# CHAPTER IV

## CORNEAL AND TOTAL OPTICAL ABERRATIONS IN A UNILATERAL APHAKIC SUBJECT

This chapter is based on the article by Barbero, S., et al. *Total and corneal aberrations in an unilateral aphakic subject.* J Cataract Refract Surg, 2002. 28(9): p. 1594.

Coauthors of the study are: Susana Marcos and Jesus Merayo-Lloves.

The contribution of Sergio Barbero to the study was to develop the methodology to measure corneal aberrations, to perform calibrations of the total and corneal aberrometry techniques, to contribute in the experimental measurements in patients, perform data analysis and, interpretation of results, as well as discussion of the conclusions.

## RESUMEN

**OBJETIVOS:** Medir las aberraciones totales y corneales en los ojos, normal (OD) y operado (OS), de un sujeto afáquico unilateral, con un doble objetivo: 1) Validación cruzada de las técnicas de aberrometría total y corneal en un ojo en el que ambas aberraciones deben ser prácticamente idénticas (ojo afáquico) 2) Estudiar las interacciones de las aberraciones corneales e internas en un ojo normal en comparación con un ojo afáquico.

**MÉTODOS:** Las aberraciones totales se midieron usando una técnica de trazado de rayos laser. Las aberraciones corneales se midieron mediante un trazado de rayos virtual sobre la superficie corneal obtenida a partir de datos de elevación de un videoqueratoscopio.

**RESULTADOS:** 1) Existe una correspondencia del 98.4% entre las aberraciones totales y corneales en el ojo afáquico (6.5 mm de diámetro de pupila). 2) En el ojo normal, la aberración esférica total es bastante menor que la aberración esférica corneal, lo cual no ocurre en el ojo afáquico.

**CONCLUSIONES:** Las aberraciones corneales y totales en un ojo afáquico, medidas con las dos técnicas de aberrometría total y corneal, basadas en distintos principios, muestran resultados muy similares. Este resultado sugiere una contribución pequeña de la cara posterior corneal a las aberraciones de la cornea normal (2% como máximo). El segundo resultado sugiere un papel compensatorio del cristalino en la aberración esférica total en ojos normales.

## ABSTRACT

**Purpose:** To measure corneal and total optical aberrations in the normal (OD) and treated eye (OS) of an unilateral aphakic subject, with a double purpose: 1) Cross-validation of techniques in an eye where corneal and total aberrations should be almost identical (aphakic eye). 2) Study the interactions of corneal and internal aberrations in the normal eye, in comparison with the aphakic eye.

**Methods:** Total aberrations were measured using Laser Ray Tracing. Corneal aberrations were obtained from corneal elevation data measured with a Humphrey Instruments corneal videokeratoscope, and using custom software that performs a virtual ray tracing on the measured front corneal surface.

**Results:** 1) There is a 98.4% correspondence between the total and corneal aberration pattern in the aphakic eye (6.5 mm pupil diameter). 2) In the normal eye, the total spherical aberration is much lower than the corneal spherical aberration, which does not occur in the aphakic eye.

**Conclusions:** The fact that in the aphakic eye both techniques provide similar aberration measurements, despite being based on different principles and assumptions, provides a cross-validation test for both techniques. This result suggests a negligible contribution of the posterior corneal surface to the aberrations of a normal cornea (2% at most). The second result suggests a compensatory role of the crystalline lens to the total spherical aberration in normal eyes.

# 1. Introduction

In the last few years there has been a rapidly increasing interest in the study of the optical quality and optical aberrations of the eye. Different techniques and measurement systems have been developed[1-4] and applications of these tools have been started to reach the clinical environment. Recent studies such as the change of optical quality with refractive surgery[5, 6] (chapter V), implanted IOL performance after cataract surgery[7] (chapter VII), or optical aberrations in corneal pathologies (i.e. keratoconus)[8] (chapter II) are examples of the capabilities of the new techniques in the clinic.

Several studies have shown that powerful information is obtained when, in the same eye, both corneal and total aberrations are measured[6, 9-11]. These two types of measurements can separate the contribution of the cornea and internal aberrations (i.e crystalline lens), as well as their inter-relationships[12]. Measurements in normal young eyes have found a strong compensation of spherical aberration of the cornea by the lens[10, 11], and even a compensation in asymmetric aberrations such as coma[10]. By comparing corneal and total wavefront maps in the same patients before and after standard LASIK refractive surgery, we will show in chapter V[6] an increase of spherical aberration toward more positive values (due to a change in corneal asphericity). However a higher increase is found in the anterior corneal spherical aberration than in total spherical aberration, indicating that surgery can induce changes in 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 on 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 can directly compare both types of measurements. In chapter III we pointed out two special cases where the hypothetical agreement between corneal and total aberrations could serve as a cross-validation test between techniques. The first case, eyes suffering from keratoconus (where the optics are dominated by the degraded corneal surface), has been described in detail in chapter III. Results proved a good agreement, particularly in moderately advanced keratoconus.

In the current chapter we study the second, even more directly comparable case: an aphakic eye (without crystalline lens). Due to the absence of crystalline lens, and the minor expected contribution of the posterior corneal surface[13], total aberrations in the aphakic eye should be almost identical to corneal aberrations. The comparison of corneal and total aberrations in the aphakic eye will support the reliability of corneal topography and aberrometry as wave aberration measurements techniques. The idea of measuring aphakic eyes to study the relative contribution of cornea and crystalline lens to the spherical aberration of the eye has been used in the past, by Bonnet et al[14], and later by Millodot & Sivak[15], who used a technique based on Young´s experiment (1801)[16]. This study did not conclude a systematic compensation of the corneal spherical aberration by the crystalline lens, when the corneal and total spherical aberration was compared in normal and aphakic eyes. In the present study, comparison between eyes of the same patient, one being aphakic and the other one normal, can provide some insight into the interactions of corneal and internal aberrations.

## 2. Patients and Methods

Total and corneal aberrations were measured on both eyes of one female patient (age 30). The left eye was aphakic, due to a congenital cataract, with lens extraction, by intracapsular cataract extraction with superior incision, at age 18. The anterior segment of the normal eye was normal. Autorefractometer refraction was +12.75 –1.00 x 18 in the aphakic eye and –0.5 –0.25 x 84 in the normal eye. Analysis performed by videokeratography (Humphrey-Zeiss Mastervue Atlas Corneal Topography system) did not reveal abnormal anterior corneal shapes.

Corneal and total aberrations measurements were carried out in the same experimental session. The patient was carefully informed about the purpose and development of the procedure, and confirmed her agreement by signing a consent form approved by institutional ethical committees. Pupils were dilated with tropicamide 1%. The aphakic pupil dilated beyond 6.5 mm, but the normal pupil did not dilate more than 5 mm.

Total aberrations were measured using a Laser Ray Tracing technique (LRT). Figure IV.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.

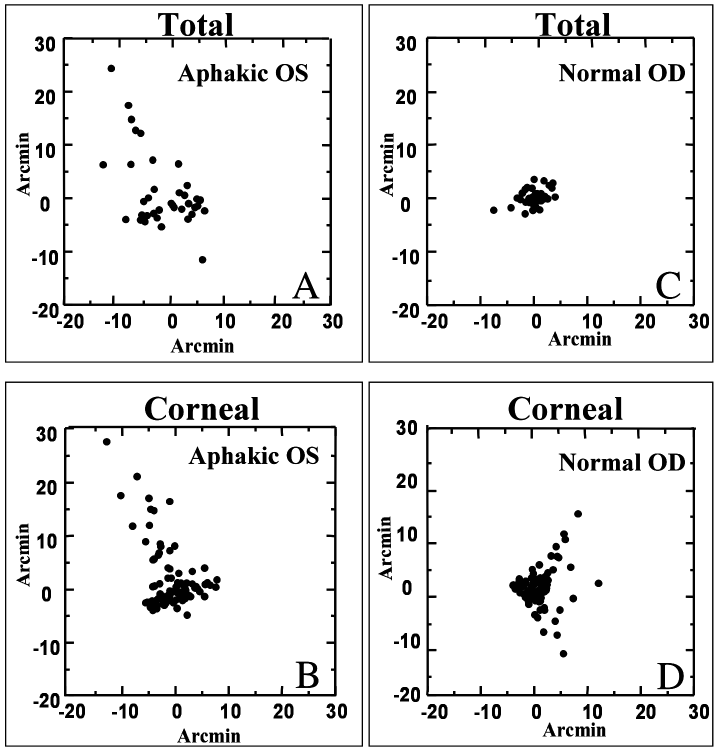


**Figure IV.1 :** Spot diagrams (set of centroids of retinal images captured in CCD camera) **A)** Total spot diagram, aphakic eye (OS). **B)** Corneal spot diagram obtained by performing simulated ray tracing on the front corneal surface (OS), applying the realignment algorithm. Pupil effective diameter was 6.51 mm for A and B. **C)** Total spot diagram for the normal eye (OD). **D)** Corneal spot diagram (OD). Pupil effective diameter was 5 mm for C and D.

High hyperopic defocus in the aphakic eye was corrected by means of a trial lens (+12D) placed in front of the eye (30 mm to pupil plane) centre around the optical axis of the instrument. Previous calibrations showed that the trial lens does not introduce additional aberrations. No trial lens was used for the normal eye. Measurements were done over a 6.51-mm pupil for the aphakic eye (step size=1 mm) and 5-mm for normal eye (step size=0.75 mm). We obtained five consecutive sets of images per eye. To compare aberrations between right and left eyes, both corneal and total aberrations of the aphakic eye were re-computed for a 5 mm sub-region.

The method to evaluate corneal aberrations has been explained in chapter II. Figure IV.1 B and D show spot diagrams corresponding to corneal sample of 91 rays for aphakic and normal eyes respectively. We obtained one corneal map per eye

## 2. Results

Figure IV.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 have been plotted at 1-μm intervals. For each eye, we used the same gray scale across maps. Pupil sizes are 6.5-mm for aphakic eye (upper row) and 5-mm for normal eye (lower row). Tilt and residual defocus have been cancelled in all cases.

There is a strong similarity between corneal and total wavefront maps in the aphakic eye, which does not occur in the normal eye. That could also been observed in Figure IV.1. Total and corneal spot diagrams in the aphakic eye are similar in shape and spread, whereas in the normal eye, the corneal spot diagram is much more spread than the total spot diagram. Figure IV.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 mm in the normal eye). For the sake of clarity, error bars have not been plotted.

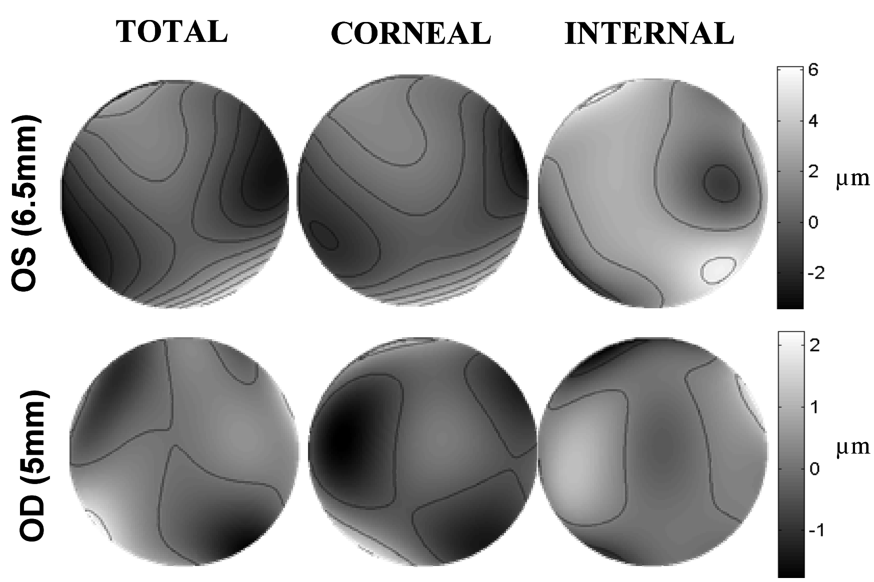


**Figure IV:2:** Wave aberration patterns (without tilts and defocus) in both eyes, for total aberrations (first column), corneal aberrations (second column) and internal aberrations (third column). The upper panels show results on the aphakic eye (OS) for a 6.51-mm pupil diameter. The lower panels show results on the normal eye (OD) for a 5-mm pupil diameter. Contour lines are plotted every 1 μm. The gray scale pattern represents wave aberration heights in microns.

For corneal aberrations, we found a standard deviation of 0.016 µm across the five measurements (averaged across terms, excluding tilts and defocus) for a control eye and after the alignment algorithm. The mean standard deviation for the total Zernike coefficients were 0.018 µm and 0.035 µm (excluding tilts and defocus) in the aphakic and the non-aphakic eyes respectively, for a 5 mm pupil diameter. For 3rd order and higher terms, these values were 0.013 µm and 0.033 µm respectively. Standard deviation for the total spherical term ($Z_4^0$ ) was 0.022 µm for the normal eye and 0.011 µm for the aphakic eye. Total RMS (for 3rd order & higher aberrations) standard deviation was 0.064 µm for the aphakic eye, and 0.040.for the normal (for a 5 mm).

Table IV.1 shows some representative terms, as well as the RMS for different orders evaluated for both eyes. In all cases, we followed the ordering and notation recommended by the Optical Society of America Standard Committee[17].

Astigmatic terms are predominant in the aphakic eye (-0.59 and –0.65 µm for astigmatism at 0-90º and at 45º respectively, for 5 mm) followed by 3rd order term $Z_3^3$ (-0.18 µm). In the normal eye, astigmatism $Z_2^{-2}$ represents also the highest contribution (0.27 µm), followed by comatic term $Z_3^{-3}$ (0.12 µm).

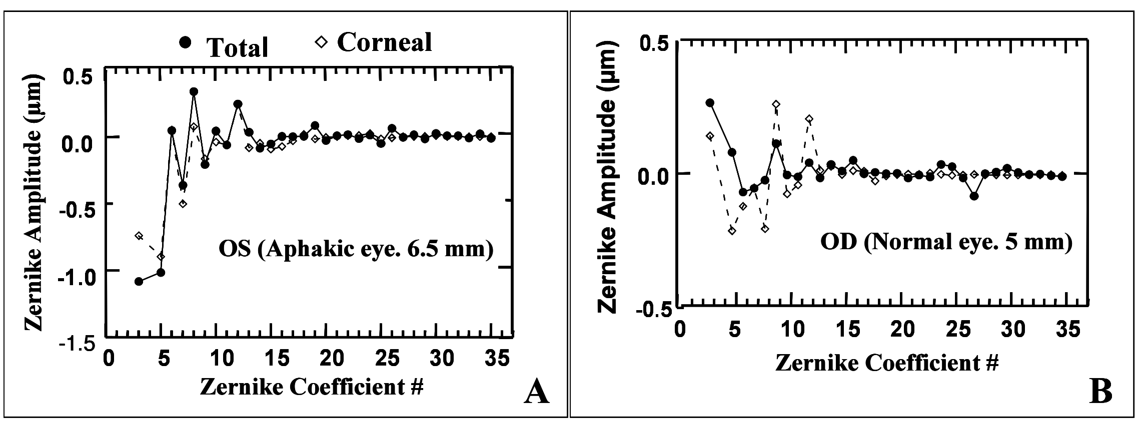


**Figure IV.3:** Total (solid circles) and corneal (empty diamonds) aberrations **A)** for the aphakic eye, (6.5-mm pupil), and **B)** for normal eye (5 mm pupil). Notation follows the OSA Standard Committee's recommendations[17].

| | OS (Aphak eye: 6.5) | | | OS (Aphakic eye: 5) | | | OD (Normal eye: 5) | | |
|---|---|---|---|---|---|---|---|---|---|
| | **Total** | **Corn** | **Inter** | **Total** | **Corn** | **Inter** | **Total** | **Corn** | **Inter** |
| $Z_2^{-2}$ | -1.08 | -0.74 | -0.34 | -0.59 | -0.38 | -0.2 | 0.27 | 0.15 | 0.12 |
| $Z_2^{+2}$ | -1.02 | -0.9 | -0.12 | -0.65 | -0.46 | -0.19 | 0.08 | - | 0.29 |
| $Z_4^{+0}$ | 0.25 | 0.24 | 0.01 | 0.08 | 0.06 | 0.01 | 0.05 | 0.21 | -0.16 |
| **RMS 2rd to 7rd order (except defocus)** | 1.62 | 1.32 | 0.52 | 0.93 | 0.64 | 0.36 | 0.34 | 0.5 | 0.46 |
| **RMS 3 order** | 0.54 | 0.54 | 0.3 | 0.29 | 0.23 | 0.19 | 0.14 | 0.36 | 0.24 |
| **RMS 3rd & higher** | 0.62 | 0.61 | 0.37 | 0.32 | 0.25 | 0.23 | 0.19 | 0.43 | 0.32 |
| **RMS 4 order** | 0.27 | 0.27 | 0.15 | 0.13 | 0.08 | 0.11 | 0.06 | 0.23 | 0.18 |
| **RMS 5rd & higher** | 0.14 | 0.13 | 0.17 | 0.05 | 0.04 | 0.05 | 0.11 | 0.03 | 0.11 |

**Table IV.1:** Individual Zernike coefficients and RMS for total and corneal aberrations for the aphakic eye (OS): 6.5 and 5 mm, and for the normal eye (OD): 5 mm.

Term by term, there is an 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 is no such similarity, although corneal aberrations tend to dominate, compared to the internal aberrations. The fact that most corneal terms are larger than the total counterparts indicates a compensatory effect of the internal aberrations in the normal eye. In terms of RMS, corneal aberrations (3$^{rd}$ & higher orders) represent 98.4% of the total RMS in the aphakic eye (6.5 mm), whereas for the normal eye they represent 226.32% of the total aberration. These results indicate that in the aphakic eye internal aberrations (the small percentage coming from the posterior corneal surface) adds to the aberrations of the anterior corneal surface, while in the normal eye the internal aberrations (presumably mainly from the crystalline lens) subtract from the corneal aberrations. This effect is particularly prominent for the spherical aberration ($Z_4^0$). In the normal eye, there is 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 however, the corneal spherical aberration (0.24 μm, for 6.5 mm) matches the total spherical aberration (0.25 μm), lacking from the compensatory effect of the internal optics.

# 4. Discussion

The optical aberrations in the aphakic and normal eyes from the same subject were measured using Laser Ray Tracing (total aberrations) and corneal topography (corneal aberrations). These techniques have proved to be reliable tools to estimate corneal and total aberrations in normal[6], surgical[6] and pathological eyes (i.e keratoconus)[8]. This study shows that while relying on very different principles, corneal topography and aberrometry can provide similar wave aberration results.

We found a very good correspondence (98.4%) between corneal aberrations and total aberrations in the aphakic eye (6.5 mm pupil diameter). This correspondence was even higher than in previously studied keratoconus eyes[8] (chapter III), where despite the clear dominance of the anterior corneal surface on the total aberration pattern, the crystalline lens was still present. The small difference that we found (0.07 μm) between anterior corneal aberrations and the total aberrations in aphakic eye could account for some contribution of the posterior corneal surface, but it is not significant and is within the measurement error.

Our study confirms that the contribution of the posterior corneal surface to the total aberrations is not significant, at least in a patient after intracapsular cataract extraction. However other studies point out the influence of the posterior corneal surface in patients after refractive surgery[6, 18, 19] and patients with some corneal pathologies[20].

Since the cornea of the aphakic eye can has been modified during the surgical procedure[21], great similarities between both corneal eyes aberrations were not necessarily expected. Figure IV.1 (B & D) are however suggestive of some bilateral symmetry. We found a left to right coefficient of correlation (with appropriate sign inversion of the odd symmetry terms[22]) 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[23-25], as it will be seen in chapter VII.

Several studies suggest a compensation of corneal and internal aberrations in normal eyes. Artal et al[26] found a great degree of compensation in 59 eyes, which was disrupted with aging[27]. A balance of a generally positive corneal spherical aberration by a negative spherical aberration of the crystalline lens seems to be a general finding. Comparison between the aphakic and normal eyes of the same patient in this study 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 the study of chapter V we will see that in 14 eyes (mean age 28.9)[6] 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 opposite sign). Smith et al[11] results on 26 eyes indicate similar results: 84.1% compensation of corneal by internal spherical aberration (on 13 eyes, mean age 24.8) and 56.2% compensation (13 eyes, mean age 66). Alternatively, Salmon and Thibos[28] found a clear compensation of the corneal aberrations by the internal aberrations only in one of the three eyes of their study, and Sivak et al[29], 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 high order and non-spherically symmetric aberrations, interactions between other terms besides spherical aberration can be studied. Artal et al found a high degree of compensation for coma (~50%)[10]. This seems to be also the case for the normal eye of the patient in this study, where 66.7% of the third order corneal RMS is compensated by the internal aberrations. Although this may not be a general result[6, 28] it is interesting that this balance can occur in certain subjects.

In summary, we have presented valuable techniques to characterise optically the corneal and internal components of the eye. Results on an aphakic eye serve us as a cross-validation test of two aberration measurement techniques (LRT and corneal topography). Contribution of the posterior corneal surface to the corneal aberrations is found to be smaller than the measurement error. Comparison with the non-treated contralateral eye of the same subject 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 implication in the intraocular lens (IOL) design[30] and cataract surgery procedures. They suggest that optimal results might be obtained, not with aberration-free IOLs, but those compensating existing aberrations of the cornea, particularly astigmatism and spherical aberration. This issue concerning with IOLs will be treated on detail in chapter VII.

# 5. References


1. G. Walsh, W. N. Charman, and H. C. Howland, "Objective technique for the determination of monochromatic aberrations of the human eye," J Opt Soc Am A 1(9), 987-992 (1984).
2. J. Liang, B. Grimm, S. Golez, and J. Bille, "Objetive measurement of wave aberrations of the human eye with the use of a Hartmann-Shack wave-front sensor," J Opt Soc Am A 11(7), 1949-1957 (1994).
3. R. Navarro and M. A. Losada, "Ray Tracing in the Living Eye with a Laser Beam. Spot Diagrams and Aberrations," presented at the O.S.A.topical meeting: Vision Science and its Applications, Santa Fe, NM, 1996.
4. M. Mrochen, M. Kaemmerer, P. Mierdel, H. E. Krinke, and T. Seiler, "Principles of Tscherning Aberrometry," J Refract Surgery 16, S570-S571 (2000).
5. E. Moreno-Barriuso, J. Merayo-Lloves, S. Marcos, R. Navarro, L. Llorente, and S. Barbero, "Ocular aberrations before and after corneal refractive surgery: LASIK-induced changes measured with Laser Ray Tracing," Invest Ophthalmol Vis Sci 42, 1396-1403 (2001).
6. S. Marcos, S. Barbero, L. Llorente, and J. Merayo-Lloves, "Optical Response to Myopic LASIK Surgery from Total and Corneal Aberration Measurements," Invest Ophthalmol Vis Sci 42, 3349-3356 (2001).
7. S. Barbero, S. Marcos, and I. Jiménez-Alfaro, "Optical aberrations of intraocular lenses measured in vivo and in vitro," J. Opt. Soc. Am. A. 20(10), 1841-1886 (2003).
8. S. Barbero, S. Marcos, J. Merayo-Lloves, and E. Moreno-Barriuso, "A validation of the estimation of corneal aberrations from videokeratography: test on keratoconus eyes," J Refract Surg 18, 267-270 (2002).
9. S. G. El Hage and F. Berny, "Contribution of the crystalline lens to the spherical aberration of the eye," Journal of the Optical Society of America 63, 205-211 (1973).
10. P. Artal and A. Guirao, "Contribution of the cornea and the lens to the aberrations of the human eyes," Opt Lett 23, 1713-1715 (1998).
11. G. Smith, M. J. Cox, R. Calver, and L. F. Garner, "The spherical aberration of the crystalline lens of the human eye," Vision Res 41, 235-243 (2001).
12. S. Marcos, S. A. Burns, P. M. Prieto, R. Navarro, and B. Baraibar, "Investigating the sources of monochromatic aberrations and transverse chromatic aberration," Vision Res 41, 3862-3871 (2001).
13. R. H. Rengstorff, "Corneal refraction: relative effects of each corneal component," J Am Optom Assoc 56(3), 218-219 (1985).
14. R. Bonnet, "La topographie Corneénne," Desroches.Paris (1964).
15. M. Millodot and J. G. Sivak, "Contribution of the cornea and lens to the spherical aberration of the eye," Vis Res 19, 685-687 (1979).
16. T. Young, "On the mechanisms of the eye," Phil. Trans. R. Soc. 19, 23-88 (1801).
17. L. N. Thibos, R. A. Applegate, J. T. Schwiegerling, R. Webb, and V. S. T. Members, "Standars for reporting the optical aberrations of eyes," Vision Science and its Applications. Tops Volume 35(2000).
18. S. Naroo and W. Charman, "Changes in posterior corneal curvature after photorefractive keratectomy," J Cataract Refract Surg 26, 872-878 (2000).
19. T. Baek, K. Lee, F. Kagaya, A. Tomidokoro, S. Amano, and T. Oshika, "Factors affecting the forward shift of posterior corneal surface after laser in situ keratomileusis," Ophthalmology 108, 317-320 (2001).
20. C. R. Bruno, C. J. Roberts, D. Castellano, A. Mahmoud, and L. Birnbaum, "Posterior corneal surface changes after laser in situ keratomileusis," Invest Ophthalmol Vis Sci (suppl) 42, S605 (2001).
21. G. Rainer, R. Menapace, C. Vass, D. Annen, O. Findl, and K. Schmetter, "Corneal shape changes after temporal and suprolateral 3.0 clear corneal incisions," J Cataract Refract Surg 25, 1121-1126 (1999).
22. S. Marcos and S. A. Burns, "On the symmetry between eyes of wavefront aberration and cone directionality," Vision Res 40, 2437-2447 (2000).
23. C. H. Mafra, A. L. Dave, C. T. Pilai, S. D. Klyce, and S. E. Wilson, "Prospective study of corneal topographic changes produced by extracapsular cataract surgery," Cornea 15(2), 196-203 (1996).
24. E. Chipont-Benabent, A. Artola, J. J. Perz-Santoja, M. Guisbert, and J. L. Alio, "Astigmatism induced by intrastromal corneal suture after small incision phacoemulsification," J Cataract Refract Surg 24, 519-523 (1998).
25. G. Beltrame, M. L. Salvetat, M. Chizzolini, and G. Driussi, "Corneal topographic changes induced by different oblique cataract incisions," J Cataract Refract Surg 27, 720-727 (2001).
26. A. Guirao, M. Redondo, and P. Artal, "Optical aberrations of the human cornea as a function of age," J Opt Soc Am A 17, 1697-1702 (2000).

27. P. Artal, E. Berrio, A. Guirao, and P. Piers, "Contribution of the cornea and internal surfaces to the change of ocular aberrations with age," J Opt Soc Am A 19, 137-143 (2002).
28. T. Salmon and L. Thibos, "Relative balance of corneal and internal aberrations in the human eye," OSA Annual Meeting. Baltimore, Md, 1998. (1998).
29. J. G. Sivak and R. O. Kreuzer, "Spherical aberration of the crystalline lens," Vis.Res. 23, 59-70 (1983).
30. D. Atchison, "Design of aspheric intraocular lenses," Ophthalmic Physiol Opt 11(2), 137-146 (1991).