic subjects than in hypermetropic subjects. This linear regression was more pronounced for the anterior surface (7.84 (±0.03) + 0.04 (±0.01) × ERE; $n = 114$; $r = 0.29$; $p = 0.002$) than for the posterior surface (6.56 (±0.03) + 0.02 (±0.01) × ERE; $n = 114$; $r = 0.19$; $p = 0.05$).

For the anterior corneal surface, there was good agreement between the results obtained with the Scheimpflug camera and the kerato-refractometer. The mean radius at the vertex ± SD of the anterior corneal surface measured with the kerato-refractometer was 7.768 ± 0.27 mm. The mean of the paired difference ± SD in the average radius of the anterior corneal surface obtained with the two methods was 0.025 mm ± 0.046 mm. The mean of the paired difference in cylinder ($\Delta R \pm$ SD) was 0.004 ± 0.065 mm, and the mean of the paired difference in axis ± SD was $2 \pm 18°$. If the difference in axis was calculated for only those subjects with a cylinder larger than 0.5 diopter, the difference ± SD decreased to $1 \pm 11°$.

3.2. Asphericity

The asphericity as a function of meridian could be fitted less well with the $\cos^2$ function than the radius (Figs. 3 and 4). The average $r^2 \pm$ SD of the fit for all subjects for the anterior and the posterior surface was 0.59 ± 0.26

Table 1
Mean and standard error values for the results of the fit of the $\cos^2$ function that was used to investigate the variation of the radius as a function of meridian

Subjects:	Males ($n = 57$)	Females ($n = 57$)	Total
Age-range:	18–65 years		
	Mean ± standard error (SE) Radius at the vertex		
Anterior cornea			
Mean radius (mm)	7.87 ± 0.04	7.72 ± 0.03	7.79 ± 0.025
R_1 (mm)	7.95 ± 0.03	7.80 ± 0.03	7.87 ± 0.025
ΔR (mm)	−0.16 ± 0.01	−0.16 ± 0.01	−0.16 ± 0.01
Axis (°)	93 ± 3	96.5 ± 4	95 ± 3
Goodnes of fit (r^2)	0.84 ± 0.03	0.83 ± 0.03	0.84 ± 0.02
Posterior cornea			
Mean radius (mm)	6.60 ± 0.03	6.456 ± 0.03	6.53 ± 0.2
R_1 (mm)	6.77 ± 0.03	6.61 ± 0.03	6.69 ± 0.02
ΔR (mm)	−0.33 ± 0.02	−0.32 ± 0.02	−0.325 ± 0.01
Axis (°)	93 ± 6	100.5 ± 5	97 ± 4
Goodnes of fit (r^2)	0.82 ± 0.02	0.83 ± 0.02	0.825 ± 0.01
Central thickness (mm)	0.581 ± 0.004	0.578 ± 0.005	0.579 ± 0.003
Ratio mean posterior/anterior radius	0.84 ± 0.02	0.84 ± 0.02	0.84 ± 0.01

Results are given for males ($n = 57$), females ($n = 57$) and the whole group ($n = 114$). R_1 refers to the flatter meridian, ΔR is the cylindrical component and the axis indicates the axis of the steepest meridian. Also shown are the corneal thickness and the ratio of the mean value of the radius of the posterior and the anterior corneal surface. The mean radius was calculated as: $R_1 + 0.5 * \Delta R$ (mm).

and 0.48 ± 0.26, respectively. Fig. 5 shows the r^2 as a function of the subjects with at least the amount of astigmatism of the anterior corneal surface indicated at the x-axis. In contrast with the radius, excluding subjects with a small astigmatism of the anterior corneal surface does not improve the goodness of fit for the asphericity. This indicates that the asphericity does not exhibit the same meridional variation as the radius. It appeared that the asphericity of both the anterior and the posterior surface was independent of the radius of curvature at the vertex and the refractive error.

Fig. 6 shows the average k value of the 12 measurements (two series of six meridians) of the anterior and posterior

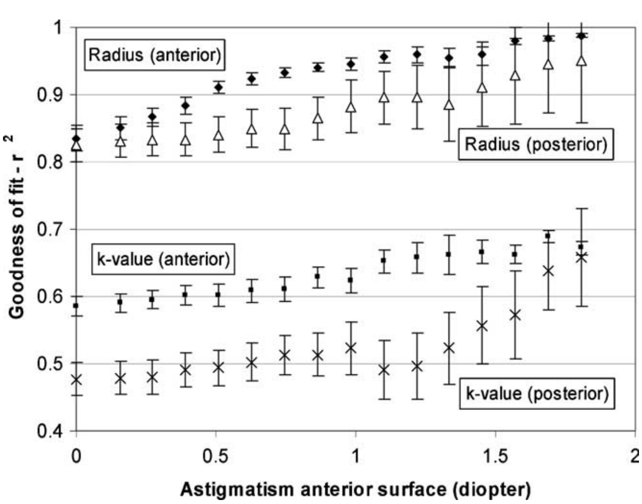

Fig. 5. The goodness of fit (r^2) of the cos2 function through the radius at the vertex and the asphericity of the anterior and the posterior corneal surface (see Figs. 3 and 4) as a function of the astigmatism of the anterior corneal surface. In contrast with the radius, the fit for the k value does not improve when the astigmatism increases.

asphericity as a function of age. The asphericity of both the anterior and the posterior surface show a significant change with age. On average, the k value for both surfaces is between 1 and 0, which indicates that the surfaces can be described by a flattened ellipse. The age-dependent increase and decrease in the k value of the anterior and the posterior surface, respectively, result in a peripheral thinning of the cornea. Fig. 7 shows the average shape of the cornea of an 18-year-old and a 65-year-old subject. Calculation shows that there was an average difference of 19 μm in peripheral thickness along the perpendicular line at 3.75 mm from the apex between the young and the old subject. Fig. 8 shows the variation in asphericity of both corneal surfaces for the six meridians in two age-groups (18 to 41.5 years and 41.5 to 65 years). For each subject, the two measurements for each meridian were averaged and the mean value (±standard error) for the age-group is given in the graph. It can be seen that there is no significant variation in the k value for each corneal meridian of the anterior corneal surface. The standard deviation (±SD) of the 12 measurements was 0.068 ± 0.029 (range 0.02–0.165), which was not age-dependent. Nevertheless, the posterior surface showed greater variation in the six meridians, with an average standard deviation (±SD) of 0.12 ± 0.042 (range 0.05–0.236). With age, this standard deviation increased significantly (linear regression: 0.09 (±0.27) + 0.0007 (±0.0003) * age; $r = 0.25$; $p = 0.007$). This greater variation with age can also be seen in Fig. 8. In the younger age-group, the maximal difference between the k values of the meridians of the posterior surface was 0.21, while it increased to 0.33 in the older age-group. For both groups the k value of the posterior surface is smallest for the vertical (90°) meridian. Table 2 shows the age-dependency of the k value for each meridian of both

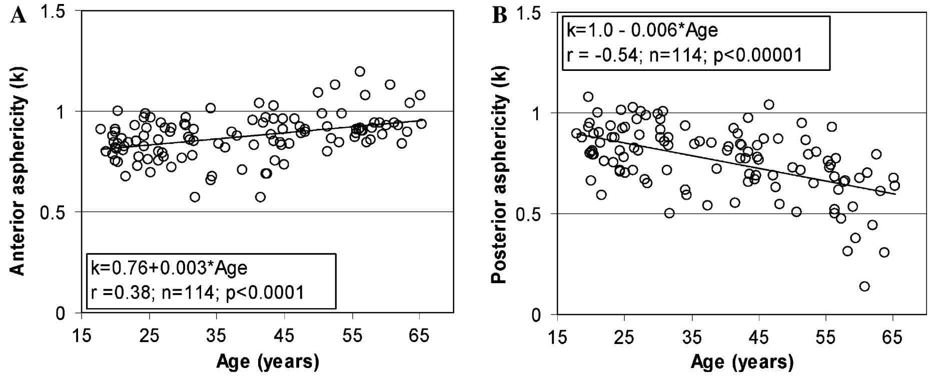

Fig. 6. The change in the mean asphericity of the anterior (A) and the posterior (B) surface of the cornea with age.

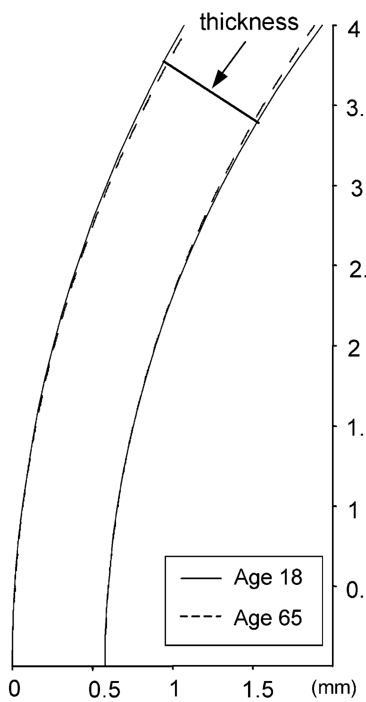

Fig. 7. Illustration of the peripheral thinning of the cornea with age. Indicated is the average shape for an 18-year-old subject (solid line) and a 65-year-old subject (dashed line).

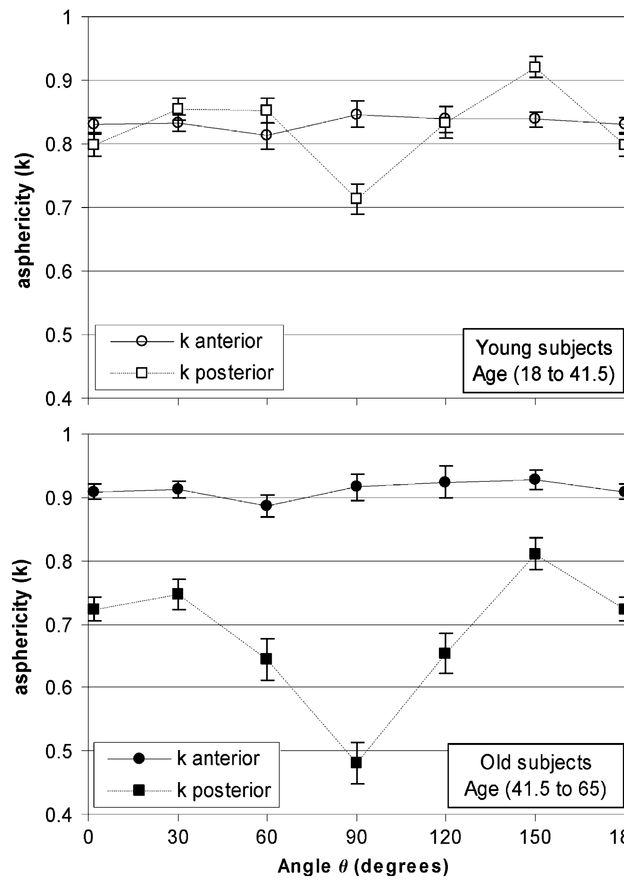

Fig. 8. Variation in asphericity as a function of meridian for both corneal surfaces for two age-groups (18 to 41.5 years and 41.5 to 65 years).

surfaces. Each meridian showed a significant change ($p < 0.01$) with age. The change with age for the anterior corneal surface did not differ significantly between meridians. For the posterior surface, the change in k value was greatest for the vertical meridian and smallest for the horizontal meridian.

Fig. 9 shows that there is no correlation between the posterior asphericity (k_p) as a function of the anterior asphericity (k_a). As a result, it is not possible to make a reliable prediction of the asphericity of the posterior surface based on the asphericity of the anterior surface alone. Nevertheless, if the anterior k value as well as the age is used, a reasonable assumption for the k value of the posterior corneal surface can be made. The multiple regression was computed to be: $k_p = 0.76 + 0.325 * k_a - 0.0072 * \text{age}$. Using this formula, the standard deviation of the difference between the predicted and measured posterior k value was 0.14. This makes it clear that, based on the age and the anterior asphericity, the posterior k value can be predicted with an accuracy of ±0.27 with a 95% confidence level.

4. Discussion

The aim of the study was to measure the radius, astigmatism, asphericity and thickness of the whole cornea, and in particular the posterior cornea as a function of age.

Table 2
The change in asphericity (k) as a function of age for all subjects ($n = 114$) and the linear correlation coefficient r

Asphericity (k)	Age-dependency	r
Anterior cornea		
Average k	0.76 (±0.027) + 0.0030 (±0.0007) × Age	0.39
0°	0.76 (±0.025) + 0.0026 (±0.0006) × Age	0.38
30°	0.77 (±0.027) + 0.0026 (±0.0007) × Age	0.36
60°	0.77 (±0.034) + 0.0022 (±0.0008) × Age	0.24
90°	0.78 (±0.04) + 0.0027 (±0.0007) × Age	0.24
120°	0.75 (±0.03) + 0.0037 (±0.0008) × Age	0.39
150°	0.76 (±0.027) + 0.0033 (±0.0007) × Age	0.43
Posterior cornea		
Average k	1.01 (±0.04) − 0.0062 (±0.0009) × Age	−0.53
0°	0.90 (±0.03) − 0.0036 (±0.0009) × Age	−0.37
30°	1.00 (±0.04) − 0.0051 (±0.001) × Age	−0.45
60°	1.09 (±0.05) − 0.0085 (±0.001) × Age	−0.58
90°	0.95 (±0.05) − 0.0087 (±0.001) × Age	−0.55
120°	1.06 (±0.05) − 0.0076 (±0.001) × Age	−0.53
150°	1.06 (±0.04) − 0.0050 (±0.001) × Age	−0.43
Ratio average k-post/k-ant	1.26 (±0.04) − 0.0095 (±0.001) × Age	−0.66

All meridians of both the anterior and the posterior corneal surface showed a significant change with age ($p < 0.01$). Also shown is the ratio of the mean value of the asphericity of the posterior (k-post) and the anterior corneal surface (k-ant), which also changed significantly with age.

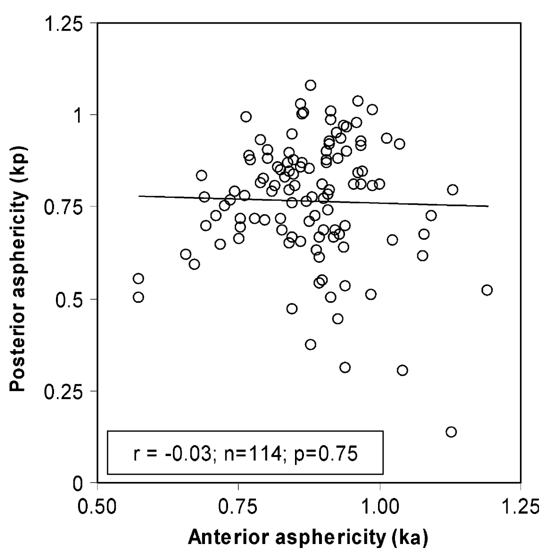

Fig. 9. The average posterior asphericity (k_p) as a function of anterior asphericity (k_a). There was no significant correlation.

4.1. Radius and astigmatism

Because the dioptric power of the anterior surface is positive while that of the posterior surface is negative, and because no significant difference was found between the cylinder axes of the two surfaces, the astigmatism of the anterior corneal surface (0.99 D) was compensated for 31% by that of the posterior corneal surface (−0.305 D). This reduction is greater than could be expected based on the astigmatism of the anterior surface, because the cylindrical component in mm of the posterior surface was almost twice the component of the anterior surface. The toricity of the posterior corneal surface thus does not simply reflect that of the anterior surface. This finding is supported by Dunne, Royston, and Barnes (1991) and Dunne et al. (1992) who reported similar results with Purkinje imaging. The fact that the cylindrical component of the posterior corneal surface is larger than that of the anterior corneal surface would imply a difference in peripheral thickness between the various corneal meridians. This has also been shown in other studies. Hirji and Larke (1978), using topographic pachometry, and Rüfer, Schröder, Arvani, and Erb (2005), using Scheimpflug imaging, found that the peripheral cornea was thicker vertically than horizontally. Because of the larger cylindrical component of the posterior surface, the ratio between the radius of the posterior and the anterior corneal surface is not constant. Usually, based on Gullstrand's values of 7.7 mm for the anterior radius and 6.8 mm for the posterior radius of the cornea, a fixed ratio of 0.883 is assumed. For the Le Grand schematic eye the ratio is 0.833 (Le Grand & El Hage, 1980). In the present study, an average ratio (±SD) of 0.84 ± 0.014 was found. For the vertical meridian, this ratio (±SD) was 0.824 ± 0.017, and for the horizontal meridian, it was 0.85 ± 0.014. These ratios agree well with the finding of earlier studies in which Purkinje imaging was used. For the vertical meridian, Garner et al. (1997) and Lam and Douthwaite (2000) found a ratio of 0.827 ± 0.017 and 0.83 ± 0.02, respectively. For the horizontal meridian, Dunne et al. (1992) and Lam and Douthwaite (2000) found both a ratio of 0.84. A fixed ratio between the radius of the anterior and posterior corneal surface is assumed to calculate an effective refractive index of the cornea. This index that varies from 1.3315 to 1.3375 is used in keratometry and cornea topography in order to estimate the corneal power from the radius of the anterior corneal surface (Bennet & Rabbets, 1998; Olsen, 1986). Nevertheless, even an effective refractive index of 1.3315, which is based on the ratio of the Gullstrand schematic eye is too high. According to the results of the present study, the average index (±SD) is 1.329 ± 0.001. Because the ratio between the radius of the anterior and posterior corneal surface is dependent on meridian, the effective refractive index (±SD) is 1.328 ± 0.001 for the vertical meridian and 1.330 ± 0.001 for the horizontal meridian. It must be noted that a change in the effective index of 0.001 gives a change in the calculated corneal power of approximately 0.13 D (Olsen, 1986).

The group was equally divided into males and females and it was found that the anterior and posterior corneal surface of the males was flatter than that of the females. For all other parameters, including asphericity and trends with age, no gender difference was observed. Dunne et al. (1992) found significantly ($p < 0.05$) more posterior corneal toricity in males ($n = 40$) than in females ($n = 40$), but in the present study, in which a larger group of subjects was measured, no significant difference was found.

4.2. Asphericity of the anterior corneal surface

In our earlier study, in which a smaller group of subjects and only the vertical meridian was measured, a significant change was only found in the asphericity of the posterior corneal surface. In the present study, in which the CCD-camera of the Scheimpflug camera had a higher resolution and a higher dynamic range, we also found an age-dependent change in asphericity of the anterior surface of the cornea. For all 6 meridians, the k value of the anterior surface showed a significant increase. Not all earlier studies found such a change in the asphericity of the anterior surface. Kiely et al. (1984), using photokeratoscopy, measured the shape of the anterior corneal surface of 54 males and 44 females ranging in age from 16 to 80 years of age, but found no significant change in asphericity with age. Using a videokeratoscope and an autokeratometer, Pardhan and Beesley (1999) measured the asphericity of the anterior surface of 20 young and 20 older subjects and found a significant shift to a more spherical surface, similar to that found in the present study. For both instruments, Pardhan and Beesley (1999) found an increase of 0.002 per year in the k value for the horizontal meridian, which is close to our finding of 0.0026 per year.

In the present study, the average k value of the anterior surface was 0.87, with a standard deviation of 0.11 and a range between 0.57 and 1.19, which indicates that the anterior surface appears to approximate an elliptical shape. The anterior surface of the cornea flattened in the periphery (k value < 1) in 97% of the subjects under the age of 40, but in only 84% of the subjects over 40 years of age. Thus, for 16% of the older subjects the k value is more than 1, which indicates that the cornea steepens toward the periphery. Fig. 8 shows that, in contrast with that of the posterior surface, the asphericity of the anterior surface does not vary significantly between meridians, which is in agreement with Kiely et al. (1984) and Guillon et al. (1986). Thus, there was no tendency for a different asphericity in any particular meridian. The average asphericity of 0.87 found in the present study, agrees well with the finding of earlier studies (ranging between 0.76 and 0.89) summarized in Eghbali, Yeung, and Maloney (1995). Furthermore, the radius, astigmatism and cylindrical axis of the anterior corneal surface measured with the kerato-refractometer were also in agreement with those obtained using the Scheimpflug camera. This was especially the case if subjects with small astigmatism were excluded.

4.3. Asphericity of the posterior corneal surface

A significant average change in the k value of −0.006 per year was found for the posterior surface, which indicates a shift to a more aspherical surface. The largest decrease was found around the vertical meridian (−0.0087 per year), while the smallest decrease was found in the horizontal meridian (−0.0036 per year). Nevertheless, all meridians showed a significant decrease with age. Because the k value for the anterior surface increases, while that of the posterior surface decreases, there will be a thinning of the cornea in the periphery. Although the change in k value of both corneal surfaces is highly significant, this peripheral thinning is only slight. At a distance of 3.75 mm from the apex, the thinning is approximately 20 μm between 18 and 65 years of age, which is on average 3% of the thickness of the cornea at that position. Rüfer et al. (2005) also found a peripheral thinning in the superior and nasal area with age. No significant change with age was found for the central corneal thickness, which is in agreement with the finding of other studies (Eysteinsson et al., 2002; Rüfer et al., 2005).

In contrast with that of the anterior surface, the asphericity of the posterior surface of the cornea varied significantly between meridians, and this variation became greater with age. The k value was smallest for the vertical meridian. There was no correlation between the posterior asphericity and the anterior asphericity and therefore, it is not possible to measure the asphericity of the anterior surface and make a reliable prediction of the asphericity of the posterior surface. Nevertheless, using the formula presented in the results section, which also considers the age, the posterior k value can be predicted with an accuracy of ± 0.27 with a 95% confidence level. Finally, the asphericity of both corneal surfaces was independent of gender and radius. This makes it clear that a steep cornea is not likely to be more or less aspheric than a flat cornea.

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