CHAPTER V

Optical Response to Myopic LASIK Surgery from Total and Corneal Aberration Measurements

This chapter is based on the article by Marcos, S., et al., *Optical Response to Myopic LASIK Surgery from Total and Corneal Aberration Measurements.* Invest Ophthalmol Vis Sci, 2001. 42: p. 3349-3356.Coauthors of the study are: Sergio Barbero, Lourdes Llorente and Jesus Merayo-Lloves.

The contribution of Sergio Barbero to the study was the development of the technique to measure corneal aberrations, computational studies of the internal changes due to the posterior corneal surface and the effects of convergence on the crystalline lens, data collection in patients, as well as contributions to the data analysis and discussion.

RESUMEN

OBJETIVOS: Medida de las aberraciones ópticas inducidas por la cirugía refractiva para corrección de miopía (LASIK) sobre la superficie anterior de la cornea y sobre el sistema óptico del ojo.

MÉTODOS: Las aberraciones totales y corneales se midieron en un grupo de 14 ojos antes y después de la cirugía (rangos de miopía pre-operatorios: -2.5 a -13 D). Las aberraciones totales se midieron con una técnica de trazado rayos. Las aberraciones corneales se estimaron mediante marcha de rayos sobre datos de elevación suministrados por un topógrafo corneal (Atlas Corneal Topography System). Las aberraciones totales y corneales se representan mediante una expansión en polinomios de Zernike. La RMS de la aberración de onda se usa como métrica de calidad óptica global.

RESULTADOS: 1) Se medió un incremento significativo de las aberraciones totales y corneales (3^{rd} y ordenes superiores) con la cirugía: un factor promedio en las totales de 1.92 y de 3.72 en las corneales. En promedio, este incremento fue más pronunciado para los ojos con miopías pre-operatorias más altas. 2) Existe una buena correlación ($r=0.97$, $p<0.0001$) entre las aberraciones totales y corneales inducidas. Sin embargo, la aberración esférica corneal crece más que la aberración esférica total, lo cual sugiere una modificación en la aberración esférica de la cara posterior corneal de signo opuesto a la de la cara anterior. 3) El centrado pupilar y las aberraciones internas juegan un papel importante en la estimación los cambios individuales con la cirugía.

CONCLUSIONES: Puesto que la cirugía LASIK modifica la superficie anterior corneal, la mayor parte de cambios en el frente de onda total se deben a cambios en las aberraciones de la cara anterior corneal. Sin embargo, debido a las interacciones individuales entre las aberraciones de la cornea y el cristalino, la medida combinada de aberraciones totales y corneales es imprescindible para entender los cambios ópticos individuales, y es de especial importancia en la aplicación de algoritmos de ablación personalizada. Los cambios observados en las aberraciones internas son consistentes con los cambios en la cara posterior corneal encontrados en trabajos previos a partir de medidas de topografía de la cara posterior de la cornea mediante barrido de lámpara de hendidura.

ABSTRACT

PURPOSE: To evaluate the optical aberrations induced by myopic LASIK refractive surgery on the anterior surface of the cornea and the entire optical system of the eye.

METHODS: Total and corneal aberrations were measured in a group of 14 eyes (pre-operative myopia ranging from -2.5 to -13 D) before and after LASIK surgery. Total aberrations were measured using a Laser Ray Tracing technique. Corneal aberrations were obtained from corneal elevation maps measured using an Atlas Corneal Topography System and custom software. Corneal and total wave aberrations were described as Zernike polynomial expansions. Root-mean-square wavefront error was used as a global optical quality metric.

RESULTS: 1) Total and corneal aberrations (3^{rd} and higher order) suffered a statistically significant increase after myopic LASIK surgery, by a factor of 1.92 (total) and 3.72 (corneal), on average. This increase was more pronounced for the highest pre-operative myopes. 2) There is a good correlation (r=0.97, p<0.0001) between the aberrations induced on the entire optical system, and those induced on the anterior corneal surface. However, the anterior corneal spherical aberration increased more than the total spherical aberration, suggesting a change (of opposite sign) in the spherical aberration of the posterior corneal surface. 3) Pupil centration and internal optical aberrations, which are not accounted for in corneal topography, play an important role in evaluating individual surgical outcomes.

CONCLUSIONS: Since LASIK surgery induces changes on the anterior corneal surface, most changes to the total aberration pattern can be attributed to changes in the anterior corneal aberrations. However, due to individual interactions of the aberrations of the ocular components, a combination of corneal and total aberration measurements is critical to understand individual outcomes, and by extension, to design custom ablation algorithms. This comparison also reveals changes in the internal aberrations, consistent with the posterior corneal changes reported using scanning slit corneal topography.

1.Introduction

Laser in situ keratomileusis (LASIK)[1, 2] has become a popular surgical alternative for the correction of myopia, and a rapidly increasing number of LASIK procedures are performed daily worldwide. In this technique, a hinged flap is created and folded back and the exposed stroma is photo-ablated using an excimer laser. In myopic LASIK, stromal tissue is removed so that the curvature of the central cornea is flattened to compensate for the excessive refractive power or longer axial length of the myopic eye. Most of the published studies evaluate the clinical outcomes of LASIK in terms of visual performance (visual acuity or contrast sensitivity)[3, 4]. Some reports evaluate the microstructural changes induced in the stroma and Bowman's layer by means of *in vivo* confocal microscopy[5]. However, there are still many open questions regarding the wound healing process[6] and the biological response of the cornea to ablation[7, 8].

Recently, the implementation of techniques to precisely measure the optical wave aberration pattern[9-14] prior to and following refractive surgery has generated significant excitement among refractive surgeons. First, the measurement of optical defects (aberrations) following refractive surgery has revealed that while conventional refractive errors (i.e. myopia or astigmatism) are reduced or cancelled, higher order aberrations (uncorrectable by conventional means) are generally induced[15, 16]. Second, along with other technical developments (i.e. scanning small spot lasers, eye trackers, etc...), the precise measurement of ocular wave aberrations has opened the potential for an improved refractive surgery, customized for each patient, aiming at canceling both low and high order aberrations present in the eye[17-20]. Two approaches are currently being pursued, both to evaluate and to guide ablation procedures: wavefront aberrations (aberrations of the entire optical system)[21, 22] and corneal topography[23, 24] (or alternatively aberrations of the anterior corneal surface). The analysis of the total aberrations of the eye provides the most direct and complete measurement of retinal image quality, and therefore can be directly related to visual performance. Previous studies show high correlations between corneal aberrations (wavefront variance) and visual performance (area under CSF)[25]. A study from our laboratory has shown that most of the decrease in contrast sensitivity found after LASIK can be explained by a decrease in the modulation transfer function computed directly from the wave aberration[25]. However, since in refractive surgery changes are induced only on the cornea, the question arises whether corneal topography could be sufficient to fully predict visual outcomes[8]. In this paper, we present corneal and total aberrations in the same eyes before and following myopic LASIK. We show that the combination of these two pieces of information is important to understanding individual surgical outcomes (which becomes critical in customizing ablation algorithms). It also provides insights to understanding the biomechanical response of the cornea (both the anterior and posterior surfaces) to laser refractive surgery.

2. Patient and methods

Fourteen eyes of 8 patients (2 males and 6 females; age 28.9 ± 5.4) were measured before (28 ± 35 days) and after (59 ± 23 days) LASIK surgery. The pre-operative spherical refractive error ranged from -2.5 D to -13 D (mean=-6.8 ± 2.9 D, and pre-operative astigmatism was <2.5 D. Post-operative recovery was uneventful and none of the patients were retreated. The procedures were reviewed and approved by institutional bio-ethical committees, and met the tenets of the Declaration of Helsinki. Each patient signed a consent form. Aberration measurements were conducted at Instituto de Optica, CSIC, Madrid, Spain. Generally, both types of measurements (total and corneal aberrations) were done bilaterally in one experimental session.

Standard LASIK surgery was conducted using a narrow-beam, flying-spot excimer laser (Chiron Technolas 217-C; Bausch & Lomb, Surgical), equipped with the PlanoScan program. This laser has a emission wavelength of 193 nm, a fixed pulse repetition rate of 50 Hz and a radiant exposure of 400 mJ. The procedure was assisted by an eye-tracker. The flap diameter (performed with a Hansatome microkeratome) was 8.5 mm and the intended depth 180 µm. Photoablation was applied to a 6-mm optical zone, with a transition zone of 9 mm. The LASIK procedures were conducted at the Instituto de Oftalmobiología Aplicada, Universidad de Valladolid, Spain.

Total wave aberrations were measured using Laser Ray Tracing (LRT), developed at the Instituto de Optica in Madrid, Spain[13]. Corneal height numerical data were obtained with an Atlas Mastervue Corneal Topography System (Humphrey Instruments-Zeiss, San Leandro, CA). In this particular experiment, we obtained only one corneal map per eye and per session.

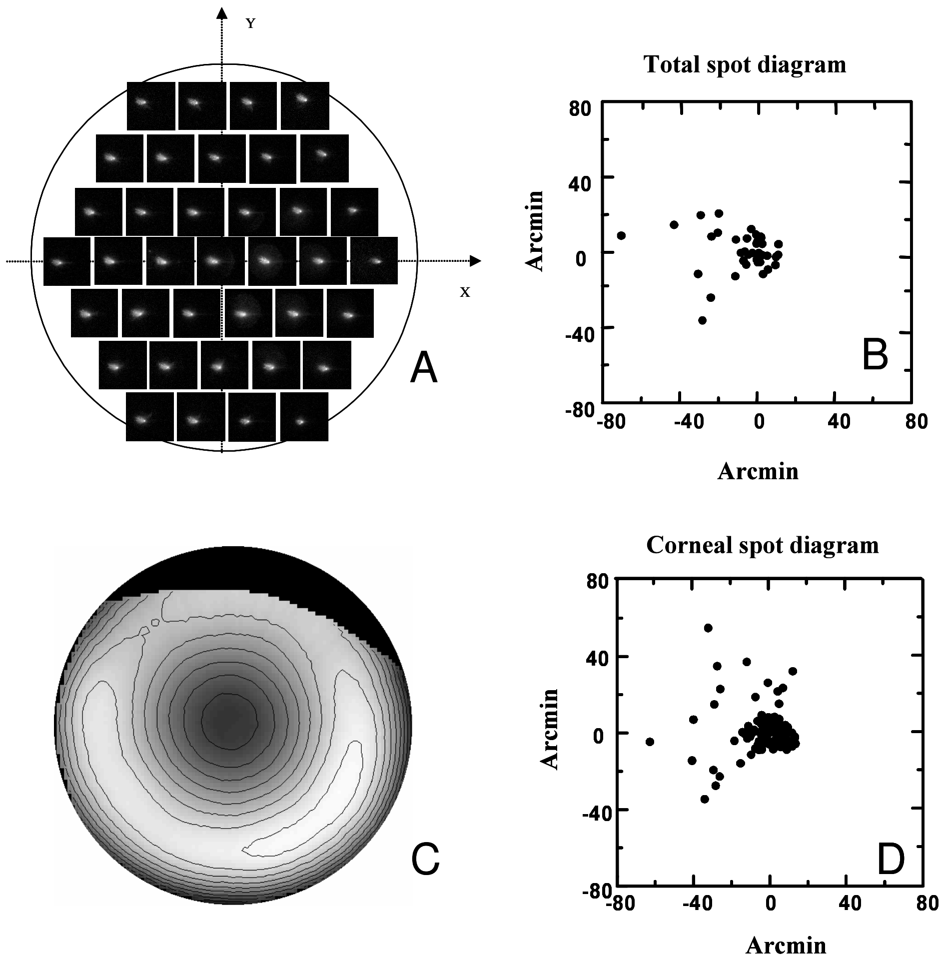

Figure V.1: A) Set of aerial images in post-LASIK eye #10, as a function of entry pupil, as recorded in Laser Ray Tracing. **B)** Retinal angular position of all centroids (spot diagram) from the series of retinal images shown in A. The deviations from the principal ray are proportional to the local derivatives of the wave aberration. **C)** Corneal elevation map (10-mm pupil, centered at the corneal reflex) from corneal topography data (eye #10). Terms 1-6 in the Zernike expansion have been excluded to reveal high-order features. Contours plotted every 0.01 mm. **D)** Simulated spot diagram from virtual ray tracing on a 6.5-mm diameter region of the corneal map shown in C. This subregion is centered at the pupil center, not the corneal reflex.

3. Results

Total and corneal wave aberration patterns

Figure V.2 shows contour plots of wave aberration patterns for total and corneal aberrations before and after LASIK surgery, for six eyes. Piston, tilts, defocus and astigmatism have been excluded in all cases, so that these patterns represent simulated best-corrected optical quality. Pupil diameter is 6.51 mm and contour lines are plotted every 1 μm. There is a clear deterioration (accounting for an increase in the number of contour lines) following surgery, both for total and corneal aberrations. Prior to surgery, total and corneal aberrations show similarities only in some of the eyes, while after surgery, total and corneal aberrations show very similar patterns, indicating the prevalence of corneal defects over the entire optics. LASIK induces a round central area (with various amounts of decentration depending on the eye) of positive aberration, surrounded by an area of negative aberration.

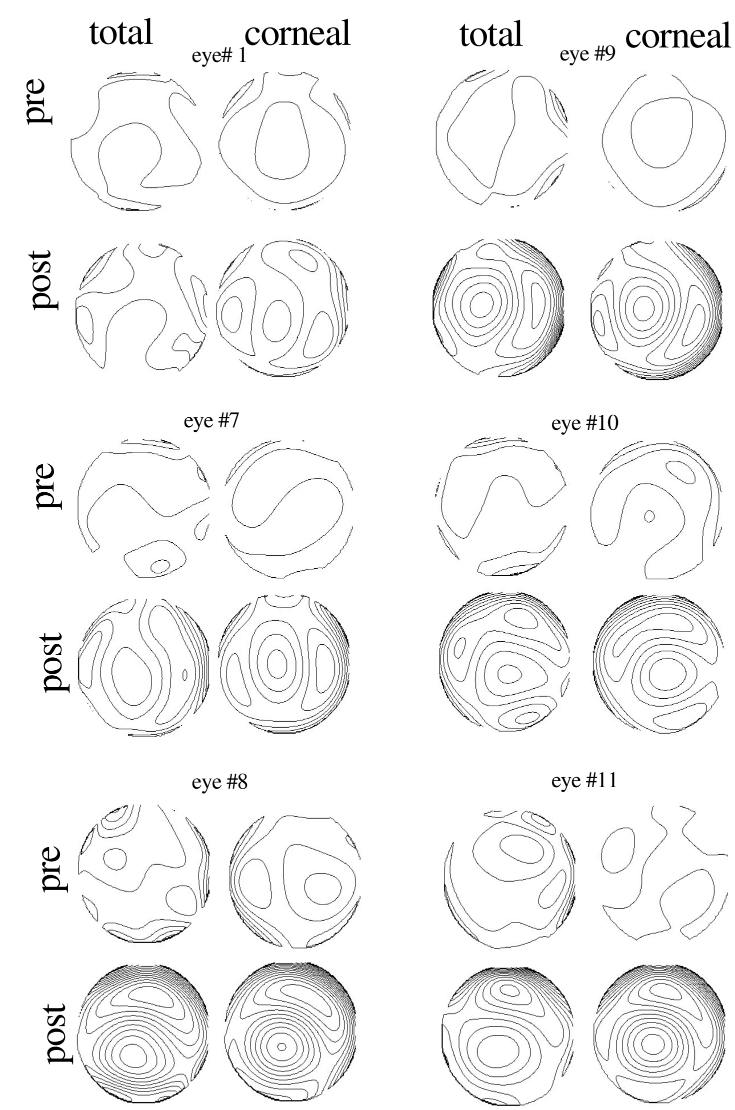

Figure V.2: Total and corneal wave aberration contour plots (3rd order and higher aberrations), pre- and post-LASIK in a subset of eyes participating in the study. Contour lines have been plotted every 1 μm. Pupil size is 6.5 mm.

Comparison of the change in total and corneal aberrations with LASIK

RMS wavefront error increases with LASIK, both for total and corneal aberrations. Figure V.3 shows RMS pre-LASIK (white bars) and post-LASIK (black bars) for 3rd and higher order aberrations, i.e. best corrected for defocus and astigmatism. Figure 3A shows the change for total aberrations, and 3B the change for corneal aberrations. The eyes are sorted by increasing pre-operative spherical refractive error.

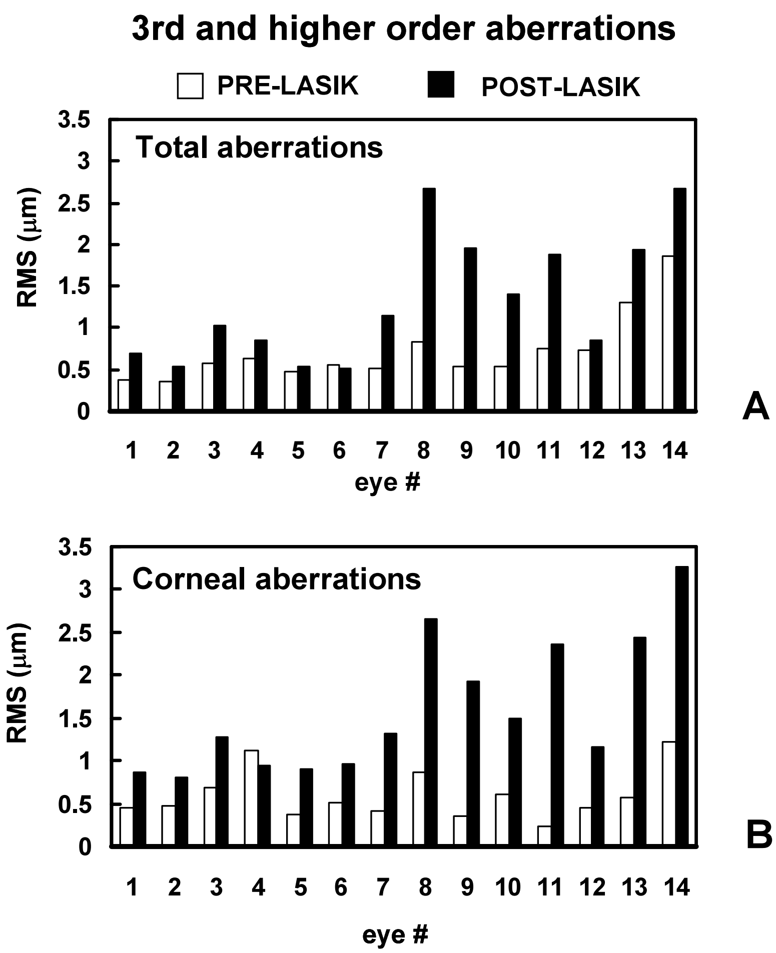

Figure V.3: Root mean square (RMS) wavefront error for 3rd and higher order aberrations, pre-LASIK (white bars) and post-LASIK (black bars) for (A) total and (B) corneal aberrations. Eyes have been sorted by increasing pre-operative spherical error.

Pre-operatively, total aberrations tend to increase with myopia[26, 27], although this tendency is not evident for corneal aberrations. Both total and corneal aberrations increase significantly after LASIK, except for eyes #5 and #6 for total aberrations, and #4 for corneal aberrations. Clearly, for both total and corneal aberrations the increase is much more pronounced in the most myopic eyes.

Total aberrations increased on average by a factor of 1.92 and corneal aberrations by a factor of 3.72. For the low pre-operative myopia group (-2.5 to -6.5 D) the average increase was 1.53 (total) and 1.97 (corneal) whereas for the high pre-operative myopia group (-6.8 to -13.1 D) the average increase was 2.29 (total) and 4.37 (corneal). In terms of RMS differences (post minus pre), total RMS difference changed from -0.05 µm to 0.80 µm, being statistically significant in 11 of the 14 eyes and corneal RMS changed from -0.16 µm to 2.04 µm, being statistically significant in 13 of the 14 eyes. Part of this increase is accounted for by an increase in the 3rd order aberrations (increasing by a factor of 1.98 for total and 2.73 for corneal), and by an increase of the 4th order aberrations (increasing by a factor of 2.54 for total and 3.93 for corneal.)

Figure V.4 shows the change of the 4th order spherical aberration coefficient (Z_4^0), both total (4A) and corneal (4B). Sign and normalization follows the convention suggested by the Optical Society of America Standardization Committee [28].

The pre-operative total spherical aberration coefficient is close to zero in most eyes (statistically significantly positive in seven eyes and statistically significantly negative in three eyes). Pre-operative corneal spherical aberration is positive in all eyes except for one eye that is not statistically significantly different from zero. Total spherical aberration increases significantly with LASIK in all eyes, and corneal spherical aberration in all but one eye.

The most dramatic increase occurs for the highest pre-operative myopes, both for total[16] and corneal aberrations[29, 30]. Total spherical aberration Z_4^0 coefficient post-pre difference ranged from 0.22 µm to 1.64 µm (0.63 µm on average), and for the cornea the differences ranged from -0.01 µm to 1.72 µm (0.74 µm on average). The increase of spherical aberration seems to be more pronounced for corneal than for total aberrations.

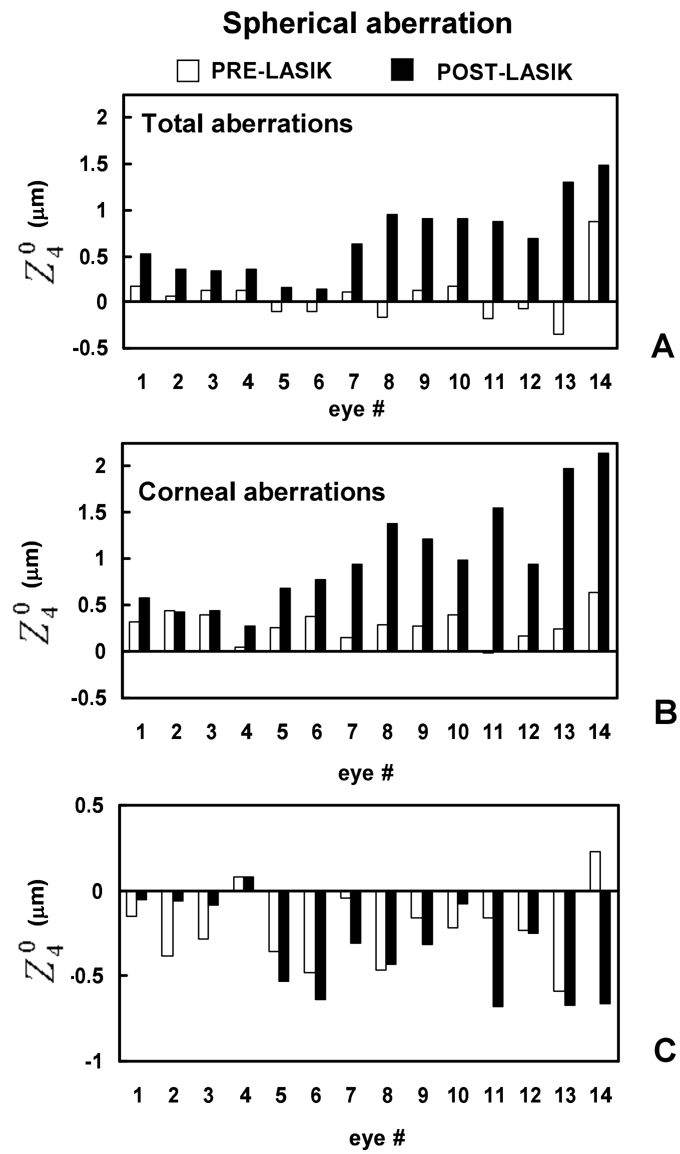

Figure V.4: Fourth order spherical aberration coefficient (Z_4^0 in the Zernike polynomial expansion), pre-LASIK (white bars) and post-LASIK (black bars) for (A) total, (B) corneal, and (C) internal aberrations. Eyes have been sorted by increasing pre-operative spherical error.

Figure V.5 shows post-LASIK corneal *vs* total aberrations, 5A for 3rd order and higher aberrations RMS values (i.e. values in black bars in Figure V.3), and 5B for RMS for spherical aberration (i.e. roughly the modulus of the values in black bars in Figure V.4, although not exactly since it includes the contribution of Z_6^0 also).

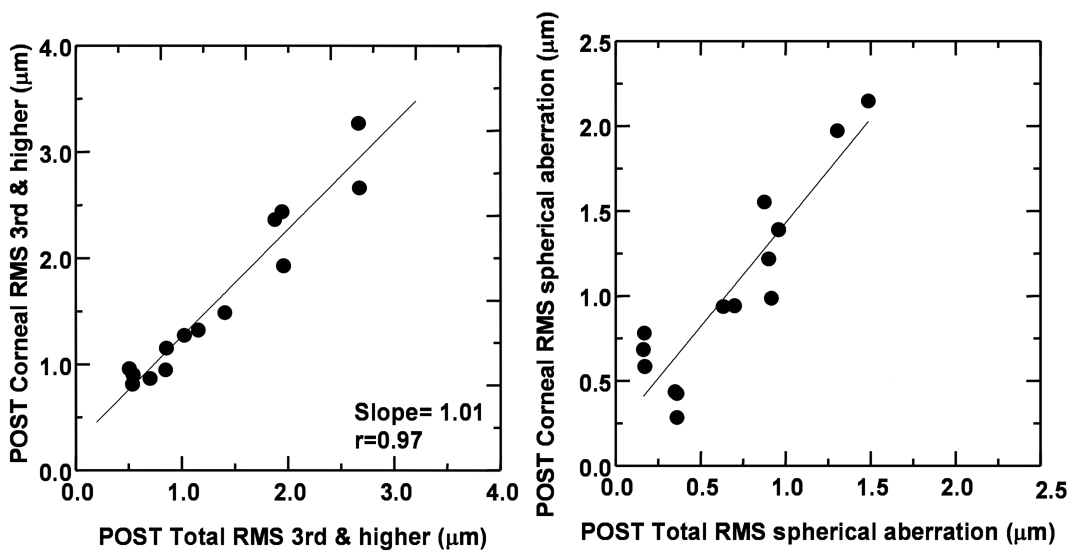

Figure V.5: Total aberrations versus corneal aberrations induced by LASIK, in terms of RMS wavefront error. (A) 3rd order and higher aberrations. (B) spherical aberration. Lines are linear regressions to the data.

There is a very good correlation between corneal and total aberrations (3rd order and higher) after LASIK (r=0.97, p<0.0001; slope=1.01; Figure V.5A)). The corneal spherical aberration post-LASIK is also well correlated to the total spherical aberration post-LASIK (r=0.91, p<0.0001; slope=1.22; Figure V.5 B)). However, the fact that the slope is significantly higher than 1 suggests that a larger spherical aberration is induced to the anterior corneal surface than to the entire eye. A higher slope in the post-LASIK corneal versus total aberration is found for the RMS of the spherical aberration, the spherical aberration coefficient (Z_4^0) and the RMS of 4th order terms, but not for 3rd order aberrations, or all high order aberrations (3rd order and higher).

Change of internal aberrations with LASIK

The internal aberrations can be computed by subtracting corneal from total aberration coefficients (see chapter I). Figure V.4 C) shows the internal aberrations before and after LASIK. We found that internal spherical aberration changed significantly in 10 eyes after LASIK. Except for the four less myopic eyes (#1-4) and eye #10, the internal spherical aberration changed toward more negative values. Experiments performed in control subjects who have undergone a surgical procedure performed in two different experimental sessions (separated by at least a month, as in the surgical eyes) did not reveal statistically significant changes in the internal aberrations across sessions. This indicates that possible changes across sessions in the accommodative state or decentrations of corneal topography data (which otherwise are compensated by the re-centration algorithm) cannot account for the observed differences in the internal optics found between pre- and post- LASIK results. Therefore these changes must be attributed to surgery –in addition with beam convergence effects, see discussion below-.

Figure V.6 shows the spherical aberration coefficient Z_4^0 after LASIK as a function of pre-operative spherical refractive error, for corneal, total, and internal aberrations. The internal aberration coefficients were computed as the total minus corneal coefficients.

There is a statistically significant increase of the absolute amount of post-operative spherical aberration for total ($r=0.80$, $p=0.0003$), corneal ($r=0.92$, $p<0.0001$) and internal ($r=0.73$, $p=0.0024$) aberrations with pre-operative refractive error. However, the total spherical aberration increases less than the spherical aberration of the anterior corneal surface, because of the spherical aberration of negative sign induced on the posterior corneal surface. The same analysis for post-LASIK 3rd order aberrations shows no statistically significant difference between corneal and total aberrations (therefore 3rd order aberrations do not seem to be induced on the posterior corneal surface).

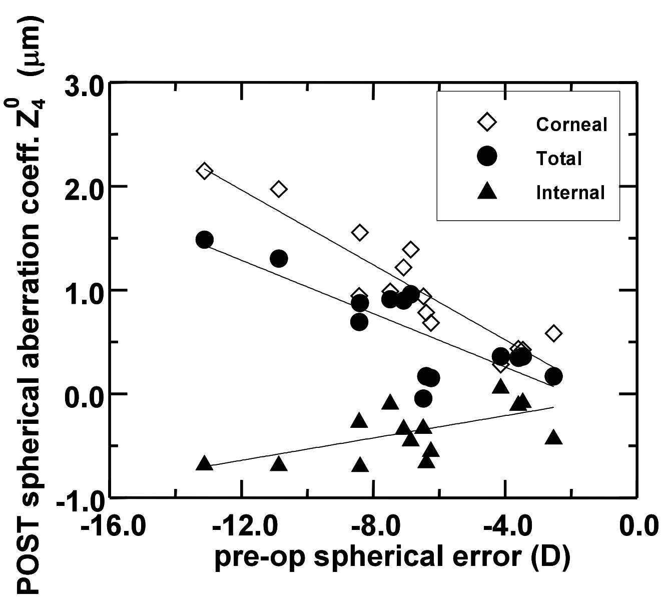

Figure V.6: Total, corneal and internal spherical aberration post-LASIK as a function of pre-operative spherical error. Lines are linear regressions to the data.

4. Discussion

Both corneal and total aberrations increase after myopic LASIK surgery: the higher the pre-operative myopia, the higher the increase. In general, while the trends are similar when looking at 3rd order and higher aberrations, we found that the spherical aberration of the anterior corneal surface was greater than the spherical aberration of the entire eye. In the following subsections, we will discuss several other factors that indicate that anterior corneal aberrations alone are not sufficient to explain surgical outcomes. We will also relate our findings to current biomechanical models of corneal response to surgery and previous observations. We will finally discuss the implications of these results in the evaluation of refractive surgery outcomes and aberration-free ablation procedures.

The role of pupil centration

Several previous studies showed the impact of myopic refractive surgery (RK and PRK) on corneal aberrations[22, 30, 31]. As in the present analysis, those studies computed the corneal aberration pattern by measuring corneal elevation maps using commercial corneal videokeratoscopes. In these devices, centration is typically achieved by aligning a set of concentric rings to the corneal reflex of the fixation light. Corneal aberrations are then typically referred to the corneal reflex rather than the pupil center. Our processing algorithms align the corneal aberration pattern with the total aberration pattern, which is referred to the pupil center. The position of the pupil is important for a correct estimation of retinal image quality[32], and should be taken into account when predicting visual performance from corneal aberration data.

The role of pre-operative internal optics

Total aberrations result from the combination of corneal and internal aberrations and their inter-relationships. Before surgery, both components contribute with comparable amounts of aberrations, in some cases even balancing each other. Figure V.2 shows that whereas, pre-operatively, the cornea dominates the total wave aberration pattern in some eyes (i.e. eye #1 or #7), in some others there is little similarity between total and corneal patterns, indicating an important contribution of the internal optics. Although the relative contribution of the internal optics is expected to be much lower after refractive surgery, interactions between corneal and internal optics may still play some role in determining the surgical outcomes. A recent study[33] indicates a high degree of balance between corneal and internal aberrations in normal young eyes. Prior to surgery, we found a term-by-term balance of at least 50% of the aberration in 28% of the 14 eyes of this study. For spherical aberration this balance increased to 57% of the eyes. In 78% of the eyes, the spherical aberration of the anterior corneal surface and the internal optics had different sign (see white bars in Figure V.4). Furthermore, it is not uncommon (35%) that the amount of negative internal spherical aberration (likely from the crystalline lens[34, 35]) exceeds the amount of positive spherical aberration of the anterior corneal surface. Figure V.8 illustrates one of these cases (eye #6), with a corneal pre-operative spherical aberration (Z_4^0) of 0.38 μm and internal pre-operative aberration of -0.48 μm. The upper row shows the measured total and corneal and the computed internal aberration patterns. The negative internal aberration dominates the central area total aberration pattern.

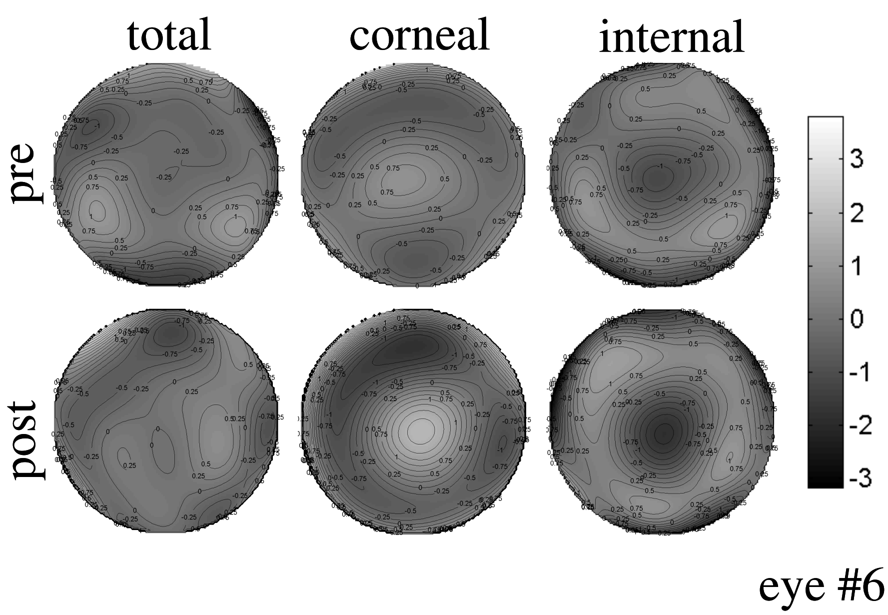

Figure V.8: Total (left), corneal (middle) and internal (right) wave aberration maps (3rd order and higher aberrations) before (top) and after (bottom) LASIK, for eye #6 (with a particularly good surgical outcome). Pre-operatively, the negative internal aberration dominates the total pattern. After LASIK, the positive spherical aberration induced on the anterior corneal surface partially cancels the pre-operative negative spherical aberration of the internal optics. Contour line spacing: 0.25 μm. Pupil diameter: 6.5 mm.

After LASIK (lower row), positive spherical aberration is induced on the anterior corneal surface, which cancels (actually overcompensates) the pre-operative negative spherical aberration of the internal optics. For this reason, the post-LASIK total aberration pattern for this eye is much better than predicted from corneal aberrations alone. Unlike other subjects with similar pre-operative myopia, and similar corneal topography post-LASIK, this subject did not show any loss of contrast sensitivity (actually improved at two spatial frequencies)[25]. An individual comparison of pre- and post- total and corneal aberration can be invoked to explain the surprisingly good surgical outcomes for this patient. In general, the possible balance between corneal and internal aberration gets disrupted with refractive surgery. In our study, compensation of more than 50% of the corneal spherical aberration by the pre-op internal aberrations decreases from 8 eyes before surgery to 4 eyes after surgery, and only happens in eyes with the lowest pre-op spherical errors (eyes #2, #3, #5, #6). However, at least in these eyes these interactions are relevant in determining the total wave aberration pattern.

Convergence effect in the estimation of internal aberrations

As it was mentioned in chapter II, section 2.4, this is particularly important when comparing internal aberrations before and after refractive surgery, where the anterior corneal surface changes and therefore the beam convergence on the lens changes with the procedure. Presumably, this effect has most influence in the spherical aberration of the lens. To evaluate the effect of the change of anterior corneal surface in the estimated internal spherical aberration we performed a simulation in ZEMAX using an eye model (see Table II.1) with a standard crystalline lens and individual pre and post LASIK surgery corneas. Posterior corneal changes were not considered in this model. The internal spherical aberration (pre and post LASIK) were obtained, as in the experimental procedure, as direct subtraction of total minus corneal aberration. Since no element is changed in the simulations except for the anterior corneal surface, any difference in the computed internal aberrations should reflect convergence effects. We found systematic differences in the estimated spherical internal aberration (mean values 0.054±0.048µm), but in the opposite direction than the differences found experimentally. This indicates that convergence effects are not responsible for the change found in the internal aberration shown in Figure V.9, which, if anything would be underestimated. Figure V.9 compares the induced internal spherical aberration measured experimentally and that obtained from computer simulations ignoring the posterior corneal surface and fixed crystalline lens, as a function of pre-operative myopia.

LASIK-induced posterior corneal aberrations and biomechanical response

Comparison of post-LASIK corneal and total aberrations reveals an increase in the amount of negative internal spherical aberration, which tends to slightly attenuate the impact of the positive spherical aberration induced on the anterior corneal surface (Figure V.6). The effect is larger as the pre-operative spherical refractive error increases and does not depend on the pre-operative internal aberrations: the correlation coefficient of post-LASIK internal spherical aberration to pre-LASIK spherical refractive error is 0.73 (p=0.0024) and the correlation coefficient of the induced internal

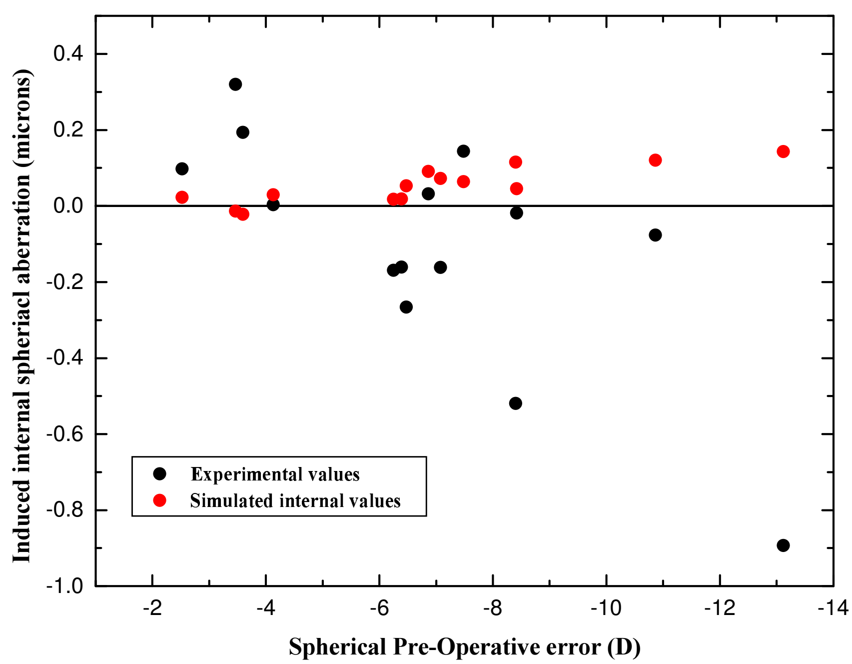

Figure V.9: Spherical aberration (µm) of the internal optics Z_4^0 of subjects after LASIK surgery minus spherical aberration before surgery as a function of spherical pre operative error (D). Black circles represent experimental values obtained by direct subtraction of total minus corneal spherical aberration. Red circles represent simulated values obtained by estimation on eye models.

spherical aberration (post- *minus* pre-) to pre-LASIK spherical refractive error is 0.74 (p=0.0016). LASIK surgery is not likely to induce changes in the crystalline lens, so the changes seem to occur on the posterior corneal surface. The effect is only present for spherical aberration, but not for other terms.

This finding is consistent with recent reports using scanning slit corneal topography. They show posterior corneal surface changes of curvature following myopic PRK[36] and LASIK[37, 38], which produce a forward shift of the posterior corneal surface. This suggests that after myopic LASIK and PRK the thinner, ablated cornea may bulge forward slightly, steepening the posterior corneal curvature. This effect has been attributed to account for the regression toward myopia that is sometimes found post-treatment, particularly in the highest pre-operative myopes[36]. We have used a simple corneal model with aspherical surfaces and found that the observed mean changes of internal spherical aberrations are consistent with the changes in power and asphericity of the posterior corneal surface that have been reported recently [39]. Seitz et al. found that the posterior central corneal power changed significantly from -6.28 D to -6.39 D after LASIK, and the asphericity P changed from 0.98 to 1.14, in a group of eyes with similar pre-op spherical refractive error than ours (range: -1.00 to -15.50, mean= -5.07 ± 2.81 D). For these values, we found that the induced spherical aberration of the posterior corneal surface is -0.103 μm, very similar to the change in internal spherical aberration that we measured experimentally (-0.110 μm, on average).

In summary, using a combination of aberrometry and anterior corneal topography, we have shown that this change in the posterior corneal shape produces also a decrease of spherical aberration with respect to that predicted from anterior corneal aberrations alone. Our results confirm that this biomechanical corneal response is correlated with the amount of pre-operative myopia (or equivalently the depth of ablated cornea). From previous studies[37], it is likely that it also depends on the pre-operative corneal thickness and pre- operative intraocular pressure.

Implications

Our results have important implications for the evaluation of standard myopic LASIK surgery outcomes, as well as for the design of wavefront-guided ablation procedures (aiming at individually canceling pre-operative aberrations). First, the results show that the combination of corneal and total aberrations is necessary to understand individual surgical outcomes and their impact on visual performance. In general, both corneal and total aberrations increase with surgery, but the particular increment depends on the individual subject. This is particularly critical in any “aberration-free” procedure, which cannot rely on the mean population response, but needs to be adapted to the individual patient. Second, total wavefront aberration measurements complement corneal topography information to gain insight into the biomechanical corneal response. Despite the fact that the ablation is applied on the anterior corneal surface, our analysis reveals changes in the shape of the posterior corneal surface, assessed by the modification of its spherical aberration.

5. References

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