Corneal and total optical aberrations in a unilateral aphakic patient

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Purpose: To measure corneal and total optical aberrations in the normal and treated eye of a unilateral aphakic patient to (1) cross-validate techniques in an eye in which corneal and total aberrations should be almost identical (aphakic eye) and (2) compare the interactions of corneal and internal aberrations in the normal eye with those in the aphakic eye.

Setting: Instituto de Óptica, Consejo Superior de Investigaciones Científicas, Madrid, Spain.

Methods: Aberrations in both eyes of a unilateral aphakic patient were measured using laser ray tracing. Corneal aberrations were obtained from corneal elevation data measured with a corneal videokeratoscope (Humphrey Instruments) using custom software that performs virtual ray tracing on the measured front corneal surface.

Results: There was a 98.4% correspondence between the total and corneal aberration pattern in the aphakic eye (6.5 mm pupil). In the normal eye, the total spherical aberration was much lower than the corneal spherical aberration; this did not occur in the aphakic eye.

Conclusions: The posterior corneal surface contributed slightly to the aberrations in the normal cornea (2% at most). The crystalline lens appears to play a compensatory role in the total spherical aberration in normal eyes.

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In the past few years, interest in the optical quality and optical aberrations of the eye has increased. Various techniques and measurement systems have been developed,[1–5] and applications of these tools have started to reach the clinical environment. Recent studies such as the change in optical quality with refractive surgery,[6] optical aberrations after keratoplasty,[7] implanted intraocular lens (IOL) performance after cataract surgery,[8] and optical aberrations in corneal pathologies (ie, keratoconus)[9,10] are examples of the capabilities of the new techniques in the clinic.

Several studies have shown that powerful information is obtained when corneal and total aberrations are measured in the same eye.[11–14] The 2 types of measurements can separate the contribution of the cornea[15] and the internal aberrations (ie, crystalline lens) as well as their interrelationship.[16] Measurements in normal young eyes have shown that the lens has a compensatory effect on the spherical aberrations of the cornea,[12,13] even in asymmetric aberrations such as coma.[12] By comparing corneal and total wavefront maps in the same patients before and after standard laser in situ keratomileusis (LASIK), Marcos and coauthors[14] noted an increase in spherical aberration toward more positive values (due to a change in the corneal asphericity). However, a higher increase was found in the anterior corneal spherical aberration than in the total spherical aberration, indicating that surgery can induce changes in the posterior corneal surface.

Techniques to evaluate total and corneal wave aberrations of the eye are based on different principles and assumptions. Whereas total aberrations are measured by projecting a light source onto the retina and estimating displacements from a reference, corneal aberrations are obtained from Placido-disk corneal topography and virtual ray tracing. It is therefore important to show that we

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can directly compare both types of measurements. In a previous report,[10] we described 2 cases in which the hypothetical agreement between corneal and total aberrations could serve as a cross-validation test between techniques. The first case, in which the eyes had keratoconus (the optics are dominated by the degraded corneal surface), has been described.[10] The results showed good cross-validation, particularly in moderately advanced keratoconus.

In this study, we looked at the second, even more directly comparable, case of an aphakic eye. Because of the absence of the crystalline lens and the minor contribution of the posterior corneal surface,[17] total aberrations in the aphakic eye should be almost identical to corneal aberrations. Comparison of corneal and total aberrations in the aphakic eye will support the reliability of corneal topography and aberrometry as wave-aberration-measurement techniques. The idea of measuring aphakic eyes to study the relative contribution of the cornea and crystalline lens to the spherical aberration of the eye has been used by Bonnet[18] and by Millodot and Sivak,[19] who used a technique based on Young's experiment.[20] The study did not find systematic compensation of the corneal spherical aberration by the crystalline lens when the corneal and total spherical aberrations were compared in normal and aphakic eyes. In the present study, comparison of eyes of the same patient, 1 aphakic and the other normal, can provide some insight into the interactions of corneal and internal aberrations.

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Patients and Methods

Total and corneal aberrations were measured in both eyes of a 30-year-old woman. The left eye was aphakic because of a congenital cataract; intracapsular cataract extraction (ICCE) with a superior incision was performed when the patient was 18 years old. The anterior segment of the right eye was normal. The autorefractometer refraction was $+12.75$ -1.00×18 in the aphakic eye and -0.50 -0.25×84 in the normal eye. Videokeratography (Humphrey-Zeiss Mastervue Atlas Corneal Topography system) did not reveal abnormal anterior corneal shapes.

Corneal and total aberration measurements were carried out in the same experimental session. The patient was fully informed about the purpose and development of the procedure and signed a consent form approved by institutional ethical committees. The pupils were dilated with tropicamide 1%. The aphakic pupil dilated beyond 6.5 mm, but the normal pupil did not dilate more than 5.0 mm.

Total aberrations were measured using a laser ray-tracing (LRT) technique that has been described.[3,21,22] A set of 37

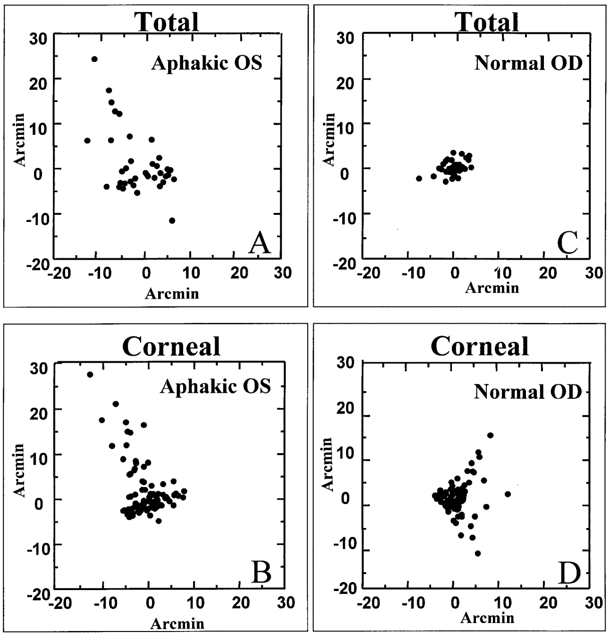

Figure 1. (Barbero) Spot diagrams (set of centroids of retinal images captured with a CCD camera). *A:* Total spot diagram, aphakic eye (left). *B:* Corneal spot diagram obtained by performing simulated ray tracing on the front corneal surface (left eye), applying the realignment algorithm. Pupil effective diameter was 6.5 mm for *A* and *B*. *C:* Total spot diagram for the normal eye (right eye). *D:* Corneal spot diagram (right eye). Pupil effective diameter was 5.0 mm for *C* and *D*.

parallel laser pencils (543 nm helium–neon [HeNe] laser) sampled the eye's pupil sequentially and uniformly using a scanning system. The rays were projected by the optics of the eye onto the retina, and the aerial images were collected in a high-resolution electronic camera. Centroids of the set of images were then computed. The deviations of the centroids from the principal ray were proportional to derivatives of the wave aberrations. Figure 1,*A* and *C*, shows a joint plot of the centroids of retinal images (spot diagram) for the patient's aphakic eye and normal eye, respectively. The wave aberration was obtained by fitting the derivatives to a Zernike polynomial expansion (up to the 7th order) using a least-mean-squares procedure. All measurements were done foveally (the patient fixates on a red point source from a 633 nm HeNe laser). Stabilization was achieved by a dental impression and forehead rest. The pupil was continuously monitored by a CCD camera and the center aligned to the optical axis of the instrument.

High hyperopic defocus in the aphakic eye was corrected by means of a trial lens (+12 diopters) placed in front of the eye (30.0 mm to pupil plane) centered around the optical axis of the instrument. Previous calibrations showed that the trial lens did not introduce additional aberrations. No trial lens was used in the normal eye. Measurements were done over a 6.51 mm pupil in the aphakic eye (step size = 1.00 mm) and 5.00 mm in the normal eye (step size = 0.75 mm). Five consecutive sets of images were obtained per eye. To compare aberrations between the right and left eyes, both corneal and total aberrations in the aphakic eye were recomputed for a 5.0 mm subregion.

The method to evaluate corneal aberrations has been described.[10] Raw data were obtained from a Mastervue Corneal Topography System (Humphrey-Zeiss). These data, containing height anterior corneal surface information, are fitted by a 7th order Zernike polynomial expansion and evaluated in a regular *x-y* sampling. This corneal surface is introduced into an optical design program, Zemax V.9 (Focus Software). Virtual ray tracing is performed in Zemax, sampling the corneal surface, which separates 2 media, air and aqueous humor (1.3391).[23,24] The wavelength was set to 543 nm. Figure 1,*B* and *D*, shows spot diagrams corresponding to a corneal sample of 91 rays for aphakic and normal eyes, respectively. Corneal wave aberration (at the plane of best focus) was described by a 7th order Zernike polynomial expansion.

While experimental LRT measurements were centered on the line of sight (axes joining the fixation point and the center of the entrance pupil), the videokeratographer used the keratometric axis for centration (passing through the fixation point and center of curvature of the cornea). These 2 axes intersect the entrance pupil at different locations and differ by an angle.[25] As the entrance pupil center is not accessible from the Humphrey videokeratographer pupil images because of the superposition of the Placido disks with the pupil margin, custom software was developed to correct for the position shift between the corneal aberration maps and the total wave aberration map.[10] This translation corrects most of the axis shift. The different angle tilt can be computed by measuring the distance between the anterior corneal intersect of both axes and using the fixation point distance for this instrument.

While the keratometric axis intersection with the anterior corneal surface could be located by means of the corneal reflex, the corneal sighting center (intersection of line of sight with anterior corneal surface) was not available in our patient. Mandell and coauthors[25] report a mean difference of 0.38 mm ± 0.10 (SD) between the corneal intersect of the keratometric axis and the corneal sighting center across 20 normal eyes. Assuming similar values in our patient and for the 148.3 mm fixation point distance in our videokeratoscope, the neglected corneal tilt (angle between keratometric axis and line of sight) was around 0.15 degree. In both eyes, considering this average tilt, the root mean square (RMS) changed by only 3.1% (aphakic eye) and 0.4% (normal) for 3rd order terms and 0.43% (aphakic eye) and 0.33% (normal eye) for spherical aberration. The effect of the tilt between the axes was then ignored.

One corneal map was obtained per eye as previous experiments in 1 control eye (RMS = 0.59 μm for 3rd order and higher-order terms) showed good measurement reproducibility, with a mean Zernike coefficient variability of 0.015 μm (averaged across terms).

The RMS wavefront error was used to describe optical quality. In all cases, the ordering and notation recommended by the Optical Society of America's Standards Committee were followed.[26]

Results

Figure 2 shows total, corneal, and internal (computed as total minus corneal) wave aberration maps for the aphakic eye (upper row) and the normal eye (lower row). Contours were plotted at 1.0 μm intervals. In each eye, the same gray scale was used across maps. Pupil sizes were 6.5 mm in the aphakic eye and 5.0 mm in the normal eye. Tilt and residual defocus were canceled in all cases. There was a strong similarity between the corneal and total wavefront maps in the aphakic eye, which did not occur in the normal eye. This is also seen in Figure 1. The total and corneal spot diagrams in the aphakic eye were similar in shape and spread; in the normal eye, the corneal spot diagram was spread more than the total spot diagram.

Figure 3 compares corneal (open diamonds) and total (solid circles) Zernike coefficients for each eye (for a pupil diameter of 6.5 mm in the aphakic eye and 5.0 mm in the normal eye). For clarity, error bars have

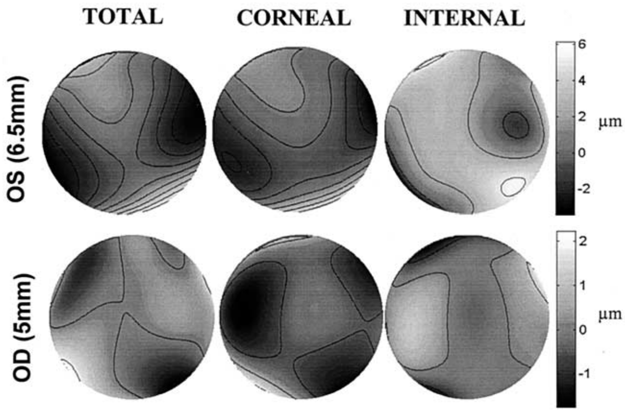

Figure 2. (Barbero) Wave aberration patterns (without tilts and defocus) in both eyes for total aberrations (first column), corneal aberrations (second column), and internal aberrations (third column). The upper panels show the results in the aphakic eye (left) for a 6.51 mm pupil diameter and the lower panels, the results in the normal eye (right) for a 5.0 mm pupil diameter. Contour lines are plotted every 1 μm. The gray-scale pattern represents wave aberration heights in microns.

not been plotted. For corneal aberrations, the standard deviation across the 5 measurements was 0.016 μm (averaged across terms excluding tilts and defocus) for a control eye and after the alignment algorithm. The mean standard deviations for the total Zernike coefficients were 0.018 μm and 0.035 μm (excluding tilts and defocus) in the aphakic and normal eyes, respectively, for a 5.0 mm pupil. For 3rd order and higher terms, the values were 0.013 μm and 0.033 μm, respectively. Standard deviation for the total spherical term (Z_4^0) was 0.022 μm in the normal eye and 0.011 μm in the aphakic eye. The total RMS (for 3rd order and higher aberrations) standard deviation was 0.064 μm in the aphakic eye and 0.040 in the normal eye for a 5.0 mm pupil.

Table 1 shows some representative terms as well as the RMS for the orders evaluated in both eyes. Astigmatic terms are predominant in the aphakic eye (−0.59 μm and −0.65 μm for astigmatism at 0 to 90 degrees and 45 degrees, respectively, for a 5.0 mm pupil) followed by the 3rd order term Z_3^3 (−0.18 μm). In the normal eye, astigmatism Z_2^{-2} represents the highest contribution (0.27 μm) followed by comatic term Z_3^{-3} (0.12 μm).

There was excellent corneal versus total correspondence in the aphakic eye except for some specific terms (Z_2^{-2}, Z_2^{-2}, Z_3^{-1}, Z_3^1). In the normal eye, there was no

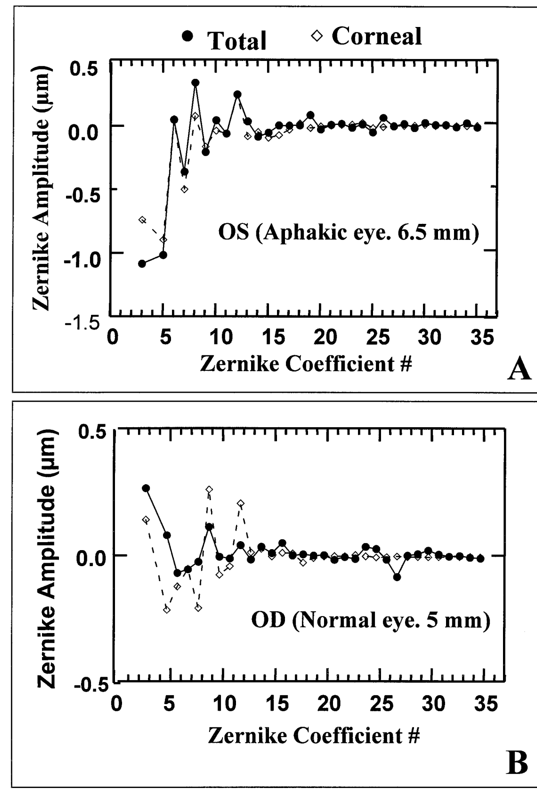

Figure 3. (Barbero) Total (solid circles) and corneal (empty diamonds) aberrations in the aphakic eye (6.5 mm pupil) (A) and the normal eye (5.0 mm pupil) (B). Notation follows the recommendations of the Standards Committee of the Optical Society of America.[27]

such similarity, although corneal aberrations tended to dominate compared to the internal aberrations. Most corneal terms were larger than the total counterparts, indicating a compensatory effect of the internal aberrations in the normal eye. Corneal aberrations (3rd and higher orders) represented 98.4% of the total RMS in the aphakic eye (6.5 mm) and 226.32% of the total aberration in the normal eye. These results indicate that in the aphakic eye, internal aberrations (the small percentage coming from the posterior corneal surface) add to the aberrations of the anterior corneal surface, while in the normal eye, the internal aberrations (presumably mainly from the crystalline lens) detract from the corneal aberrations. This effect is particularly prominent for the spherical aberration (Z_4^0). In the normal eye, there was an almost perfect match between the corneal positive spherical aberration (0.21 μm) and the internal negative spherical aberration (−0.16 μm). In the aphakic eye, the corneal spherical aberration (0.24 μm for a 6.5 mm pupil) matched the total spherical aberration

Table 1. Individual Zernike coefficients and RMS for total and corneal aberrations.

	Aphakic Eye						Normal Eye (5.0 mm Pupil)		
	6.5 mm Pupil			5.0 mm Pupil					
Zernike Coefficient/RMS	Total	Corn	Int	Total	Corn	Int	Total	Corn	Int
Z_2^{-2}	−1.08	−0.74	−0.34	−0.59	−0.38	−0.20	0.27	0.15	0.12
Z_2^{+2}	−1.02	−0.90	−0.12	−0.65	−0.46	−0.19	0.08	−0.21	0.29
Z_4^{+10}	0.25	0.24	0.01	0.08	0.06	0.01	0.05	0.21	−0.16
RMS 2nd to 7th order (except defocus)	1.62	1.32	0.52	0.93	0.64	0.36	0.34	0.50	0.46
RMS 3rd order	0.54	0.54	0.30	0.29	0.23	0.19	0.14	0.36	0.24
RMS 3rd and higher orders	0.62	0.61	0.37	0.32	0.25	0.23	0.19	0.43	0.32
RMS 4th order	0.27	0.27	0.15	0.13	0.08	0.11	0.06	0.23	0.18
RMS 5th and higher orders	0.14	0.13	0.17	0.05	0.04	0.05	0.11	0.03	0.11

(0.25 μm), lacking the compensatory effect of the internal optics.

Discussion

The optical aberrations in the aphakic and normal eyes of 1 patient were measured using LRT (total aberrations) and corneal topography (corneal aberrations). These techniques have proved to be reliable tools to estimate corneal and total aberrations in normal,[14] surgical,[14] and pathologic (ie, keratoconus) eyes.[10] This study showed that while relying on very different principles, corneal topography and aberrometry can provide similar wave aberration results.

We found good correspondence (98.4%) between corneal aberrations and total aberrations in the aphakic eye (6.5 mm pupil). This correspondence was even higher than in keratoconus eyes,[10] in which despite the clear dominance of the anterior corneal surface on the total aberration pattern, the crystalline lens was present. The small difference that we found between anterior corneal aberrations and total aberrations in the aphakic eye could account for some contribution of the posterior corneal surface, but it was not significant and was within the measurement error.

The accuracy of the corneal elevation measurement is limited by the corneal topography device[28–30] and the surface fitting[31] and has a mean error of 4.54 ± 0.7 μm.[10,32] This value induces a mean corneal wavefront error of 0.02 μm, calculated by inducing random topography data separated from the original data by a mean value of 4.54 μm. Schultze[32] reports that in the Mastervue Altas corneal videokeratoscope, the elevation measurement error increases with the corneal radius. This systematic error induces a mean corneal wavefront error of 0.03 μm. In addition, we found a corneal and total wavefront measuring variability (RMS standard deviations) of 0.04 μm (the average of control subjects)[10] and 0.064 μm for the aphakic eye in this study, respectively. These errors are within the difference between total and corneal aberrations in the aphakic eye.

Our study confirms that the contribution of the posterior corneal surface to the total aberrations is not significant, at least not after ICCE. However, other studies point out the influence of the posterior corneal surface in patients after refractive surgery[14,33–35] and patients with some corneal pathologies.[36]

Since the cornea of the aphakic eye has been modified during the surgical procedure,[37] similarities between both corneal eye aberrations were not necessarily expected. Figure 1,*B* and *D*, is, however, suggestive of some bilateral symmetry. We found a left-to-right coefficient of correlation (with appropriate sign inversion of the odd symmetry terms[38]) of $r = 0.57$. The major difference occurs in the corneal astigmatic terms (2.36 times larger in the aphakic eye than the normal eye). An increase in corneal astigmatism is not uncommon after cataract surgery.[39–41]

Several studies suggest a compensatory effect of corneal and internal aberrations in normal eyes. Guirao and coauthors[42] report a large degree of compensation in 59 eyes, which is disrupted with aging.[43] Balance of a generally positive corneal spherical aberration by a negative spherical aberration of the crystalline lens seems to be a general finding. In our study, comparison of the aphakic and normal eyes of the same patient indicates compensatory effects between the cornea and lens in the normal eye. Whereas the spherical aberration of the normal eye is close to zero (with an almost perfect balance of corneal and internal aberrations), the spherical aberration of the aphakic eye (equal to that of the cornea) is larger. In a previous study of 14 eyes (mean age 28.9 years),[14] we found that in 57% of the eyes, the internal spherical aberration balanced at least 50% of the corneal spherical aberration (with 78% of the eyes having internal and corneal spherical aberrations of the opposite sign). Smith and coauthors'[13] study of 26 eyes had similar results: 84.1% compensation of corneal aberrations by internal spherical aberration in young eyes (13 eyes, mean age 24.8 years) and 56.2% compensation in old eyes (13 eyes, mean age 66 years). Salmon and Thibos found clear compensation of the corneal spherical aberrations by the internal aberrations in only 1 of the 3 eyes in their study (T. Salmon, MD, L. Thibos, PhD, "Relative Balance of Corneal and Internal Aberrations in the Human Eye," presented at the annual meeting of the Optical Society of America, Baltimore, Maryland, USA, October 1998), and Sivak and Kreuzer,[44] using aphakic and control eyes as we did in this study, observed that in most cases lens and cornea spherical aberration add up.

With the recent availability of techniques to measure higher-order and nonspherically symmetric aberrations, interactions between terms in addition to spherical aberration can be studied. Artal and Guirao[12] found a high degree of compensation for coma (~50%). This appears to be the case for the normal eye of the patient in this study, in which 66.7% of the 3rd order corneal RMS was compensated for by the internal aberrations. Although this may not be a general result,[14,44] it is interesting that this balance can occur in certain patients.

In summary, we have presented useful techniques to optically characterize the corneal and internal components of the eye. Results in an aphakic eye served as a cross-validation test of 2 aberration measurement techniques (LRT and corneal topography). The contribution of the posterior corneal surface to the corneal aberrations was found to be smaller than the measurement error. Comparison of findings in the nontreated contralateral eye of the same patient has allowed us to discuss the contribution of the crystalline lens as an attenuating element of the corneal aberrations, particularly the spherical aberration. These new tools and results have important implications for intraocular lens (IOL) design[45] and cataract surgery procedures. They suggest that optimal results might be obtained not with aberration-free IOLs but with the compensating existing aberrations of the cornea, particularly astigmatism and spherical aberration.

References

1. Walsh G, Charman WN, Howland HC. Objective technique for the determination of monochromatic aberrations of the human eye. J Opt Soc Am A 1984; 1:987–992
2. Liang J, Grimm B, Golez S, Bille JF. Objective measurement of wave aberrations of the human eye with the use of a Hartmann-Shack wave-front sensor. J Opt Soc Am A 1994; 11:1949–1957
3. Navarro R, Losada MA. Aberrations and relative efficiency of light pencils in the living human eye. Optom Vis Sci 1997; 74:540–547
4. He JC, Marcos S, Webb RH, Burns SA. Measurement of the wave-front aberration of the eye by a fast psychophysical procedure. J Opt Soc Am A 1998; 15:2449–2456
5. Mrochen M, Kaemmerer M, Mierdel P, et al. Principles of Tscherning aberrometry. J Refract Surg 2000; 16:S570–S571
6. Moreno-Barriuso E, Merayo Lloves J, Marcos S, et al. Ocular aberrations before and after myopic corneal refractive surgery: LASIK-induced changes measured with laser ray tracing. Invest Ophthalmol Vis Sci 2001; 42:1396–1403
7. López-Gil N, Marin JM, Castejón-Mochón JF, et al. Ocular and corneal aberrations after corneal transplantation. ARVO abstract 2841. Invest Ophthalmol Vis Sci 2001; 42(4):S529
8. Artal P, Marcos S, Navarro R, et al. Through focus image quality of eyes implanted with monofocal and multifocal intraocular lenses. Opt Eng 1995; 34:772–779
9. Klein SA, Garcia DD, Barsky BA. Problems with representations of wavefront aberrations, and solutions. ARVO abstract 548. Invest Ophthalmol Vis Sci 2000; 41(4):S105
10. Barbero S, Marcos S, Merayo-Lloves J, et al. A validation of the estimation of corneal aberrations from videokeratography: test on keratoconus eyes. J Refract Surg 2002; 18:263–270
11. El Hage SG, Berny F. Contribution of the crystalline lens to the spherical aberration of the eye. J OSA 1973; 63:205–211
12. Artal P, Guirao A. Contributions of the cornea and the lens to the aberrations of the human eyes. Opt Lett 1998; 23:1713–1715

13. Smith G, Cox MJ, Calver R, Garner LF. The spherical aberration of the crystalline lens of the human eye. Vision Res 2001; 41:235–243
14. Marcos S, Barbero S, Llorente L, Merayo-Lloves J. Optical response to myopic LASIK surgery for myopia from total and corneal aberration measurements. Invest Ophthalmol Vis Sci 2001; 42:3349–3356
15. Applegate RA, Hilmantel G, Howland HC, et al. Corneal first surface optical aberrations and visual performance. J Refract Surg 2000; 16:507–514
16. Marcos S, Burns SA, Prieto PM, et al. Investigating sources of variability of monochromatic and transverse chromatic aberrations across eyes. Vision Res 2001; 41: 3861–3871
17. Rengstorff RH. Corneal refraction: relative effects of each corneal component. J Am Optom Assoc 1985; 56:218–219
18. Bonnet R. La topographie Corneénne. Paris, Desroches, 1964
19. Millodot M, Sivak J. Contribution of the cornea and lens to the spherical aberration of the eye. Vision Res 1979; 19:685–687
20. Young T. On the mechanism of the eye. Phil Trans R Soc 1801; 19:23–88
21. Navarro R, Moreno-Barriuso E. Laser ray tracing method for optical testing. Opt Lett 1999; 24:951–953
22. Moreno-Barriuso E, Marcos S, Navarro R, Burns SA. Comparing laser ray tracing, the spatially resolved refractometer, and the Hartmann-Shack sensor to measure the ocular wave aberration. Optom Vis Sci 2001; 78:152–156
23. Escudero-Sanz I, Navarro R. Off-axis aberrations of a wide-angle schematic eye model. J Opt Soc Am A 1999; 16:1881–1891
24. Navarro R, Santamaría J, Bescós J. Accommodation-dependent model of the human eye with aspherics. J Opt Soc Am A 1985; 2:1273–1281
25. Mandell RB, Chiang CS, Klein SA. Location of the major corneal reference points. Optom Vis Sci 1995; 72:776–784
26. Thibos LN, Applegate RA, Schwiegerling JT, et al. Standards for reporting the optical aberrations of eyes. In: Lakshminarayanan V, ed, Trends in Optics and Photonics; Vision Science and Its Applications. Washington, DC, Optical Society of America, 2000; 35:232–244
27. Applegate RA, Thibos LN, Bradley A, et al. Reference axis selection: subcommitte report of the OSA working group to establish standards for measurement and reporting of optical aberrations of the eye. J Refract Surg 2000; 16:S656–S658
28. Applegate RA, Nuñez R, Buettner J, Howland HC. How accurately can videokeratographic systems measure surface elevation? Optom Vis Sci 1995; 72:785–792
29. Priest D, Munger R. Comparative study of the elevation topography of complex shapes. J Cataract Refract Surg 1998; 24:741–750
30. Tang T, Collins MJ, Carney L, Davis B. The accuracy and precision performance of four videokeratoscopes in measuring test surfaces. Optom Vis Sci 2000; 77:483–491
31. Iskander DR, Collins MJ, Davis B. Optimal modeling of corneal surfaces with Zernike polynomials. IEEE Trans Biomed Eng 2001; 48:87–95
32. Schultze RL. Accuracy of corneal elevation with four corneal topography systems. J Refract Surg 1998; 14:100–104
33. Naroo S, Charman WN. Changes in posterior corneal curvature after photorefractive keratectomy. J Cataract Refract Surg 2000; 26:872–878
34. Baek T, Lee KH, Kagaya F, et al. Factors affecting the forward shift of posterior corneal surface after laser in situ keratomileusis. Ophthalmology 2001; 108:317–320
35. Bruno CR, Roberts CJ, Castellano D, et al. Posterior corneal surface changes after laser in situ keratomileusis. ARVO abstract 3252. Invest Ophthalmol Vis Sci 2001; 42(4):S605
36. Mannis MJ, Lightman J, Plotnik RD. Corneal topography of posterior keratoconus. Cornea 1992; 11:351–354
37. Rainer G, Menapace R, Vass C, et al. Corneal shape changes after temporal and superolateral 3.0 mm clear corneal incisions. J Cataract Refract Surg 1999; 25: 1121–1126
38. Marcos S, Burns SA. On the symmetry between eyes of wavefront aberration and cone directionality. Vision Res 2000; 40:2437–2447
39. Mafra CH, Dave AS, Pilai CT, et al. Prospective study of corneal topographic changes produced by extracapsular cataract surgery. Cornea 1996; 15:196–203
40. Chipont-Benabent E, Artola Roig A, Pérez-Santonja JJ, et al. Astigmatism induced by intrastromal corneal suture after small incision phacoemulsification. J Cataract Refract Surg 1998; 24:519–523
41. Beltrame G, Salvetat ML, Chizzolini M, Driussi G. Corneal topographic changes induced by different oblique cataract incisions. J Cataract Refract Surg 2001; 27:720–727
42. Guirao A, Redondo M, Artal P. Optical aberrations of the human cornea as a function of age. J Opt Soc Am A 2000; 17:1697–1702
43. Artal P, Berrio E, Guirao A, et al. Contribution of the cornea and internal surfaces to the change of ocular aberrations with age. J Opt Soc Am A 2002; 19:137–143
44. Sivak JG, Kreuzer RO. Spherical aberration of the crystalline lens. Vision Res 1983; 23:59–70
45. Atchison D. Design of aspheric intraocular lenses. Ophthalmic Physiol Opt 1991; 11:137–146