Aberrometry: basic science and clinical applications

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ABSTRACT

This paper addresses the concept, measurement and applications of wave aberrations. The ocular optics is not perfect. Apart from conventional low order aberrations (such as defocus and astigmatism) retinal images are degraded by other high order aberrations. Aberrometers typically measure ray deviations at the retinal plane, as a function of pupil position, i.e. local derivatives of the wave aberration. The paper discusses state of the art technology to measure the aberrations of the eye (cornea and crystalline lens), both monochromatic and polychromatic. The aberrometers described include the Hartmann-Shack wavefront sensor, laser ray tracing, spatially resolved refractometer or the corneal aberrations. This technology has been used to advance our understanding on several visual mechanisms, ocular conditions, and corrective methods. Applications include accommodation, myopia, aging, myopia, keratoconus, corneal refractive surgery, cataract surgery or contact lenses.

KEYWORDS

Ocular aberrations, accommodation, aging, myopia, refractive surgery, intraocular and contact lenses

RÉSUMÉ

Cet article présente le concept, la mesure et les applications d'aberrations d'onde. L'optique oculaire n'est pas parfaite. Hormis les aberrations conventionnelles de faible ordre (tels que le flou et l'astigmatisme), les images rétiniennes sont dégradées par d'autres aberrations d'ordre élevé. Les aberromètres mesurent typiquement les déviations de rayons au niveau du plan rétinien, en fonction de la position de la pupille, c'est-à-dire les dérivés locaux de l'aberration d'onde. L'article traite de la technologie de pointe permettant de mesurer les aberrations de l'œil (cornée et cristallin), tant monochromatiques que polychromatiques. Les aberromètres décrits incluent le capteur de front d'onde Hartmann-Shack, le traçage au rayon laser, le réfractomètre à résolution spatiale ou les aberrations cornéennes. Cette technologie a été utilisée pour nous aider à mieux comprendre plusieurs mécanismes visuels, conditions oculaires et procédés de correction. Les applications incluent l'accommodation, la myopie, le vieillissement, le kératocône, la chirurgie cornéenne réfractive, la chirurgie de la cataracte ou les lentilles de contact.

MOTS-CLÉS

Aberrations oculaires, accommodation, vieillissement, myopie, chirurgie réfractive, lentilles intraoculaires et de contact

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INTRODUCTION

This paper presents some of the latest investigations in aberrometry of the Visual Optics and Biophotonics Laboratory at the Instituto de Optica ''Daza de Valdés'', Consejo Superior de Investigaciones Científicas (CSIC). The CSIC is the largest national multidisciplinary research institution in Spain, with more than 100 research institutes. Refounded in 1939, it was based on the Junta para Ampliación de Estudios e Investigaciones Científicas, founded in 1907, with Nobel Prize Santiago Ramón y Cajal as its first President. The Instituto de Optica ''Daza de Valdés'' was one of the oldest institutes, and vision research was one of the pillars from its foundation. Pioneering work by Aguilar, Otero and Durán in 40's and 50's on Stiles-Crawford effect and night myopia, among other topics, was followed by very recognized work in the 80's and 90's on physiological optics (double-pass retinal image quality, schematic eye models, ray tracing…) by Santamaría, Bescós, Artal or Navarro. The institute owes its name to Benito Daza de Valdés, who published the first book on Optics in Spanish language in 1623 entitled ''On the use of spectacles''. He provided wide information on the use of lenses to improve vision, optical correction on myopia and hyperopia, presbyopia and aphakia or the use of sunglasses. He is also credited for the idea of using implanted lenses in cataract surgery. Many of Daza de Valdés' interests remain hot topics of basic and clinical investigation today and are research areas covered by our group. Our work builds on the experience accumulated at the institute, novel state-of-the art technology and cooperation and support from our long-term collaborators at the Schepens Eye Research Institute. We are inspired by the Schepens' multidisciplinary approach to advance in vision research, and the direct application in the clinical practice. For this reason, our clinical collaborations with the Institute of Ophthalmobiology (University of Valladolid) and Fundación Jiménez Díaz (Madrid) are of extreme importance.

FACTORS CONTRIBUTING TO RETINAL IMAGE DEGRADATION

The eye is an optical instrument that projects scenes of the visual world onto the retina. It has been known for many years that the eye is far from being a perfect optical system, in particular for large pupil diameters. Refractive anomalies (defocus or astigmatism) occur frequently in the eye.

In western countries myopia affects to about 30% of the population, although its prevalence is much higher (more than 80 %) in certain Asian societies.[25] But the eye suffers also from other optical imperfections (called high order aberrations), which are not typically measured in the clinic and cannot be corrected by conventional means. Like defocus, optical aberrations blur the retinal image, reducing image contrast and limiting the range of spatial frequencies available to further stages of the visual processing. The contribution of aberrations to optical degradation is typically smaller than defocus or astigmatism. The blurring effect of aberrations becomes more noticeable for large pupils. For small pupil sizes diffraction effects, associated to the limited aperture size, predominate over the aberrations.

Along with diffraction and aberrations, scattering also contributes to degradation of retinal image quality. Scattering occurs at the cornea,[29] and particularly the lens.[74] Although typically scattering is small in normal, young eyes, it is well-known that it increases with age (due to changes in the crystalline lens [68]) and after PRK refractive surgery.[55]

THE OCULAR WAVE ABERRATION

Optical designers often make use of geometrical optics to assess the optical quality of an imaging system, by computing the optical path of a set of parallel rays entering the optical system. In a perfect optical system rays entering through different parts of the pupil hit the image plane

(the retina in case of the eye) at the same location. Imperfections of the optics cause departure of those rays from the ideal location. These angular deviations are called transverse aberrations.[13,42] The most common representation of the aberrations of the optical system is in terms of the wave aberration, which is defined as the departure of the wave aberration from its ideal wave form. The wave-front is normal to the trajectories of the rays. This wave-front is a spherical wave for the perfect optical system, and a distorted wave for an aberrated system. The difference of the aberrated wave-front from the ideal spherical wave-front is called wave aberration. The wave aberration is measured at the pupil plane, and is represented as "topographical" map. For a perfect optical system, the wave aberration is flat across the pupil. A typical wave to describe the wave aberration is in terms of a Zernike polynomial expansion.[41-42,72] Zernike coefficients represent the weight of each of simpler polynomial in the wave aberration. The low order terms correspond to conventional refractive errors: 1st order terms represent prism, and 2nd order terms defocus and astigmatism. High order terms include other well-known monochromatic aberrations: i.e. spherical aberration (due to changes in focus with pupil size) or coma (a 3rd order, non-rotationally symmetric aberration). The root-mean-square (RMS) wave-front error can be estimated from the wave aberration, and it is used as a global optical quality metric. Fourier optics allow direct estimation of the PSF and MTF from the wave aberration.[24] The phase of the pupil function is proportional to the wave aberration. The PSF is the squared modulus of the Fourier Transform of the Pupil Function, and the MTF is the modulus of the inverse Fourier Transform of the PSF. It should be noted that, unlike the MTF estimated from double-pass measurements, the MTF computed from the wave aberration does not contain the effects of scattering. However, while the MTF is easily obtained from the wave aberration (for any pupil size, and computationally, for every focus), the wave aberration or even the PSF cannot be estimated directly from the double-pass MTF estimates.

MEASUREMENT OF MONOCHROMATRIC ABERRATIONS WITH ABERROMETERS

Most current aberrometers measure the transverse aberration as a function of pupil position. The transverse aberrations are proportional to the local derivative (slope) of the wave aberration, therefore the wave aberration can be easily retrieved from the transverse aberration. Transverse aberration can be measured as the test beam goes into the eye (ingoing aberrometry) or as the wave-front emerges from the eye (outgoing aberrometry). Figure 1 shows the basic principles of these two types of aberrometers, as well as views of the optical set-ups. We will describe briefly the aberrometers used in the experimental studies shown in the next sections: the Shack-Hartmann wave-front sensor (S-H), which is an outgoing aberrometer, and two ingoing aberrometers, the Laser Ray Tracing (LRT), and Spatially Resolved Refractometer (SRR). In the SH [36] a narrow beam from a point light source is imaged by the eye onto the retina. The reflected wave travels through a lenslet array which focuses multiple spots (one per lenslet) onto a CCD camera. Each lenslet samples a small part of the wave-front corresponding to a certain pupil location. For a perfect optical system, the spots will be imaged at the focal point of each lenslet. The aberrations will cause local tilts of the wave-front, and therefore the spots will get deviated from the focal points. The transverse ray aberration associated to each lenslet can be determined from the departure of the centroid of its corresponding image with respect to the ideal position. In the LRT [50,57] the pupil is sampled sequentially, as a laser beam is scanned across the dilated pupil and projects a spot onto the retina. A CCD in a plane conjugate to the retina captures the aerial images as a function of entry pupil. By the effect of aberrations rays entering the eye through eccentric locations get deviated from the central ray. The local transverse aberration is measured as the angular distance between the centroid of each of the aerial images and the centroid of the image corresponding to a centered entry pupil. Again, the wave aberration is estimated from the set of local transverse aberrations. The SRR [14,30,57,75] is also a sequential technique, and also

measures the aberrations in the first pass. The principle is similar to that of the LRT. Instead of capturing the image reflected by the retina onto a CCD camera, the subject aligns a cross-hair target viewed through a centered pupil with spots viewed through eccentric pupils. These three techniques have been used extensively in the laboratory to understand the optical properties of the normal eye, as well as in clinical applications. For normal subjects it has been demonstrated that the three techniques provide similar results. Most recent imaging system use infrared illumination, while for many applications aberration data in visible light are required. It has been shown experimentally that, in general, measurements in IR (780 nm) and in green light (543 nm) are equivalent,[37] provided that the ocular longitudinal chromatic aberration (see next section) is taken into account. Also, the aberration data are unaffected by the state of polarization of the test beam.[50,63]

The methods described above measure the aberrations of the entire optical system of the eye. Conventional corneal topography can be used to measure the aberrations of the cornea alone.[3,10-11,27] By performing virtual ray tracing on corneal elevation maps (obtained from placido disk corneal topography) the transverse aberration of the anterior corneal surface can be measured. From these data the corneal wave aberration can be obtained as described above.

CHROMATIC ABERRATIONS

The aberrometry techniques described above use monochromatic illumination, and therefore measure monochromatic image quality. However, the visual world is polychromatic, and chromatic aberrations play an important role in image quality. The two major chromatic aberrations are the longitudinal chromatic aberration (LCA, change of focus with wavelength) and the transverse chromatic aberration (TCA, change of angular deviations with wavelength), and both are a major consequence of the wavelength dependence of the refractive index of the ocular media.[70] The LCA has been measured both through psychophysical techniques (see for example reviews by Charman [19] and Atchison and Smith [9]) or using a double pass techniques at different wavelengths.[18,65] We recently obtained LCA from aberration measurements (defocus term in the Zernike polynomial expansion) using the SRR at various wavelengths in the visible. Thibos et al.[71] proposed an equation, based on Cornu's expression for the dependence of the refractive index with wavelength, that fitted the experimental data. The average chromatic difference of focus between the blue (450 nm) and the red (650 nm) is 1.4 D. While the LCA of the human eye has been well studied, there are few reports for the TCA. Thibos et al.[70] and Simonet and Campbell [69] used a psychophysical vernier acuity technique to measure foveal transverse chromatic aberration. Typically, the TCA is not zero at the pupil center. Foveal TCA reaches a minimum at a particular pupil position, known as visual axis. TCA is generally attributed to the fact that the eye is not a centered optical system (the fovea does not lie on the optical axis) and pupil decentrations.[64,70] Marcos et al.[43] used the SRR to measure TCA (angular deviations between a blue and red test spots), and studied the influence of the aberrations and cone directionality on TCA. They concluded that TCA varied significantly across the population. However, this variability was not related to the variability in the foveal location or pupil centration, but rather may be associated with irregularities in the ocular components.[49] Measurements with the SRR at different wavelengths allowed estimations of high order monochromatic aberrations with various wavelengths, as well as the chromatic aberrations.[43] These data were used to generate the polychromatic PSF and MTF. PSFs for each wavelength were computed as described in the previous section. The individual PSFs were added, with appropriate interpolation, and the shift predicted by the TCA, and weighted by the spectral sensitivity curve. MTFs were computed from the PSF. As shown in figure 2 for a single subject, the white light MTF is significantly lower than the monochromatic MTF. It should be noted that a perfect optical system, subject to LCA and TCA shows a relatively larger contrast degradation by the effect of chromatic aberrations than an aberrated optical system. A similar approach was applied to the estimation of the MTF available for each cone class. McLellan et al.[54] showed that for a perfect optical eye, the MTF for S-cones in largely degraded

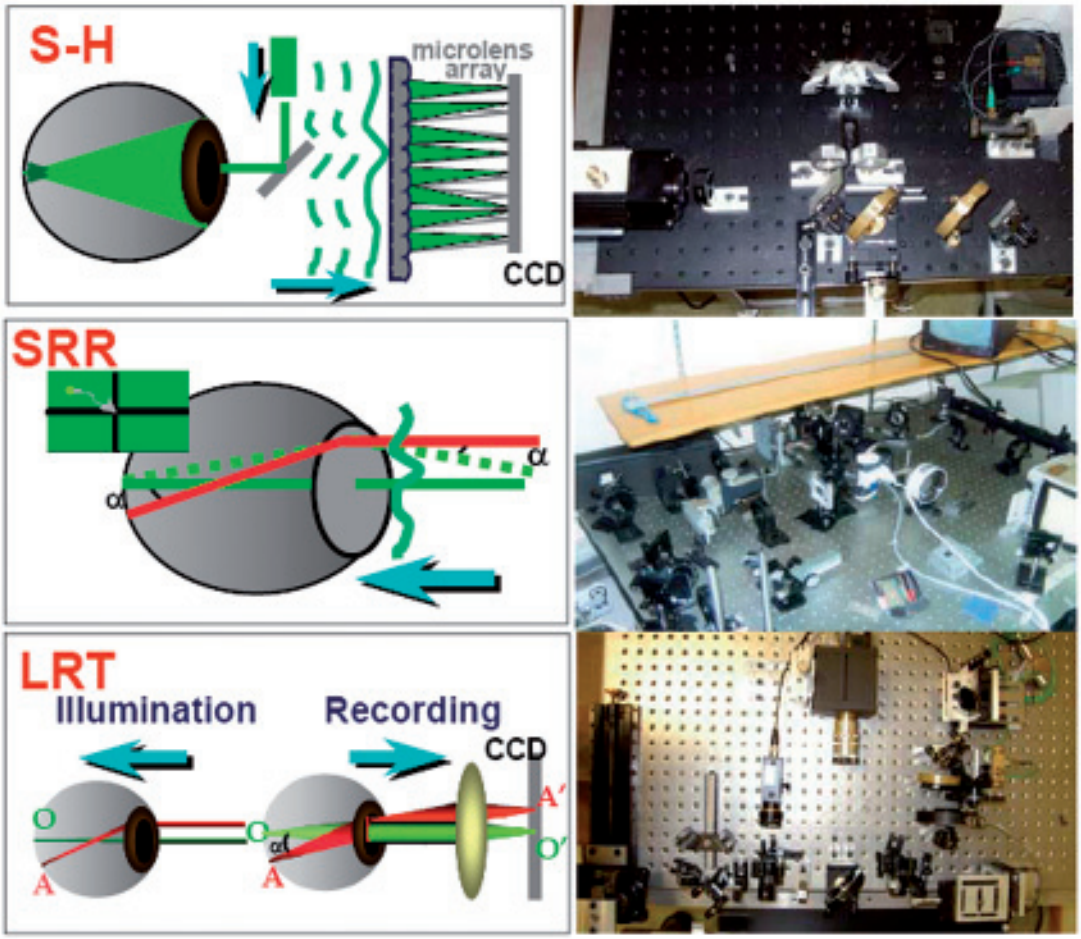

Fig. 1. Basic concept and views of the laboratory optical set-ups from different aberrometers: Shack-Hartmann (S-H), Spatially Resolved Refractometer (SRR) and Laser Ray Tracing (LRT). Optical set-ups at the Institute of Optics (CSIC), Madrid (SH and LRT) and Schepens Eye Research Institute (Harvard University), Boston (LRT). The SH (top panel) is an outgoing aberrometer; the wavefront is sampled by a microlens array as it exits the eye. The SRR and LRT are ingoing aberrometers. In these two aberrometers, rays of light enter the eye through different parts of the pupil. By the effect of aberrations, eccentric beams get deviated with respect the principal ray. In LRT the aerial images are captured onto a CCD camera, as a beam scans the pupil. In SRR the subject aligns the beam with respect to a centered reference by means of a joystick. In all cases, the raw data are the derivatives of the wave aberration.

by chromatic defocus, compared to the MTF for M and L cones. However, for real eyes, while the MTF for M and L cones is reduced compared to the perfect optical system, the MTF for S-cones is not significantly reduced (with respect to the M and L MTF). This fact indicates a certain degree of balance of optical (monochromatic and polychromatic) aberrations in the eye.

OPTICAL ABERRATIONS OF THE NORMAL HUMAN EYE

Variation across individuals

The amount and distribution of aberrations vary greatly among the population. Several population studies show a wide distribution of the aberrations in human eyes,[16,62] typically all high

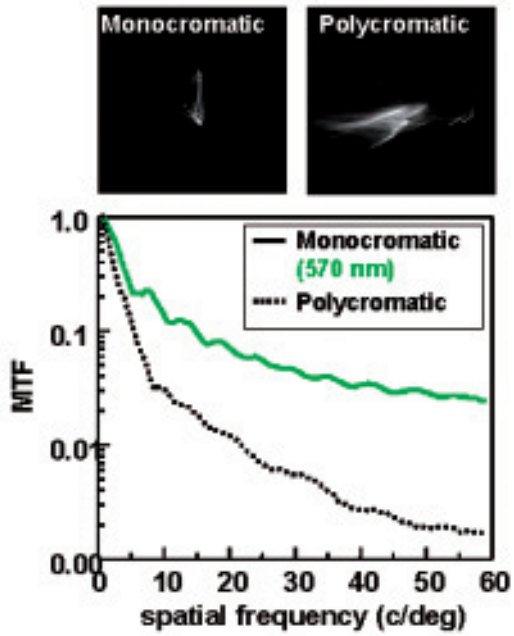

Fig. 2. Monochromatic and polychromatic PSFs for a normal subject, and the corresponding MTFs (radial profiles). Wave aberrations were measured at different wavelengths (from 450 to 650 nm) using the SRR technique. CA and TCA were obtained from the same set of data. Polychromatic PSFs were generated by superposition of monochromatic PSF, weighted by the retinal spectral sensitivity. Best focus was set at 570 nm, the rest of wavelengths being defocused according to the LCA. Each monochromatic PSF was shifted to account for the effect of the TCA. Data for 6-mm pupils. Plot adapted from Marcos et al.[8]

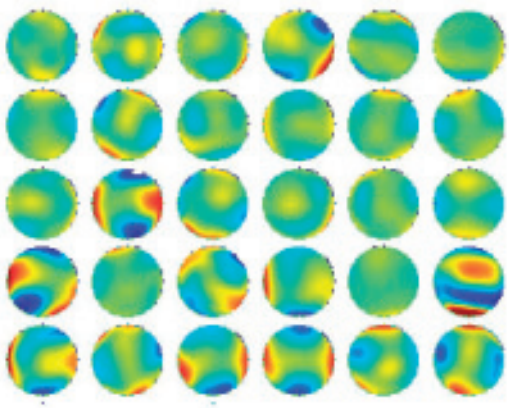

Fig. 3. Examples of wave aberration maps for a group of 30 normal subjects, all plotted in the same scale, and with defocus cancellation.

order terms averaging to zero, except for the spherical aberration that tends to be slightly positive. This variation in high order aberrations parallels well know variation in refractive errors. Figure 3 shows examples of the wave aberrations of a group of normal, young subjects. Aberrations tend to be mirror symmetric between left and right eyes, although similarly to anisometropia, subjects with very different left to right wave aberration patterns are not uncommon.[44]

Sources of aberrations in the eye

The cornea and the crystalline lens are the major refractive components in the eye, and aberrations of the individual components are expected to contribute to overall image quality. It has been shown that at least for young eyes, a proportion of the corneal aberrations are compensated by aberrations of the crystalline lens. A partial compensation of corneal astigmatism by the crystalline lens was well known in the clinical optometry literature (Java's rule).[35] Also, the fact that, the spherical aberration of the cornea is typically positive, while the spherical aberration of the crystalline lens tends to be negative has been known for several years.[56] Interestingly, a partial compensation of asymmetric aberrations, such as coma, also seems to occur, at least in young, low myopic eyes.[7] Several models have been attempted to explain the interactions of corneal and internal aberrations. However, simple tilts and decentrations of the ocular components are not sufficient to explain the complex structure of the total wave aberration pattern.

Changes with accommodation

The fact that the retinal image quality changes with accommodation has been shown in double pass [49] or aberrometry studies.[8,31] He et al.[31] reported aberration measures in a group of eyes for accommodation stimuli ranging from 0 D (infinity) to 6 D, using the SRR. As reported earlier in the literature, the lag of accommodation increases with accommodation demand. As shown in figure 4 A, optimal optical quality (excluding defocus and astigmatism) was attained for about 2 D, while the RMS increased by about 1 μm on average for 6 D of accommodation. The most systematic changes were found for the spherical aberration term (decreasing in all subjects, and going from positive to negative in several subjects) and the higher order aberrations. These changes are likely related to changes in the shape of the crystalline lens during the accommodation process. Hofer et al.[32] measured dynamic changes of high order aberrations during the accommodation process (from 0 to 2 D), and found temporal changes even when the accommodation was paralyzed by topical drugs.

Changes with age

Double pass MTFs show a decline of contrast transfer at all spatial frequencies between young and old subjects.[4] Part of the degradation is likely due to an increase of intraocular scattering with age.[73] However, aberration measurements have revealed that part of the decrease in retinal image quality with age is due to an increase in ocular aberrations.[53] McLellan et al.[53] showed (in a group of 38 subjects, ranging from 23 to 65 years) that 3rd and higher order aberrations increase with age (from 0.7 μm to 1 μm, for a 7.3 mm pupil, on average). Results from this study are shown in figure 4 B. While no significant changes were found for 3rd order terms, the correlation of spherical aberration and 5th and higher order terms with age was highly statistically significant. Artal et al.,[7] measuring corneal and total aberrations in a group 0,3 of 17 subjects (from 20 to 70 years), showed that part of the increase of optical aberrations with age was due disruption of the compensation of corneal and internal aberrations, which was common in young subjects.[6] This is not surprising for spherical aberration, since ex vivo measurements have shown that the spherical aberration of the crystalline lens shifted toward positive values with age.[23] The reasons why this also happens for asymmetric terms is still to be understood.

Relationship with refractive error

Several cross-sectional studies have measured high order aberrations as a function of myopic refractive error, all showing a tendency of poorer optical quality in the higher myopes.[20] Marcos et al.[45,47] reported results on 53 eyes (see figure 4 C), showing a statistically significant increase of 3rd and higher order RMS with myopia (from 0.3 μm for -0.25 D to 1 μm for 12 D, on average, for a 6.5 mm pupil). Corneal and internal aberrations also increased with myopia, but

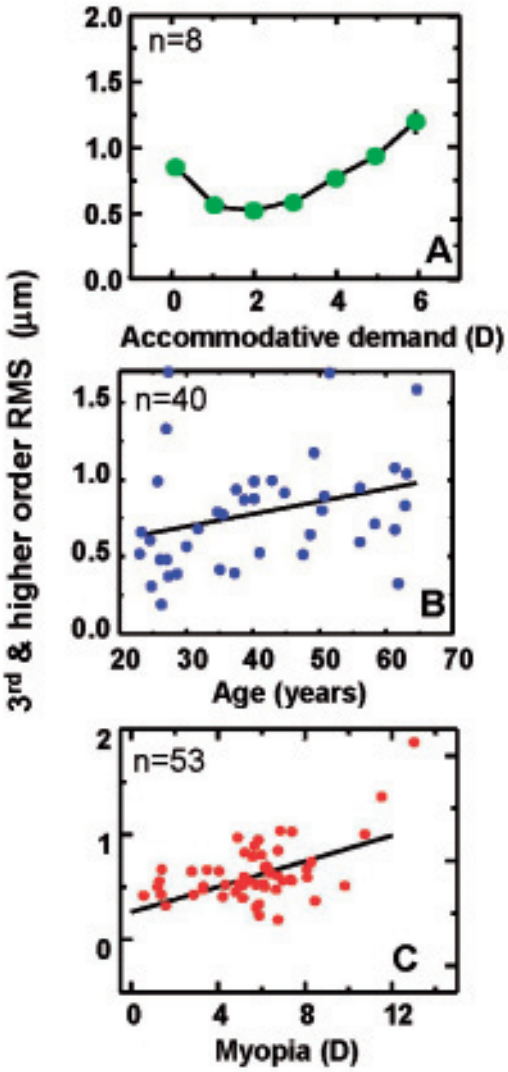

Fig. 4. Root-mean square (RMS) wavefront error for 3rd and higher order aberrations (A). As a function of accommodation (data from He et al.[1]), (B) as a function of age (data from McLellan et al.[9]), (C) as a function of refractive error (data from Marcos et al.[11]).

at lower rates. Total spherical aberration did not change significantly with myopia. Corneal spherical aberrations increased toward more positive values for increasing myopia (associated to an increase in corneal asphericity), but tended to be compensated by the internal spherical aberration, which increased toward more negative values for increasing myopia. The major cause of increasing optical degradation with myopia was increased coma and higher order aberrations. We also found biometric and optical differences between hyperopic and myopic eyes. A study comparing two groups of hyperopic and myopic eyes (matched in age and in absolute refractive error) showed higher amounts of corneal asphericity and corneal spherical aberration in the hyperopic group (Fig. 5), apart from longer axial lengths. The corneal/internal balance seemed to be comprised in the hyperopic group at an earlier age.[38]

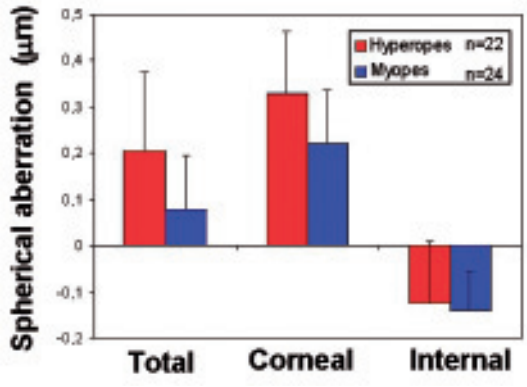

Fig. 5. Mean spherical aberration (total, corneal, internal) for hyperopic and myopic eyes (age and refraction matched). Plot adapted from Llorente et al.[3]

Changes with eccentricity

Monochromatic image quality as a function of the visual angle has also been studied both through double-pass [33,59] and aberrometry.[26,60] Double pass studies showed a decline in retinal image quality with eccentricity. The largest degradation was found for visual angles beyond 20 deg. In the central 20 deg field Strehl ratio drops only from about 0.14 to 0.9 (average of 4 subjects), suggesting that the eye follows a wide-angle lens design (non-optimal quality on-axis, i.e. on the line of sight, but constant image quality over a wide visual field). Astigmatism and coma increase with retinal eccentricity. Once peripheral and astigmatic defocus are corrected, higher order aberrations do not increase dramatically off-axis. Navarro et al. reported average increases in 3rd and higher order RMS (for 6.5 mm pupil) from 0.45 μm at the fovea to 1.1 μm at 40 deg.[60]

OPTICAL ABERRATIONS OF THE PATHOLOGICAL AND SURGICAL EYE

The previous sections refer to retinal image quality in normal eyes. The techniques to measure retinal image quality and aberrations described above have been applied clinically. They have proved to be valuable diagnostic and evaluation tools.

Optical aberrations in keratoconus

Progressive distortion of the cornea in keratoconus leads to abnormal corneal topography and decreased visual performance in keratoconus patients. At least in early and moderate stages of the disease, most changes occur on the anterior corneal surface (i.e. the total aberration pattern is practically identical to the corneal aberration pattern. Further changes in the posterior corneal surface may occur in the most advanced stages).[17] Astigmatism is typically high in these patients. Additionally, coma (normally in the vertical direction) is much higher than in normal subjects[11,66] (3.7 times on average, in Barbero et al.[11] study). Figure 6 shows an example of the corneal and total wave aberration in a keratoconic eye. The great similarity between both patterns indicate that the optical degradation occurs primarily on the anterior corneal surface.

Change of optical aberrations after refractive surgery

Corneal refractive surgery has become a popular alternative for correction of refractive errors. Early studies based on corneal topography showed that while defocus or astigmatism are gene-

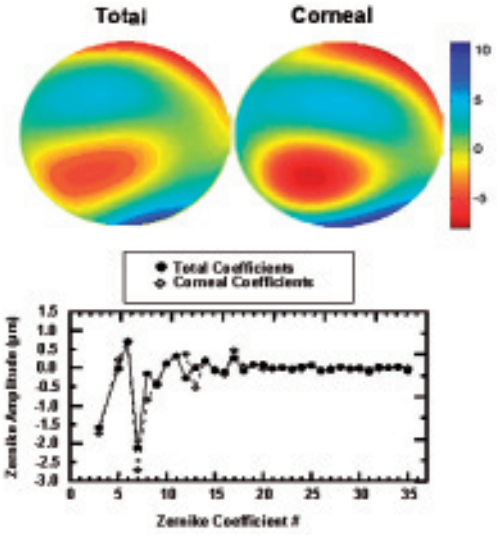

Fig. 6. Example of total and corneal wave aberration (for 3rd and higher order aberrations) and corresponding Zernike coefficients for an eye with keratoconus. Third order coma is the dominant aberration. Data from Barbero et al.[5]

rally successfully corrected, refractive surgery (RK, PRK and LASIK) increased the amount of corneal aberrations.[2,61] In addition, the distribution of aberrations changed from the third order dominance found in normal subjects, to fourth order dominance. This increase in corneal aberrations correlates well with the decrease found in contrast sensitivity.[3] Seiler et al.[67] in standard myopic PRK (15 eyes, mean pre-op spherical error = -4.8 D) and Moreno-Barriuso et al.[58] for LASIK (22 eyes, mean pre-op spherical error = -6.5 D) measured for the first time the changes in the total aberration pattern induced by surgery. Both studies found a significant increase in 3rd and higher order aberrations (by a factor of 4.2 and 1.9 in the RMS, respectively). The larger increase occurred for spherical and 3rd order aberrations. Figure 7 A shows an example of total and corneal aberrations (3rd and higher order) for one patient before and after myopic LASIK, and the corresponding RMS. Marcos et al.[46] found that the decrease in the MTF computed from wave aberrations agreed with the decrease in contrast sensitivity measured psychophysically in those subjects. The changes of total spherical aberrations are not fully accounted by changes in the anterior corneal surface.[48] In all eyes, total spherical aberration increased slightly less than corneal aberrations, likely due to significant changes in the posterior corneal shape (shifting toward more negative values of spherical aberration). The increase in the total spherical aberration is highly correlated to the amount of spherical error corrected, and it is associated to an increase in corneal asphericity. However, the causes of the increased asphericity are still not well understood.[22,34] Computer simulations of the post-operative corneal shape after subtraction of the standard ablation pattern (Munnerlyn equation) performed on real pre-operative corneal elevation maps do not show the increased corneal asphericity found clinically.[51] A parabolic approximation of this equation induces a slight increase of corneal asphericity, but much less than found experimentally.[15,51] It is likely that much of the discrepancy is due to the fact that the energy is not properly transferred onto the cornea, due to changes in laser efficiency across the corneal surface.[1,15] Figure 8 shows average results on 13 patients of post-operative corneal asphericities after computer simulation of the Munnerlyn ablation pattern (and its parabolic approximation), directly or considering laser efficiency changes across the cornea, in comparison with average pre-operative asphericities and real post-operative asphericities in the same eyes. Refinement of ablation algorithms and a better understanding of the corneal biomechanical changes are needed to avoid induction of high order aberrations.

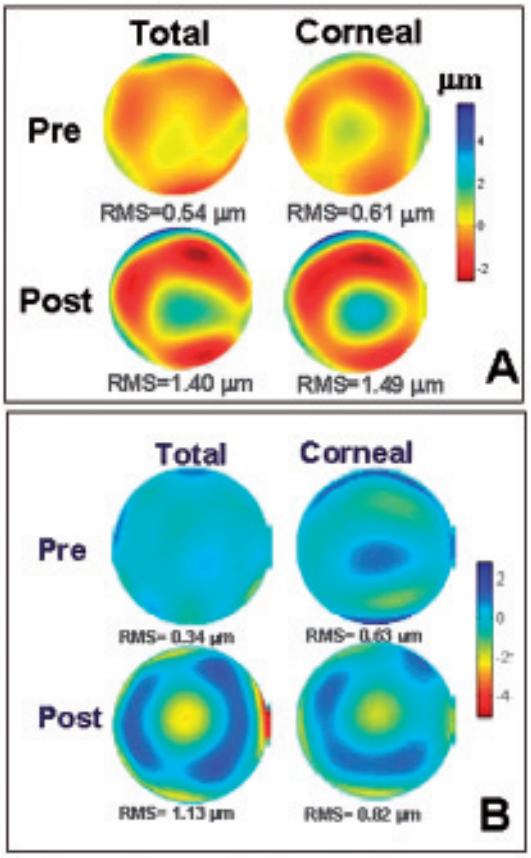

Fig. 7. A. Example of total and corneal aberrations (3rd and higher order) for an eye before and after LASIK for myopia. Data from Marcos et al.[69] B. Example of total and corneal aberrations (3rd and higher order) for an eye before and after LASIK for hyperopia. Data from Llorente et al.[2]

Changes of corneal and total aberrations with LASIK surgery for hyperopia have also been studied by our laboratory.[39] We found a systematic increase of high order aberrations with the procedure. Figure 7 A shows an example of total and corneal aberrations (3rd and higher order) for one patient before and after myopic LASIK, and the corresponding RMS. While spherical aberration becomes more positive after myopic LASIK, it shifts toward negative values after hyperopic LASIK. For the same absolute amount of correction, the absolute increase of corneal spherical aberration is larger with hyperopic LASIK. Figure 9 compares the induced aberration (total and corneal) after myopic and hyperopic LASIK respectively.

Optical aberrations and cataract surgery

In virtually all cataract procedures, the natural crystalline lens is replaced by an artificial intraocular lenses (IOL). IOL manufacturers typically assess the optical quality of these lenses by measuring the MTF and the resolution in vitro. The first measurements of the optical quality of patients with implanted IOLs were done using a double pass technique.[5,28] Post-surgical MTFs were lower than the MTFs of young eyes, and optical performance was worst with multifocal than with monofocal lenses. Recently, the aberrations of the IOL have been measured for the first time in vivo.[12] Corneal and total aberrations were measured using a videokeratoscope and Laser Ray Tracing respectively. The aberrations of the IOL were estimated as the total minus

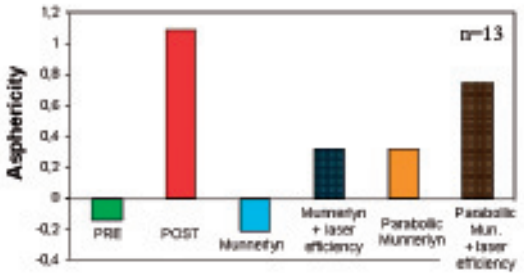

Fig. 8. Average corneal asphericity before and after myopic LASIK: clinical data, and after subtraction of Munnerlyn and parabolic munnerlyn algorithms (considering and not considering laser efficiency changes). From Marcos et al.[4] and Cano et al.[10]

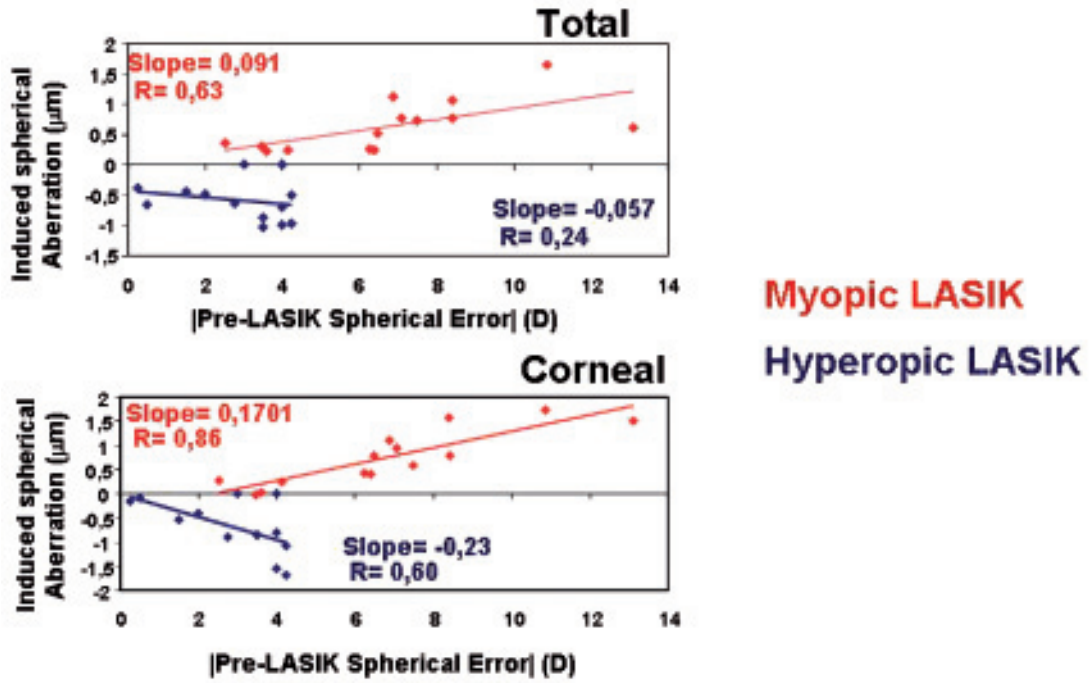

Fig. 9. Comparison of spherical aberration (total and corneal) induced by myopic (n=13) and hyperopic LASIK (n=14). From Llorente et al.[2]

corneal aberrations. Figure 10 shows average total, corneal and internal spherical aberrations in patients before and after cataract surgery from Barbero et al.'s study.[12] While scattering is removed with the extraction of the cataract and replacement by IOL, aberrations are not reduced. Corneal aberrations tend to increase with surgery, probably due to the incision. Pre and post cataract surgery aberrations are significantly larger than in a young control group. Measurements in vitro showed that the IOL is not aberration-free. The amount of aberrations (particularly astigmatism and 3rd order) increase after implantation, likely due to tilt and decentration of the lens. Similarly to what Artal et al.[7] reported for old eyes, post surgical eyes do not show a good balance of corneal and internal (IOL) aberrations. This is particularly due to the fact that the spherical aberration of the IOL tends to be positive. Further improvements of the surgical procedures and a lens design aiming at canceling the spherical aberration of the cornea may result in

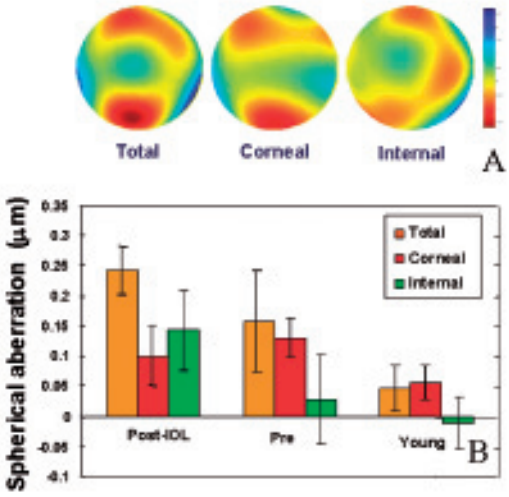

Fig. 10. A. Example of total, corneal and internal wave aberration (3rd order and higher) for an eye after cataract surgery (with spherical IOL implant). B. Spherical aberration in a group of patients before cataract surgery (n=6), after cataract surgery by phacomulsification and spherical IOL implant (n=9), and a group of young emmetropic eyes (n=14), from Barbero et al.[7]

better optical outcomes of cataract surgery. We found that patients implanted with aspheric IOLs showed negative internal aberration and significantly lower spherical aberration than patients with spherical IOLs, resulting in better optical quality in focus (not significantly different when astigmatism was taken into account, though).[52] As a drawback, depth-of-field (both referred to relative and absolute criteria) was decreased in patients with aspheric IOLs.

Optical aberrations and contact lenses

Measurements of corneal and total aberrations with and without contact lenses in rigid gas permeable (RGP) contact lens wearers revealed that RGP contact lenses can correct significant amounts of aberrations.[21] The correction is particularly prominent in eyes with great amounts of corneal aberrations. Only one eye of the study (with particular good corneal/internal compensation) showed lower optical quality (for high order aberrations) with the contact lens on than with the naked eye. A comparison of the aberrations of the anterior surface with and without the contact lens allows to evaluate the flexure of the lens, i.e. its conformity to the cornea, which is material-dependent. A comparison of the internal aberrations with and without the contact lens allows to evaluate the optical contribution of the tear lens, which we found to show negative spherical aberration (partially compensating the positive spherical aberration produced by spherical lenses).

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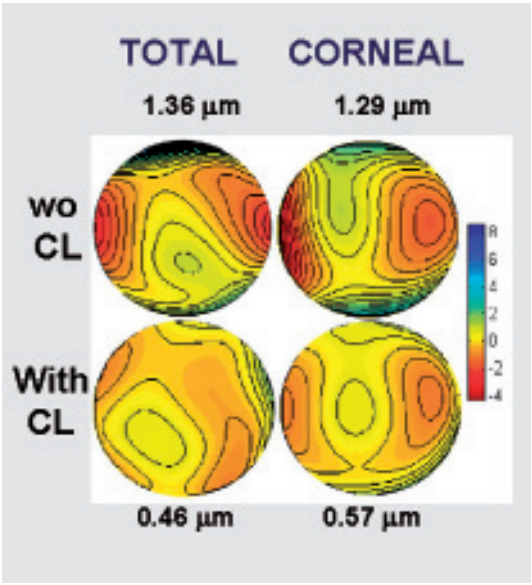

Fig. 11. Example of total and corneal wave aberrations (3rd order and higher) for an eye with and without an RGP contact lens on, demonstrating the capability of RGP lenses to correct corneal (and total) high order aberrations. Data from Dorronsoro et al.[6]

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