Optical aberrations of the human cornea as a function of age

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We investigated how the optical aberrations associated with the anterior surface of the human cornea change with age in a normal population. Aberrations were computed for a central part of the cornea (4, 5, and 6 mm in diameter) from the elevation data provided by a videokeratographic system. Measurements were obtained in 59 normal healthy, near-emmetropic [spherical equivalent lower than 2 diopters (D)] subjects of three age ranges: younger (20–30 years old), middle-aged (40–50 years old), and older (60–70 years old). The average corneal radius decreased with age and the cornea became more spherical. As a consequence, spherical aberration was significantly larger in the middle-aged and older corneas. Coma and other higher-order aberrations also were correlated with age. The root mean square of the wave aberration exhibited a linear positive correlation ($P < 0.003$) with age for the three ranges of pupil diameter. Despite a large intersubject variability, the average amount of aberration in the human cornea tends to increase moderately with age. However, this increase alone is not enough to explain the substantial reduction previously found in retinal image quality with age. The change in the aberrations of the lens with age and the possible loss of part of the balance between corneal and lenticular aberrations in youth may be the main factors responsible for the reduction of retinal image quality through the life span.
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1. INTRODUCTION

Many aspects of human vision, and in particular spatial vision, deteriorate with age.[1] The contrast sensitivity function is lower in older subjects, in particular at middle and high spatial frequencies.[2] Although a combination of optical and neural factors are responsible for this deterioration, the reduction in retinal image quality seems to account for an important fraction of this loss in spatial vision.[3,4] The average ocular modulation transfer function (MTF), previously measured in three age groups, declines progressively with age.[4] This suggests that, in addition to an increase in intraocular scattering, there is a significant and steady increment in ocular aberrations with age, which produces a degraded retinal image.

The underlying causes for this increment in the aberrations of the aging eye are not yet completely understood. Although several studies have shown a changing crystalline lens through the life span,[5,6] the final retinal image depends on the balance between the aberrations of the lens and of the cornea.[7,8] Despite the fact that the change with age of the corneal radius and of the astigmatism axis are well known, very few studies have explored the change in the optical quality of the cornea with age.[9,10] In this paper we further study how the aberrations associated with the anterior surface of the cornea, measured by computerized videokeratography, change with age in a normal healthy population, and we discuss the impact of this change on final image quality.

2. METHODS AND SUBJECTS

A. Procedure to Estimate the Aberrations from Corneal Elevations

We applied a computational procedure to estimate the optical aberrations produced by the anterior corneal surface (see Ref. 11 for complete details describing the procedure and its accuracy). The corneal elevations (height), z, provided by a videokeratographic system (MasterVue system, Humphrey Instruments) were fitted to a fourth-order Zernike expansion (Table 1),[12]

$$z(\rho, \theta) = \sum_{i=1}^{15} a_i Z_i(\rho, \theta), \tag{1}$$

by use of a Gram–Schmidt orthogonalization method.[13] From the Zernike coefficients a_4 and a_9, the average radius (R) and asphericity (K) of the cornea were calculated by means of the equations

$$R = \frac{{r_0}^2}{2(2\sqrt{3}a_4 - 6\sqrt{5}a_9)}, \qquad K^2 = \frac{8R^3}{{r_0}^4} 6\sqrt{5}a_9, \tag{2}$$

where r_0 is the radius of the pupil. The wave aberration for the cornea (W) was calculated as the difference in optical path between the chief ray and the marginal rays over the pupil. A pupil centered on the videokeratographic axis was considered. Taking into account the

Table 1. Zernike Polynomials up to Fourth Order (15 Terms) Used in This Study

a_k	$Z_k\ (\rho, \theta)$	Correspondence to Seidel Aberrations
a_1	1	Constant
a_2	$2\rho \cos \theta$	Tilt
a_3	$2\rho \sin \theta$	Tilt
a_4	$\sqrt{3}(2\rho^2 - 1)$	Defocus
a_5	$\sqrt{6}\rho^2 \cos 2\theta$	Astigmatism
a_6	$\sqrt{6}\rho^2 \sin 2\theta$	Astigmatism
a_7	$\sqrt{8}(3\rho^3 - 2\rho)\cos \theta$	Coma
a_8	$\sqrt{8}(3\rho^3 - 2\rho)\sin \theta$	Coma
a_9	$\sqrt{5}(6\rho^4 - 6\rho^2 + 1)$	3rd-order spherical
a_{10}	$\sqrt{8}\rho^3 \cos 3\theta$	
a_{11}	$\sqrt{8}\rho^3 \sin 3\theta$	
a_{12}	$\sqrt{10}(4\rho^4 - 3\rho^2)\cos 2\theta$	
a_{13}	$\sqrt{10}(4\rho^4 - 3\rho^2)\sin 2\theta$	
a_{14}	$\sqrt{10}\rho^4 \cos 4\theta$	
a_{15}	$\sqrt{10}\rho^4 \sin 4\theta$	

Zernike representation for the corneal surface [Eq. (1)], we also obtained the wave aberration as a Zernike expansion,

$$W(\rho, \theta) = \sum_{i=1}^{15} A_i Z_i(\rho, \theta), \tag{3}$$

where the coefficients A_i are linear combinations of the coefficients a_i. The Seidel spherical and Seidel coma aberrations (SSA's and SC's, respectively) were calculated by

$$\mathrm{SSA} = 6\sqrt{5}A_9, \qquad \mathrm{SC} = 3\sqrt{8}\sqrt{{A_7}^2 + {A_8}^2}, \tag{4}$$

and the root mean square (RMS) of the wave aberration, used as an overall index of image quality, was computed from the Zernike coefficients as

$$\mathrm{RMS} = \sqrt{\sum_{j=7}^{15} {A_j}^2}. \tag{5}$$

The MTF for the anterior corneal surface was also computed from the wave aberration,[14] allowing comparison of these functions with those previously measured for the complete eye.[4] Wave aberrations and MTF's were obtained for pupils of 4, 5, and 6 mm diameter.

For a pupil of 4–6 mm diameter, the procedure, tested with calibrated reference surfaces,[11] permits estimation of the corneal height with an accuracy of 1–2 μm. These values allow us to estimate the corneal wave aberration with an accuracy of 0.05–0.2 μm, which renders the method sufficiently accurate for this study.

B. Selection of Subjects

The subjects participating in the study were selected to represent a normal healthy population. Measurements were obtained in three groups of subjects: (1) 27 young subjects (20–30 years old: 16 women, 11 men) with a mean age of 24 years (3 yr standard deviation; (2) 15 middle-aged subjects (40–50 years old: 5 women, 9 men) with a mean age of 46 years (3 yr standard deviation); and (3) 17 older subjects (60–70 years old: 9 women, 8 men) with a mean age of 63 years (3 yr standard deviation). The subjects were Caucasian and were selected after

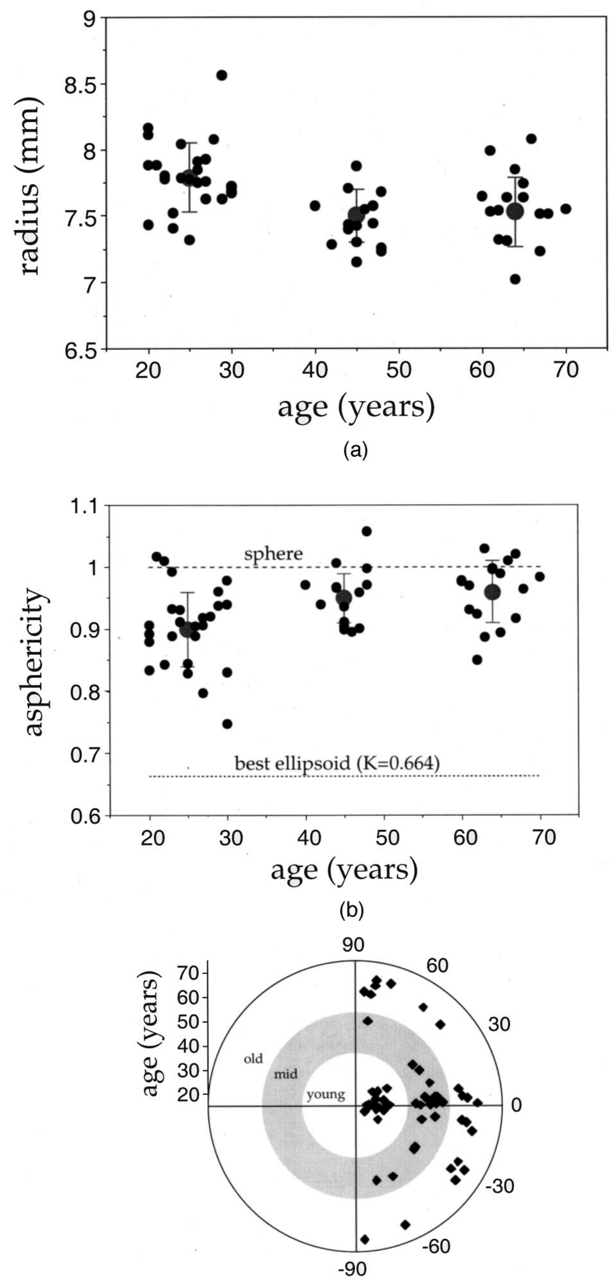


Fig. 1. (a) Corneal radius of curvature for each subject and mean value for each age group; error bars are two standard deviations. (Significant correlation with age: $r = -0.37$; Student t test, two tailed, $t = -3.04$, $P < 0.004$). (b) Asphericity for each subject and mean value with error bars for each age group. Value of 1 corresponds to a sphere. Value of 0.664 corresponds to an ellipsoid with null third-order spherical aberration; we used $n' = 1.3375$. (Significant correlation: $r = 0.42$; $t = 3.49$, $P < 0.001$). (c) Axis of the corneal meridian with larger curvature for each subject. The radius in the polar plot represents the subject's age.

passing an ophthalmologic exam. The following exclusion criteria were used to limit the study population to healthy eyes: refractive error (spherical equivalent) more than 2 D, keratometric astigmatism more than 1.5 D, corrected visual acuity lower than 1 (0.8 for the group of older subjects), any previous surgery on the eye to be tested, amblyopia, any known ocular or retinal pathology (assessed by slit-lamp with and without retroillumination with standard clinical criteria) and any systemic diseases affecting refractive error (diabetes or disorders of the nervous system). Signed informed consent was obtained from each subject after the nature and all possible consequences of the study had been explained.

3. RESULTS

Figures 1(a), 1(b), and 1(c) show the values of the corneal radius (R), asphericity (K), and axis of astigmatism, respectively, as a function of the age of each subject. The mean corneal radius decreases with age, and the overall shape of the cornea tends to a sphere from an ellipsoid as age increases. These changes are statistically significant (Student t test, two tailed: $t = -3.04$, $P < 0.004$, for the radius; and $t = 3.49$, $P < 0.001$, for the asphericity), and they occur mostly between the younger and the middle-aged-subjects. In addition, as is well known clinically, astigmatism is largely horizontal (with the rule) in the younger subjects, becoming predominantly vertical (against the rule) and oblique in the older subjects.

Figures 2(a) and 2(b) show the amount of the Seidel spherical aberration and coma, respectively, expressed in micrometers, as a function of the age of each subject, for a pupil 4 mm in diameter. The average magnitude of the spherical aberration was larger (more negative) in the middle-aged and older corneas than in the younger counterparts. The correlation of spherical aberration with age is statistically significant (correlation coefficient: $r = -0.54$; Student t test, two tailed: $t = -4.88$, $P < 0.0001$). Coma shows larger variability, although the mean value increases linearly with age. The correlation of coma with age is weak but statistically significant ($r = 0.26$; $t = 2.03$, $P < 0.05$).

The other third-order terms in the Zernike expansion of the wave aberration also increased with age. Figure 3 shows the RMS of the wave aberration for each subject in micrometers, for a 4-mm-diameter pupil. The RMS exhibits a strong positive correlation with age ($r = 0.5$; $t = 4.33$, $P<0.0001$).

For pupils 5 mm and 6 mm in diameter, the corneal aberrations (coma, spherical, and other higher-order aberrations) also showed a statistically significant increment with age. The RMS of the wave aberration with age presents a linear positive correlation (5 mm: $r = 0.44$; $t = 3.63$, $P < 0.001$; 6 mm: $r = 0.37$; $t = 3.03$, $P < 0.03$). Table 2 shows the mean values and the standard deviation of the corneal aberrations for pupils of 4 mm and 6 mm for the three age groups. The hypothesis testing showed significant differences between the means of each pair of groups for both pupil diameters except for the case of spherical aberration, which presents a mean that is statistically equal in the middle-aged and the older groups.

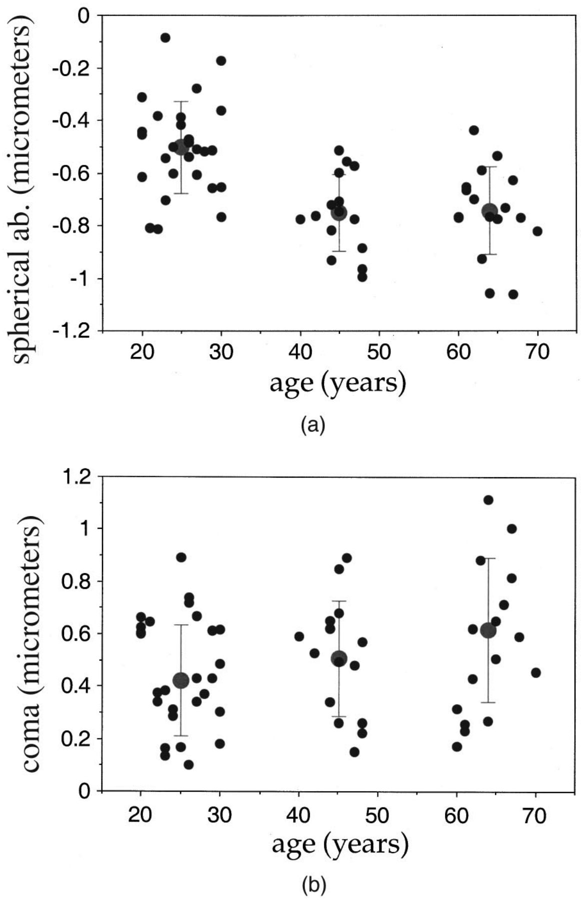


Fig. 2. (a) SSA coefficient for 4-mm-diameter pupil, as a function of the age of each subject, and mean value with error bars (two standard deviations) for the three groups. (Significant correlation with age: $r = -0.54$; $t = -4.88$, $P < 0.0001$). (b) SC, 4-mm pupil for each subject and mean value with error bars (two standard deviations). (Significant correlation: $r = 0.26$; $t = 2.03$, $P < 0.05$).

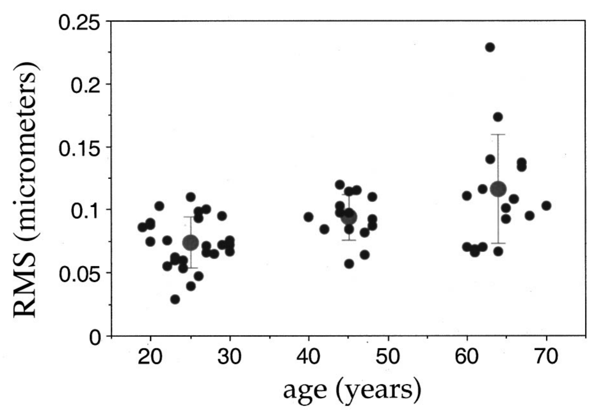


Fig. 3. Statistically significant correlation with age of the RMS of the corneal wave aberration (4-mm-diameter pupil) and mean values. ($r = 0.5$; $t = 4.33$, $P < 0.0001$).

Figure 4 presents, as an example, wave-aberration maps for four younger and four older subjects. The maps corresponding to older subjects present a larger magnitude of aberrations (represented by more gray-level variations and line phase steps), and they are also more irregular.

The corneal MTF was calculated from the estimated wave aberration in each subject. Figures 5(a) and 5(b) show the averaged MTF's, for 4 mm and 6 mm, respectively, for the younger subjects (solid curves), the middle-aged subjects (dashed curves) and the older subjects (dotted curves). Although owing to the increase in corneal aberrations these MTF's deteriorate with age, this cannot alone explain the substantial reduction found in the overall ocular MTF [Fig. 7(b) of Ref. 4]. For example, for the 4-mm pupil the ocular MTF decreased ~45% from the middle-aged to the older group, while it remains practically constant for the cornea.

4. DISCUSSION

The average amount of aberrations in the human cornea tends to increase with age. Although there is large inter-subject variability, the tendency for middle-aged and older corneas to be more aberrated than the younger counterparts is statistically significant. The increment of coma, spherical aberration, and higher-order aberrations with age is significant for all pupil sizes considered (4, 5, and 6 mm). These results are in part different from those obtained recently by Oshika *et al.*,[10] since those authors obtained an increment in overall aberrations with age only for the larger pupil diameter (7 mm) and an invariant spherical aberration with age. An explanation for these somewhat different results could be the different analysis procedures used in the two studies. The calculation used by Oshika *et al.*,[10] based on obtaining a remainder lens after subtracting the best-fitted sphere, could underestimate the actual results of the spherical aberration in the cornea.[11]

The results presented here suggest that the optical performance of the anterior corneal surface decreases with

Table 2. Mean Values of the Corneal Aberrations in the Three Age Groups and Statistical Significance of the Differences between Younger and Older Subjects

	4-mm-Diameter Pupil			6-mm-Diameter Pupil		
Age Group	SSA (μm)	SC (μm)	RMS (μm)	SSA (μm)	SC (μm)	RMS (μm)
Younger	-0.50 ± 0.17	0.45 ± 0.21	0.07 ± 0.02	-2.57 ± 0.77	1.59 ± 0.76	0.22 ± 0.08
Middle	-0.75 ± 0.14	0.51 ± 0.22	0.09 ± 0.02	-3.47 ± 0.68	1.71 ± 0.76	0.27 ± 0.08
Older	-0.74 ± 0.16	0.57 ± 0.28	0.11 ± 0.04	-3.55 ± 0.72	2.00 ± 0.80	0.30 ± 0.11
Confidence level	99.98%	87.1%	99.98%	99.98%	90.9%	99.1%

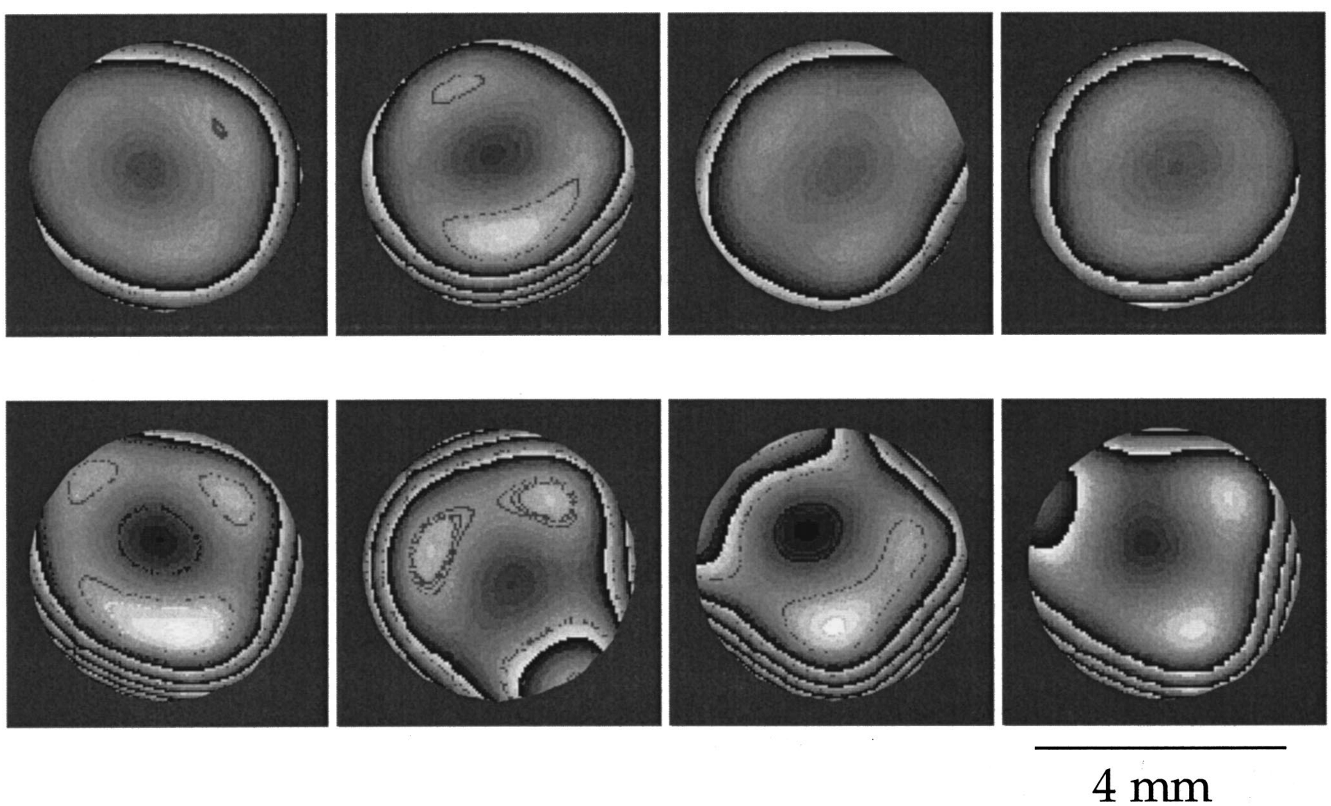
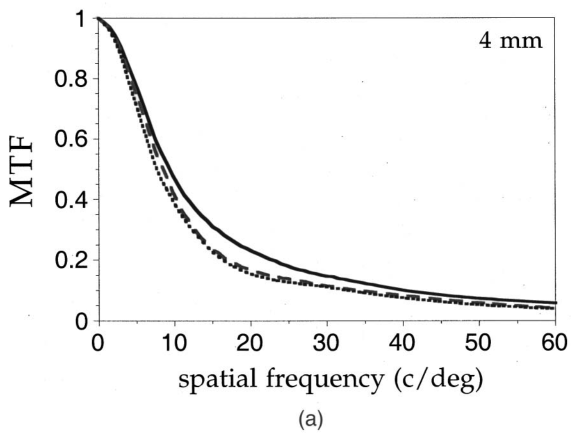


Fig. 4. Example of wave-aberration maps (wrapped to π phase steps), for a pupil of 4 mm for the corneas of four younger subjects (upper images) and four older subjects (lower images). The larger number of fringes in the older group indicates a larger amount of aberrations than in the younger group.



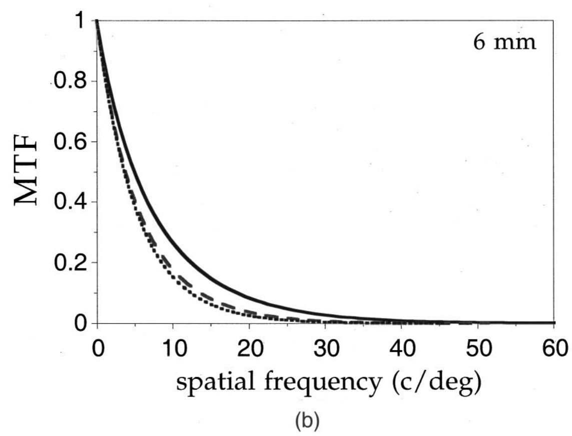


Fig. 5. MTF's for the average cornea for the three age groups: younger (solid curves), middle-aged (dashed curves) and older subjects (dotted curves). (a) 4-mm pupil, (b) 6-mm pupil.

age in healthy subjects. This could be understood as a tendency of the cornea to become more spherical with age, increasing spherical aberration, and more irregular, increasing coma and other higher-order asymmetric aberrations.

A nonlinear model may be more adequate to describe the correlation of spherical aberration with age. The increase in spherical aberration is due to a change in the asphericity of the cornea, which occurs from younger to middle-aged subjects. Figure 1(b) suggests that an asymptotic change of the cornea reaches a spherical shape (mechanically stable) from an initial ellipsoid. If the cornea stabilizes in a spherical shape, a continuous linear increase in spherical aberration (with an exponential model analysis the correlation coefficient increases up to 0.6) should not be expected.

It is important to point out the large intersubject variability. There are individual subjects in the older group with lower aberrations than others in the younger group, although the trend of increasing aberrations is consistent. It is not possible to know from this cross-sectional study whether the older subjects with good corneal image quality are precisely those who also had corneas with good image quality in their youth.

These results were derived from the corneal elevation data provided by computerized videokeratography. One major concern is whether these devices measure the corneal shape with enough accuracy to produce fine-aberration results.[15] In fact, there are two major sources of error when the aberrations are obtained from the shape of the cornea. One is the measurement of the corneal shape itself, and the other is the calculation procedure used to obtain the aberrations. In an earlier study[11] we tested the procedure with calibrated surfaces, obtaining a difference between the theoretical and the measured aberration of 0.05 μm for pupils 4 mm in diameter and ~0.2 μm for 6-mm pupil diameter. These errors are one order of magnitude lower than the values of corneal aberrations measured for the same pupils (see, for example, spherical aberration and coma in Table 2) and 3–5 times lower than their standard deviation.

Considerable effort is being devoted to the development of standards for reporting ocular aberrations. One recommendation is the use of the line of sight as the reference axis.[16] We obtained corneal aberrations for a pupil centered on the videokeratographic axis. Oshika *et al.*[10] calculated them for a pupil centered on the eye's natural pupil. These alignments might differ from an alignment coaxially with the line of sight. This possibility should be taken into account when one is comparing absolute aberrations measured under various conditions. However, this issue does not affect the conclusions from our comparative study in different age groups, since the same alignment was systematically carried out for all subjects.

Our current study deals only with the anterior surface of the cornea, which contributes the most to corneal aberrations. We used an effective refractive index (1.3375) in the calculation of the aberrations, which incorporates, in part, the effect of a constant back corneal surface. Although the posterior surface may also evolve with age, modifying somewhat the amount of aberrations of the complete cornea, it is highly unlikely that the effect of the second surface, separating media with similar refractive indexes, will modify the tendency to larger aberrations with age found in the anterior surface.

The average reduction found in the image quality of the cornea cannot explain completely the observed decrease in the optical performance of the complete eye with age.[3,4] This fact leads us to another important question: How does age change the relationship between the aberrations of the cornea and of the internal surfaces of the eye? In other words, is the increase in the aberrations of the whole eye with age due to an increment in the aberrations of each ocular component, or rather to a progressive decoupling of the aberrations? In the younger subjects the spherical aberration of cornea and lens are usually opposite in sign, leading to an eye with lower spherical aberration.[7,8,17] We have suggested that other corneal aberrations may also be compensated by the lens,[8] although other studies did not find a systematic compensation of the aberrations of cornea and lens.[18] The lens dramatically changes its shape and effective refractive indices, and consequently its aberrations, with age. Studies in isolated lenses[6] show that spherical aberration changes in sign and magnitude during the life span. On the other hand, our results show that also the aberrations of the cornea evolve with age, although to a lesser degree than those of the complete eye. It is possible that at least a part of the increment in aberrations of the eye with age is due to the loss of the aberration balance between cornea and lens that seems to be present in the younger eye.

Finally, this study contains a series of clinical implications. For instance, the design of intraocular lenses and contact lenses should in general be adapted to the optical properties of the aging cornea, and the ranges of normality of the corneal optics for a population should be divided into appropriate age ranges. Furthermore, any attempt to improve vision by correcting higher-order aberration (contact lenses or laser surgery) should consider the change of the cornea through the life span.

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