Contributions of the cornea and the lens to the aberrations of the human eye

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The relative contributions of optical aberrations of the cornea and the crystalline lens to the final image quality of the human eye were studied. The aberrations of the entire eye were obtained from pairs of double-pass retinal images, and the aberrations of the cornea were obtained from videokeratographic data. Third-order spherical aberration and coma were significantly larger for the cornea than for the complete eye, indicating a significant role of the lens in compensating for corneal aberrations. In a second experiment retinal images were recorded in an eye before and after we neutralized the aberrations of the cornea by having the subjects wear swimming goggles filled with saline water, providing a direct estimate of the optical performance of the crystalline lens.

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Optical aberrations in the human eye impose a major physical limit on spatial visual performance. The two main contributors to the overall aberrations in the eye are the anterior surface of the cornea and the crystalline lens. How the aberrations of the cornea and the lens contribute to the final quality of the images on the retina is a central problem in physiological optics. In 1801 Young[1] performed an experiment in which he tried to measure the contribution of the lens to the entire ocular astigmatism in his own eye after compensating for the corneal contribution by immersing the eye in water. Other more recent studies carried out to separate out the aberrations of cornea and lens in the eye have concentrated mostly on spherical aberration.[2,3] To explore further the relative contributions of the cornea and the lens to overall ocular aberration, we performed two complementary experiments. First, the aberrations of the entire eye were calculated from pairs of double-pass retinal images, and the aberrations of the cornea were obtained from videokeratographic data. Third-order spherical aberration and coma were significantly larger for the cornea than for the complete eye, which suggests that the lens compensates for the corneal aberrations. This prediction was confirmed in a second experiment, in which retinal images were recorded in an eye before and after we neutralized the aberrations of the cornea by having the subjects wear swimming goggles filled with saline water, providing a direct estimate of the optical performance of the crystalline lens.

The first experiment consisted of measuring the wave aberration (WA) of both the cornea and the complete eye. By combining these two sets of data, we estimated the aberrations of the lens by direct subtraction. The procedure that we used to measure the WA of the entire eye involved recording double-pass retinal images and subjecting them to further computations. Retinal images of a point source were recorded with a scientific-grade cooled CCD camera after light was reflected back into the retina and double passed through the ocular medium.[4] Two different double-pass retinal images, one with equal-diameter pupils for both the entrance and the exit apertures and the other with unequal pupil diameters,[5,6] were required for a correct estimate of the ocular aberrations. From these two double-pass retinal images the ocular point-spread function of the eye was reconstructed.[7] Next the WA was computed[8] from the point-spread function as a Zernike polynomial expansion[9] by use of phase-retrieval techniques, whereas the aberrations introduced by the anterior surface of the cornea were calculated from the corneal shape,[10] measured with a videokeratographic device (MasterVue corneal topography system; Humphrey Instruments, San Leandro, Calif.). Once the anterior corneal surface was modeled, the difference in optical path between the chief ray and a marginal ray over the pupil yielded the WA for the cornea and also a Zernike polynomial expansion. A calibration of the complete procedure for measurement of corneal aberrations was performed with reference surfaces.[11] For a central area of 4 mm in diameter in the cornea, the rms error between the actual and the measured aberrations was $\sim 0.1\ \mu$m, which means that the method was accurate for this study.

From the WA's, the relative contribution of the cornea to the overall ocular aberrations and the role of the lens were evaluated. In a simple model, with two series of aberration coefficients for the Zernike terms for both the cornea and the eye, the aberrations of the lens were obtained by direct subtraction of each pair of coefficients. We carried out the complete set of measurements and subsequent calculations with data from the eyes of five normal young subjects. Double-pass retinal images were recorded with paralyzed accommodation (we used cyclopentholate 1%), monochromatic green light (543 nm), and an artificial pupil of 4 mm in diameter. Figure 1 shows the results for one of the subjects. In this subject, and in all the others with small amounts of astigmatism, the magnitude of corneal aberrations was significantly larger than the aberrations in the complete eye. This result implies that the lens compensates, at least in part, for aberrations of the cornea.

Since a different balance of aberrations between cornea and lens was found for each subject, a more

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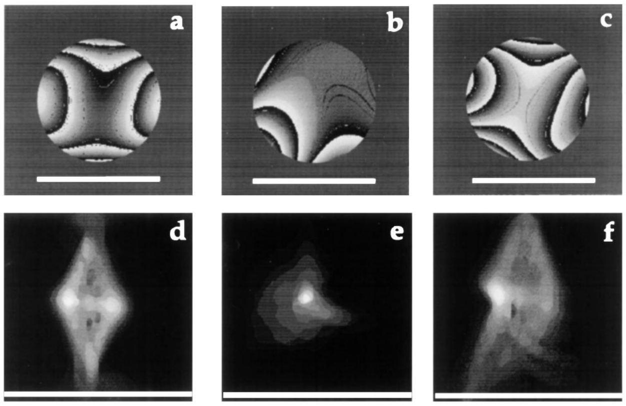

Fig. 1. Results for subject AG: WA's, represented module-$\boldsymbol{\lambda}$, for a, the cornea, b, the complete eye, and c, the lens. The bars represent 4 mm over the pupil. The associated point-spread functions for d, the cornea, e, the complete eye, and f, the lens, were calculated at best focus. The bars represent 20 min of arc of visual field.

detailed analysis in terms of the Seidel aberrations and the overall quality is also presented. Table 1 shows the values of the third-order spherical aberration, coma, and astigmatism for the cornea, the lens, and the whole eye in the five subjects. In every case, confirming previous findings,[2,3] most of the negative spherical aberration of the cornea should be canceled by the lens, since the complete eye presents a smaller amount of spherical aberration. On average, ~80% of the spherical aberration of the cornea is compensated for by the lens. The magnitude of third-order coma of the cornea was also reduced by the lens in every subject. The complete eye presented an average reduction of ~50% in the magnitude of coma in comparison with the cornea. However, astigmatism was modified differently in each subject. In three of the subjects significant values of corneal astigmatism were practically canceled by the lens, and in the other two subjects the overall astigmatism was larger than that of the cornea. Although in general (except for astigmatism in two subjects) the main Seidel aberrations are smaller in the entire eye than in the cornea, the contribution of the asymmetric fourth-order terms of the aberrations was larger in the complete eye than in the cornea in every subject. However, it should be noted that the fourth-order terms are one order of magnitude smaller than the third-order aberrations. To estimate the overall contribution to the image quality, we computed the modulation transfer function (MTF) for the complete eye, the cornea, and the lens (Fig. 2). For eyes with total astigmatism of less than 0.5 D, in terms of the overall image quality the complete eye performed better than either the isolated cornea or the lens. This indicates a significant reduction in the magnitude of the aberrations from the cornea to the complete eye in those subjects. In all the subjects the magnitude of the aberrations of the isolated lens was larger than the overall aberrations in the complete eye.

To further validate the previous results, we performed a second experiment with one of the subjects (PA). We modified a double-pass apparatus to record double-pass retinal images at best focus when the corneal contribution to the refractive power of the eye, and to the aberrations, was canceled by immersion of the eye in saline water.[12] A hole in the swimming goggles along the optical axis was covered by a high-quality optical window, and the goggles were filled with saline water. Since the eye becomes extremely hyperopic in water, we specifically constructed the double-pass setup to compensate for large amounts of defocus. The subject (an experienced subject for this type of experiment) looked for the best subjective centration and focus. Double-pass images were recorded without goggles and with the goggles filled with water, and then the MTF's were obtained from the double-pass images.[6] These two MTF's, one for the entire eye and the other corresponding approximately to only the lens, are presented in Fig. 3. According to the results in the first series of measurements, in this particular subject the isolated lens should have a lower MTF than the complete eye. A comparison of Figs. 2b and 3 shows that this is in fact the case. This second experiment further confirms, from the point of view of the overall optical performance, that corneal and lens aberrations tend to cancel each other. This result represents an example of the coupling of two optical systems, in this case the cornea and the lens, both with relatively poor optical quality, to form a system with better optical performance. This balance of aberrations may explain some poorly understood facts. For

Table 1. Values (in λ) of the Seidel Aberrations (4-mm Pupil Diameter)

		Subject				
Seidel Aberration	Structure	AP	PA	AG	RP	PR
Spherical	Cornea	−1.63	−1.34	−1.57	−0.7	−0.65
	Complete eye	−0.12	−0.05	−0.36	−0.14	−0.45
	Lens	1.51	1.29	1.21	0.56	0.2
Coma	Cornea	2.01	0.61	0.31	0.69	0.56
	Complete eye	1.27	0.32	0.15	0.21	0.17
	Lens	−0.74	−0.29	−0.16	−0.48	−0.39
Astigmatism	Cornea	1.45	2.1	3.43	1.21	2.55
	Complete eye	2	0.98	1.63	1.77	0.24
	Lens	0.55	−1.12	−1.8	0.56	−2.31

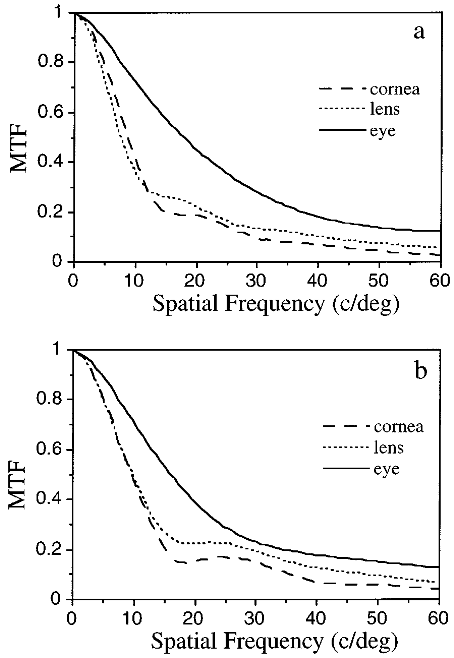

Fig. 2. MTF's calculated from the WA's of the cornea, the complete eye, and the lens at best focus, with a 4-mm pupil diameter, for two subjects, a, PR and b, PA.

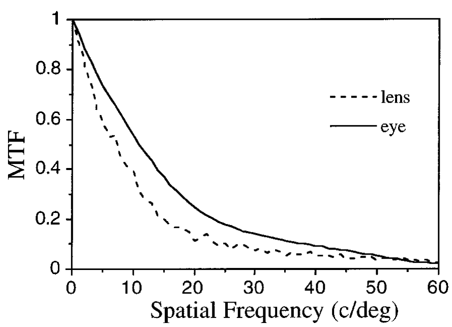

Fig. 3. MTF's measured for the complete eye and for the lens (with the subject wearing swimming goggles filled with saline water) at best focus with 4-mm pupil diameter for subject PA. These MTF's were computed directly from the double-pass retinal images and therefore include all the aberrations, so they are lower than the MTF's in Fig. 2b for the same subject, which include only 15 terms in the expansion of the Zernike polynomials.

instance, after implantation of intraocular lenses with extremely good image quality when measured in isolation on an optical bench, the final optical performance in the implanted eye is lower than expected. In particular, the MTF measured in patients implanted with monofocal intraocular lenses[13] was found on average to be similar to that of normal subjects of a similar age.[14] The reason could be that the ideal substitute for the natural lens is not the intraocular lens with the best performance when measured in isolation but that which is compensating for the aberrations of each cornea.

The results that have been presented here may have an effect on applications. Intraocular and contact lenses could be designed with an aberration profile matching that of the cornea or the lens, which would maximize the quality of the retinal image. Future procedures in refractive surgery could reflect consideration of the most adequate corneal shape in terms of the best retinal image that one can achieve after considering the patient's lens aberrations. In addition, there are also some possible applications in studies of development and aging of the human eye, for instance, to understand better how aberrations of the lens evolve with age and their relationship to presbiopya or how in the earlier stages of ocular development the cornea and the lens reach the final compensation for aberrations. An additional question is how this aberration compensation develops, that is, whether it is genetically determined or there are actually feedback mechanisms during earlier development stages that optimize image quality.

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