Chapter 7

CHANGE IN OPTICAL ABERRATIONS OF THE EYE WITH LASIK FOR MYOPIA AND LASIK FOR HYPEROPIA.

This chapter is based on the articles "Optical response to LASIK surgery for myopia from total and corneal aberration measurements" by Marcos et al. (2001), and "Total and corneal optical aberrations induced by Laser in situ Keratomileusis for hyperopia" by Llorente et al. (2004c). The coauthors of these studies were Sergio Barbero, and Jesús Merayo-Lloves.

The contribution of the author of this thesis to the study includes participation in data collection and processing of ocular aberrations in both, myopic and hyperopic LASIK. In the case of hyperopic LASIK study the author also contributed in data analysis, and writing of the corresponding article.

7.1.- ABSTRACT

PURPOSE: To evaluate the changes induced by myopic and hyperopic LASIK on ocular (total) and (anterior) corneal optical quality.

METHODS: Ocular and corneal aberrations were measured before and after myopic and hyperopic LASIK surgery in a group of 14

(preoperative myopia ranging from -2.50 to -13.00 D; mean ± std, -6.8±2.9) and a group of 13 (pre-operative hyperopia ranging from +2.50 to +5.50D; mean ± std, +3.60±1.06 D) eyes, respectively. Ocular aberrations were measured using a LRT and corneal aberrations were estimated from a videokeratoscope. RMS for both ocular and corneal aberrations was used as a global optical quality metric.

RESULTS: Ocular and corneal aberrations (HOA) showed a statistically significant increase after both, myopic and hyperopic LASIK. SA (SA) changed towards positive and negative values after myopic and hyperopic LASIK, respectively. However, the anterior corneal SA increased more than the ocular SA, suggesting also a change in the SA of the posterior corneal surface. Changes in internal SA were of opposite sign to those induced on the corneal anterior surface. Hyperopic LASIK induced larger changes than myopic LASIK. Induced ocular SA was, in absolute value, 3.3 times larger, and induced corneal SA was 6 times larger after hyperopic LASIK, for a similar range of correction, and of opposite sign.

CONCLUSIONS: Because LASIK surgery induces changes in the anterior corneal surface, most changes in the ocular aberration pattern can be attributed to changes in the anterior corneal aberrations. The largest increase occurred in SA, which showed a shift towards positive values in the case of myopic LASIK and towards negative values in the case of hyperopic LASIK, the increase being greater for hyperopic than for myopic LASIK. However, due to individual interactions of the aberrations in the ocular components, a combination of corneal and ocular aberration measurements is critical to understand individual outcomes, and by extension, to design custom ablation algorithms.

7.2.- INTRODUCTION

Laser in situ keratomileusis (LASIK) (Pallikaris et al., 1990, Farah et al., 1998) is nowadays a popular surgical alternative for the correction of myopia. A description of this technique can be found in the Chapter 1, section 1.4.- of this thesis. LASIK clinical outcomes have been widely studied in terms of predictability and accuracy of the achieved correction and visual performance (visual acuity or contrast sensitivity) (Knorz et al., 1998, Lindstrom et al., 1999, Nakamura et al., 2001, Mutyala et al., 2000), or from a biological point of view (Vesaluoma et al., 2000). The implementation of techniques for ocular wave aberration measurement (Charman, 1991a, He et al., 1998, Liang et al., 1994, Navarro and Losada, 1997, Liang and Williams, 1997, Mierdel et al., 1997, Howland and Howland, 1977, Webb et al., 1992, Seiler et al., 2000, Moreno-Barriuso et al., 2001a) and estimation of the wave aberration of the anterior corneal surface from corneal topography (Guirao and Artal, 2000, Barbero et al., 2001, Schwiegerling and Greivenkamp, 1997) have allowed objective assessment of the effect of corneal refractive surgery on the optical quality of the eye (Seiler et al., 2000, Moreno-Barriuso et al., 2001b) and the anterior cornea (Oshika et al., 1999b, Applegate and al, 1998, Dausch et al., 2000).

Oliver et al. (1997) assessed the outcomes of PRK (a -6D attempted correction) before and 1 year after surgery for 50 myopic eyes using anterior corneal aberrations for 5 and 7 mm pupils. They reported a significant increase of corneal SA and coma-like aberrations, the former increasing less for the larger of the ablation zones they tested. This increase in aberrations affected the corneal MTF. Oshika et al. (1999a) studied the corneal aberrations for 3 and 7mm pupils before and up to 1 year after LASIK and PRK surgery bilaterally on 22 subjects. Both surgical procedures significantly increased high order aberrations for both studied pupil sizes, and the effect remained even 12 months after the surgery.

Although no changes were found for 3 mm pupils when comparing both surgical procedures, aberrations after LASIK were significantly higher for 7 mm pupils, specifically for spherical-like aberrations, which they attributed to the smaller transition zone in this procedure. Whereas for 3 mm pupils the proportion of coma-like aberration increased after both procedures, for 7 mm pupils, SA became dominant. Schwiegerling and Snyder (2000) computed corneal SA induced by PRK on 16 eyes and found that the magnitude of induced SA was correlated with the attempted correction. Kohnen et al., (Kohnen et al., 2004) compared the change in corneal aberrations in 50 eyes after LASIK for myopia and 50 eyes after LASIK for hyperopia. In the myopic eyes they found an increase in HOA, SA, coma and 5th order aberrations.

In terms of corneal Q, Holladay et al. (1999a) found that Q turned more positive (more oblate corneal shape- see Chapter 1, section 1.1.1.-) after myopic LASIK, reducing corneal optical quality, and some years later, Holladay and Janes (2002) found that Q increased more with increasing attempted correction. Hersh et al. (2003) confirmed the previous findings regarding an increase in Q after three different laser refractive surgical procedures (LASIK, LASEK and PRK), and they found that the corresponding change in SA was well predicted by a mathematical model that considered the ablation rate drop off in the periphery due to the change of the angle of incidence.

In terms of ocular aberrations, Seiler et al. (2000) and Yamane et al. (2004) reported a significant increase in HOA after (3 months and 1 month, respectively) PRK and LASIK, respectively, particularly in coma-like terms and spherical-like terms. SA changed towards positive values, as reported by previous studies for corneal aberrations. These optical changes were related with a decrease in the ocular visual performance.

Previous studies of hyperopic correction with excimer laser also suggest an increase of optical aberrations with the procedure. Oliver et al.

(2001) studied anterior corneal aberrations induced by photorefractive keratectomy (PRK) for hyperopia in nine eyes. They reported a change in corneal SA, which was positive in all eyes prior to surgery, towards negative values for 5.5-mm and 7-mm pupil diameters. A significant increase in coma RMS was also reported. Comparing the results of this study with those obtained in a previous study on myopic PRK (Oliver et al., 1997) they found that the change of anterior corneal aberrations following PRK for hyperopia was greater than those after myopic PRK. In their study previously described, Kohnen et al. (2004) also measured 50 hyperopic eyes (SE ranging from +0.25 to +5.00D) and found a significant increment of HOA and coma RMSs for a 6 mm pupil. Fifth order RMS also increased. When comparing these results with those for the myopic group in their study, they found, in agreement with Oliver et al. (2001), that hyperopic LASIK induced more 3rd and 5th order coma-like aberrations than the myopic procedure. Wang et al. (2003a) also studied the effect of hyperopic LASIK on corneal aberrations for a 6mm pupil in 40 eyes, finding the significant decrease in corneal SA previously reported, and that this decrease was significantly correlated with the attempted correction. They also found a significant increase in HOA after surgery when SA term was excluded.

Chen et al. (2002) studied corneal Q in a corneal radius of 4.5mm for 33 eyes before and after hyperopic LASIK. They found a significant change in corneal Q towards more negative values, which resulted in a shift of SA in the same direction. Ma et al. (2004) compared wave aberrations for a 6 mm pupil in 29 control eyes with 59 eyes after LASIK and lensectomy corrections (with intraocular lens implantation) for hyperopia. The LASIK group had the highest RMS aberration, and the most negative corneal and ocular SA. In addition, they found significant differences in the internal SA in the LASIK group.

In this chapter, corneal and ocular aberrations in the same eyes before and after LASIK for myopia and before and after LASIK for hyperopia are presented. It is shown that the combination of these two pieces of information is important for understanding individual surgical outcomes (which becomes critical in customizing ablation algorithms). It also provides insights into the biomechanical response of the cornea (both the anterior and posterior surfaces) to laser refractive surgery. In addition, a comparison of the outcomes of the myopic and hyperopic LASIK is presented.

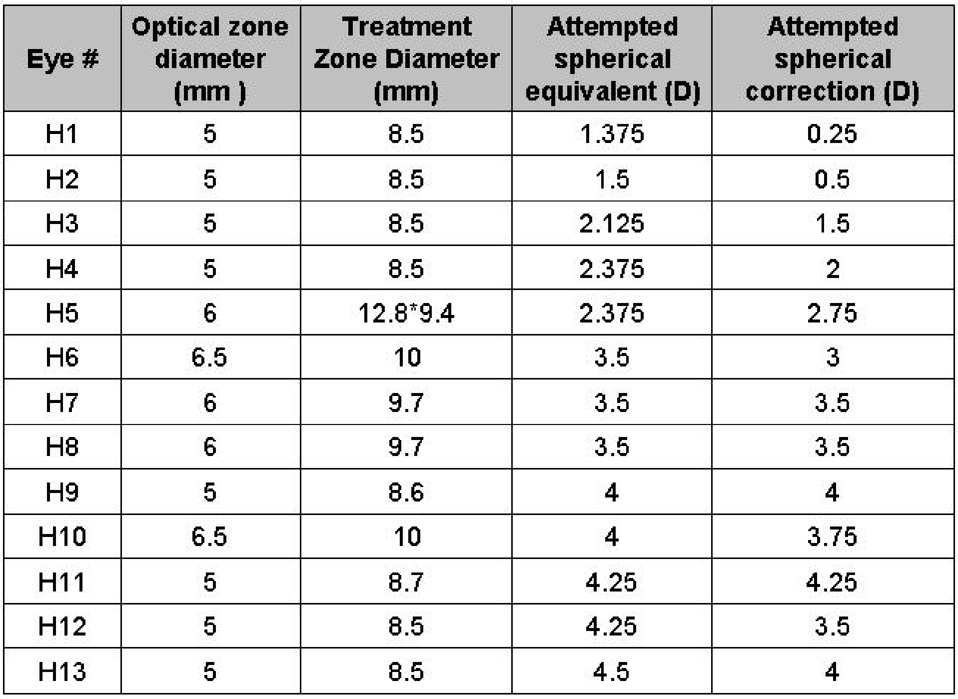
7.3.- METHODS

7.3.1.- SUBJECTS

The group of myopic eyes consisted of fourteen eyes of eight patients (six women and two men; mean age, 28.9± 5.4 years; age range 23 to 39 years), which were measured before (28± 35 days) and after (59±23 days) myopic LASIK surgery. The preoperative spherical refractive error ranged from -2.50 to -13.00 D (mean, -6.79±2.90 D) in these eyes. The hyperopic group consisted on thirteen eyes from seven patients (three women and four men; mean±std age, 37 ± 11 years; age range 24 to 54 years), which were measured before (15 ± 17 days) and after (68 ± 43 days) LASIK for hyperopia. The preoperative spherical refractive error ranged from +2.50 to +5.50 diopters (D) (mean±std +3.60 ± 1.06 D) in this group of eyes. Postoperative recovery was uneventful and none of the patients was retreated.

7.3.2.- LASIK SURGERY

The standard LASIK procedure was applied in all eyes by the same surgeon, using the same laser system (a narrow beam, flying spot excimer laser, Chiron Technolas 217-C, equipped with the PlanoScan software; Bausch & Lomb Surgical, Munich, Germany). The laser had an emission wavelength of 193 nm, a fixed pulse repetition rate of 50 Hz, and a radiant exposure of 400 mJ. The flap diameter (created using a Hansatome microkeratome; Bausch & Lomb Surgical, Munich, Germany) was 8.5 mm with an intended depth of 180 µm for all myopic eyes, and 9.5 mm with an intended depth of 160 µm for all hyperopic eyes except three (H5, H12 and H13), in which the intended depth was 180 µm. The treatment zone diameter was 9 mm with an optical zone diameter of 6 mm for the myopic eyes. For the hyperopic eyes, the treatment and optical zones varied across eyes as shown in Table 7.1. The hinge was always superior, and the procedure was assisted by an eye-tracker. All the LASIK procedures were conducted at the Instituto de Oftalmobiología Aplicada (IOBA), Universidad de Valladolid, Spain, except for three hyperopic patients (eyes H5, H6, H7, H8 and H10) whose surgery took place at Centro Oftalmológico de Madrid (COM), Madrid, Spain, using identical equipment.



Eye #	Optical zone diameter (mm)	Treatment Zone Diameter (mm)	Attempted spherical equivalent (D)	Attempted spherical correction (D)
H1	5	8.5	1.375	0.25
H2	5	8.5	1.5	0.5
H3	5	8.5	2.125	1.5
H4	5	8.5	2.375	2
H5	6	12.8*9.4	2.375	2.75
H6	6.5	10	3.5	3
H7	6	9.7	3.5	3.5
H8	6	9.7	3.5	3.5
H9	5	8.6	4	4
H10	6.5	10	4	3.75
H11	5	8.7	4.25	4.25
H12	5	8.5	4.25	3.5
H13	5	8.5	4.5	4

Table 7.1 Refractive surgery data for hyperopic eyes. Asterisk (*) indicates that the treatment area for this eye was elliptical; numbers indicate the length in millimetres of the main axes of the elliptical treatment area.

7.3.3.- MEASUREMENTS AND STATISTICAL ANALYSIS

Ocular aberrations were measured using LRT1 (see Chapter 2). The illumination wavelength used was 543 nm for the myopic LASIK study and 786 nm for the hyperopic LASIK study. (See Chapter 4 for a verification of the results using both wavelengths). Corneal aberrations were estimated from corneal topography as previously discussed in Chapter 6, section 6.3.4.- of this thesis. CR and Q were obtained by fitting the anterior corneal height data to a conicoid (see Chapter 1, section 1.1.1.-) using custom software written in Matlab.

A paired Student t-test was applied when the comparisons were performed in the same refractive group, and an unpaired Student t-test was applied when the different refractive groups were compared. A Pearson's correlation test was applied to find the strength of linear correlations, followed by a t-test to test its significability.

7.4.- RESULTS

7.4.1.- OCULAR AND CORNEAL WAVE ABERRATION PATTERNS

Figure 7.1 and Figure 7.2 show ocular (left) and corneal (right) wave aberration maps for six significant myopic and six significant hyperopic eyes before (upper row) and after (lower row) LASIK surgery. Piston tilts, defocus, and astigmatism have been excluded in all cases, so that these maps represent simulated best refraction corrected optical quality. Pupil diameter is 6.5 mm for all eyes, and the same scale has been used for the four diagrams corresponding to each eye. Contour lines are plotted every 1 μm for each eye, with thicker and thinner lines indicating positive and negative values of the wave aberration, respectively. The number below each map indicates the corresponding RMS for HOA.

The pre-operative maps reflect the behaviours described in Chapter 6, section 6.4.2.-: in most eyes the ocular map shows less positive SA than the corneal map, indicating compensation by the internal optics (crystalline lens); in some of the eyes, however, no compensation exists, and ocular and corneal aberration maps show similar patterns of SA. Most of these eyes are hyperopic and belong to subjects over thirty years old (internal SA $< \pm 0.1$ μm in 8 out of the 13 hyperopic eyes, or 62%, mean age 41±9 years old), as described in Chapter 6, section 6.5.2.-. The pre-operative mean (± std) HOA RMS (i.e. excluding tilts, defocus and astigmatism) was 0.72±0.40 μm for ocular and 0.60±0.29 μm for corneal aberrations for the myopic eyes, and 0.63 ± 0.22 μm for ocular and 0.68 ± 0.13 μm for corneal aberrations across the hyperopic eyes included in this study.

Regarding post-operative maps, ocular and corneal wave aberration patterns were very similar one to another in both, myopic and hyperopic eyes, showing the dominance of the corneal aberrations after the procedure. The mean (± std) post-operative HOA RMS was 1.33±0.76 μm for ocular and 1.60±0.79 μm for corneal aberrations in the myopic group, and 1.23±0.45 μm for ocular and 1.18±0.51 μm for corneal aberrations in the hyperopic group. There was a significant increase of aberrations after both types of surgery, indicated by the increase in the number of contour lines of both, corneal and ocular diagrams, and by the increase in the corresponding RMS wavefront error. In the case of myopic correction, LASIK induced a round central area (with various amounts of decentration, depending on the eye) of positive aberration, surrounded by an area of negative aberration. In the case of hyperopic LASIK, the pattern is the opposite, with a central area of negative aberration surrounded by an area of positive aberration. This indicates that positive and negative SA is induced by standard myopic and hyperopic LASIK procedures, respectively, as will be shown later. These changes in SA are consistent with a change in corneal Q towards more positive and negative values, respectively (see Chapter 1, section 1.1.1.-)

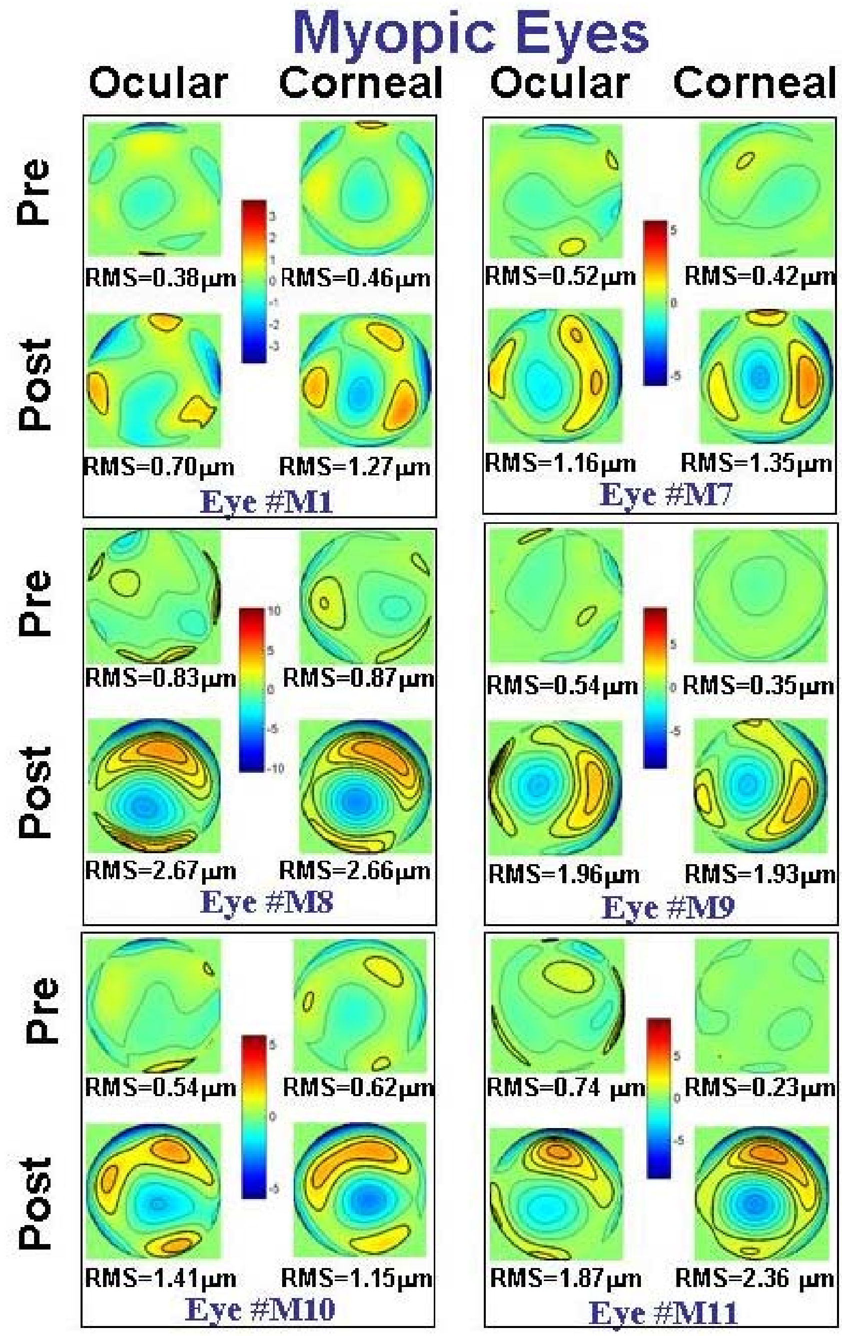


Figure 7.1. A.- Wave aberration maps for HOA, before and after LASIK surgery for myopic correction. For each eye, the maps on the upper row show the wave aberrations before surgery, and the maps on the lower row show the aberrations after LASIK surgery. The maps on the right correspond to corneal (anterior surface) aberrations and on the left to ocular (whole eye) aberrations. All four maps corresponding to the same subject are plotted in the same scale. The number below each map indicates RMS values for HOA in microns. Contour lines are plotted every 1 µm. Pupil size is 6.5 mm.

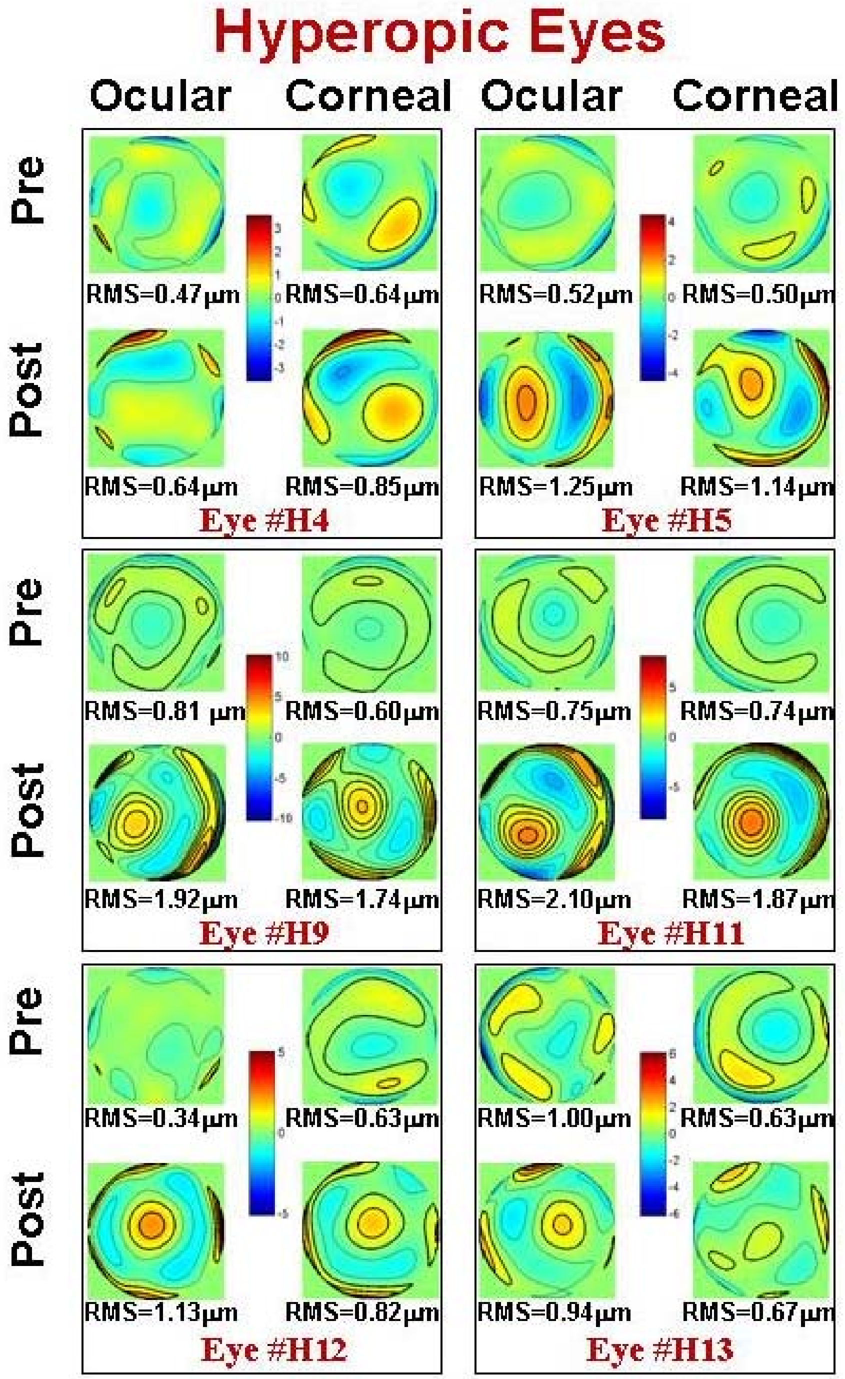


Figure 7.2. B.- Wave aberration maps for HOA, before and after LASIK surgery for hyperopic correction. For each eye, the maps on the upper row show the wave aberrations before surgery, and the maps on the lower row show the aberrations after LASIK surgery. The maps on the right correspond to corneal (anterior surface) aberrations and on the left to ocular (whole eye) aberrations. All four maps corresponding to the same subject are plotted in the same scale. The number below each map indicates RMS values for HOA in microns. Contour lines are plotted every 1 µm. Pupil size is 6.5 mm.

7.4.2.- Change in Ocular and corneal aberrations with myopic LASIK

Figure 7.3 A shows ocular (left panel) and corneal (right panel) RMS for HOA —that is, best corrected for defocus and astigmatism— before (lighter bars) and after (darker bars) LASIK for myopia. Eyes were sorted by increasing preoperative spherical refractive error. Before surgery, ocular aberrations tended to increase with absolute value of refractive error, although this tendency was not evident in corneal aberrations. Both ocular and corneal aberrations increased after LASIK, except for eye M6 for ocular aberrations, and eye M4 for corneal aberrations. For both ocular and corneal aberrations the post-operative increase was much more pronounced in the most myopic eyes, i.e., in those eyes undergoing higher refractive corrections.

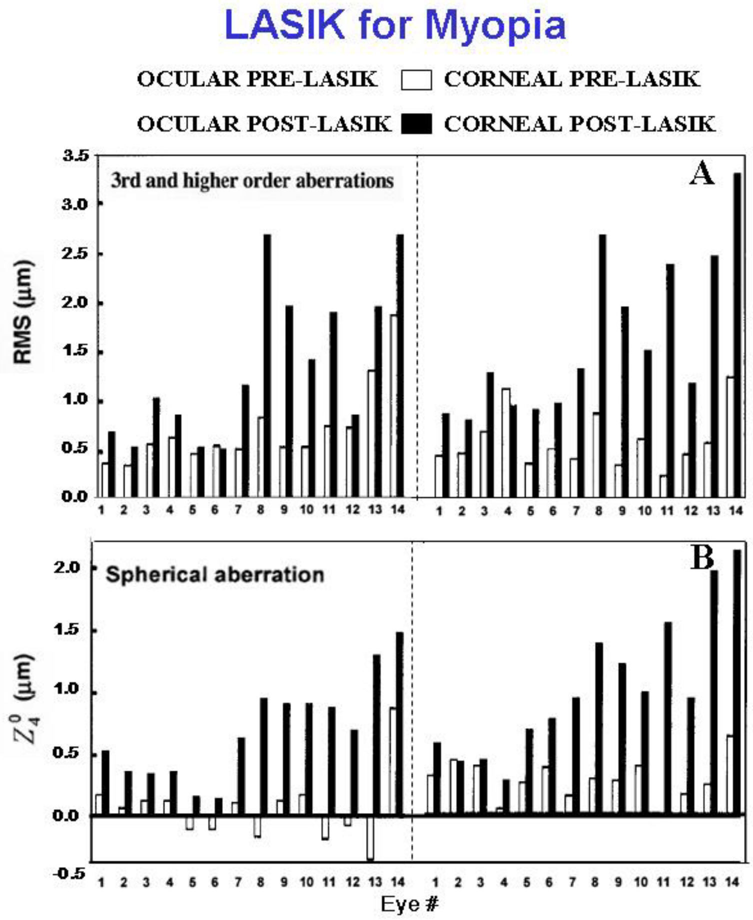


Figure 7.3. Ocular (left) and Corneal (right) HOA RMS values (A) and SA (B) before (light bars) and after (dark bars) LASIK surgery for myopia. Eyes are sorted by increasing preoperative spherical refraction. Pupil size=6.5 mm.

Ocular aberrations increased on average by a factor of 1.92±0.82 (range: 0.90 to 3.64) and corneal aberrations by a factor of 3.72 ±2.34 (range: 0.85 to 10.29) in this group. Ocular and corneal RMS differences (post- minus pre-surgical values) ranged from -0.05 to 0.80 µm, and from -0.16 to 2.04 µm, respectively. Part of this increase is accounted for by an increase in third- (increasing by an average factor of 1.98 for ocular and 2.73 for corneal aberrations), and fourth-order aberrations (increasing by an average factor of 2.54 for ocular and 3.94 for corneal aberrations). Figure 7.4 represents the pre- and post-operative RMS values for different orders averaged across the eyes of the myopic with error bars indicating std values across the eyes. Significant differences ($p<0.05$) between pre- and post-surgical values exist for third, fourth and third and higher orders.

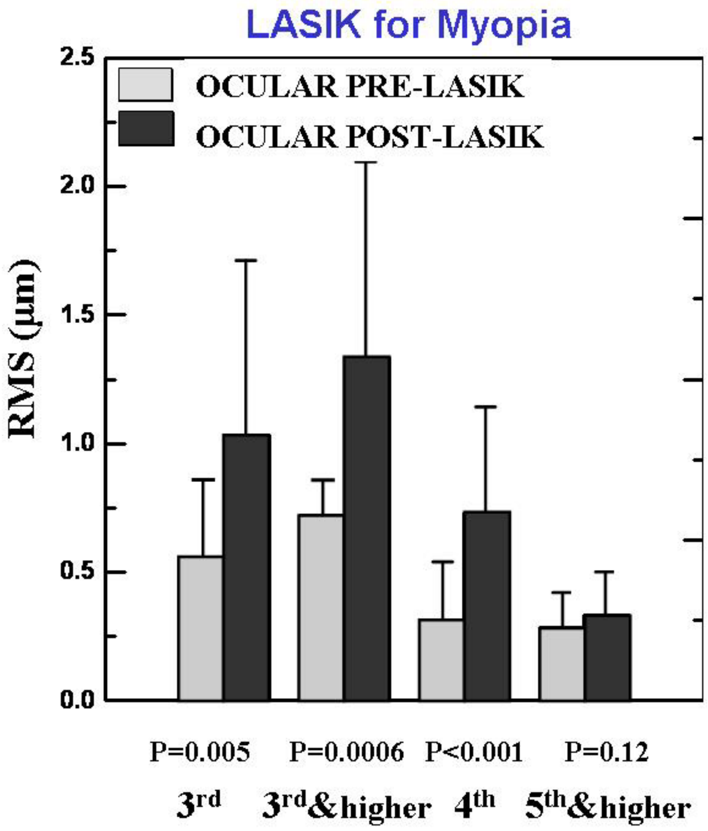


Figure 7.4. Pre- (light bars) and post-operative (dark bars) RMS wavefront error, averaged across all myopic eyes, for 3rd and higher order aberrations, 3rd order aberrations, 4th order aberrations and 5th and higher order aberrations, for a 6.5-mm pupil. Statistical significability of differences between pre and postoperative values is indicated by p.

Since the SA pattern was dominant in the wave aberration maps, the the trends followed by SA in this group were verified. Figure 7.3 B shows ocular (left) and corneal (right) fourth order SA (Z_4^0) before and after LASIK for myopia. The preoperative ocular SA coefficient was close to zero in most eyes, whereas preoperative corneal SA was positive in all eyes. Ocular and corneal SA increased significantly after LASIK: from 0.06±0.28 μm to 0.66±0.43 μm; p<0.00001, and from 0.28±0.17 μm to 1.02±0.57 μm; p<0.00001). The most dramatic increase occurred in patients with the highest preoperative myopia, both for ocular and corneal aberrations. As expected from the changes found in SA, corneal Q (computed from our videokeratographic data) shifted significantly (p=0.001) towards more positive values (from -0.14 to 1.09) after myopic LASIK.

Time after surgery ranged from about 1 month to three months in our group of subjects. Within this sample of eyes, no correlation between post-operative SA (p=0.66 for the cornea, p=0.82 for the ocular eye) and time after surgery was found.

7.4.3.- CHANGE IN OCULAR AND CORNEAL ABERRATIONS WITH HYPEROPIC LASIK

Figure 7.5 A shows ocular (left panel) and corneal (right panel) RMS for HOA, before (lighter bars) and after (darker bars) LASIK for hyperopia, with eyes sorted by increasing preoperative spherical refractive error. Both ocular and corneal aberrations increased after LASIK, except for eyes H1 and H13 for ocular aberrations, and eyes H1 and H13 for corneal aberrations. For both ocular and corneal aberrations the post-operative increase was much more pronounced in those eyes undergoing higher refractive corrections.

For this group, the average increase factor was 2.15±1.02 (range: 0.91 to 4.03) for ocular aberrations and 1.77±0.75 (range: 0.76 to 3.03) for corneal aberrations. Ocular and corneal RMS differences (post- minus pre-surgical values) ranged from -0.08 to 1.35 µm, and from -0.27 to 1.53 µm, respectively across the eyes in this group. Third- (2.16 µm for ocular and 2.06 µm for corneal) and fourth-order (2.52 µm for ocular and 1.49 µm for corneal increase average factor**)** aberrations account for most of this increase.

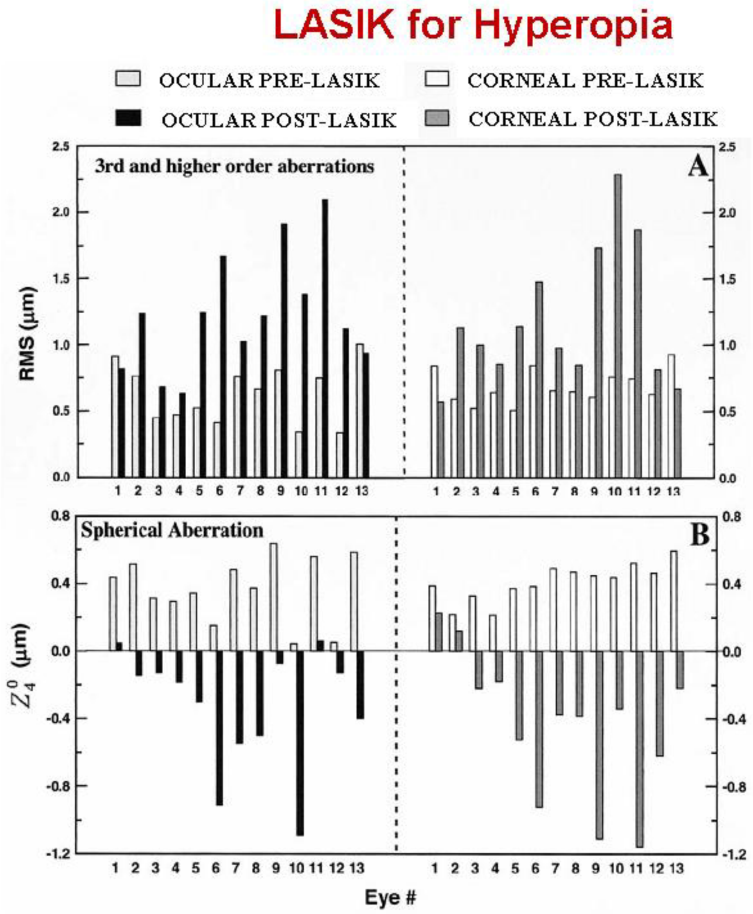


Figure 7.5. Ocular (left) and Corneal (right) HOA RMS wavefront error (A) and SA (B) before (light bars) and after (dark bars) LASIK surgery for hyperopia.

Eyes are sorted by increasing preoperative spherical refraction. Pupil size=6.5 mm.

Figure 7.6 represents the pre- and post-operative average RMS values for different orders. Error bars indicate std values across the eyes. Significability (p) less than 0.05 indicates that differences are statistically significant. Significant differences between pre- and post-surgical values exist for third, fourth and third and higher orders, as happened after LASIK for myopia. However, for these eyes significant differences are also found for fifth and higher order aberrations.

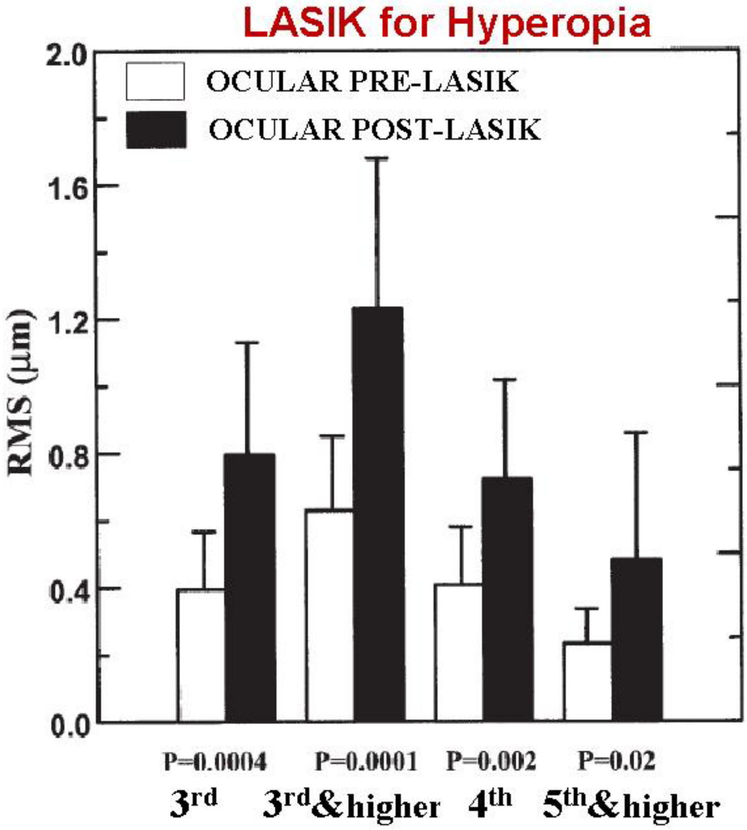


Figure 7.6. Pre- (light bars) and post-operative (dark bars) RMS wavefront error, averaged across all hyperopic eyes, for HOA, 3rd order aberrations, 4th order aberrations and 5th and higher order aberrations, for a 6.5-mm pupil. Statistical significability of differences between pre and postoperative values is indicated by p.

Figure 7.5 B shows ocular (left) and corneal (right) fourth order SA (Z_4^0) before (light bars) and after (dark bars) hyperopic LASIK. Preoperative ocular and corneal SA coefficient was positive for all eyes (0.37±0.19 μm and 0.41±0.11 μm, respectively). SA changed significantly ($p<0.00001$ for both, ocular and corneal) towards more negative values (-0.33±0.35 μm and -0.44± 0.43 μm, respectively) after surgery, turning into negative in most cases (11 out of 13 eyes). Ocular SA decreased on average by -0.70 ± 0.30 μm, and corneal SA decreased on average by –0.85± 0.48 μm. Consistently, corneal Q changed significantly ($p<0.00001$) towards more negative values (from -0.21 to -0.54) for these eyes.

It should be noted that, although different optical zones were programmed for different eyes, aberrations in eyes with smaller optical zones (5 mm as opposed to 6 or 6.5 mm) did not increase more than in those with the largest optical zone. The aberrations of all subjects were calculated for a 5-mm pupil and similar increase factors were obtained: 2.1 for 3rd order aberrations and higher, and 2.2 for 3rd order aberrations alone. In addition, SA in eyes with smaller optical zones (5 mm) was not found to be greater than in eyes with larger optical zones (6 or 6.5 mm), for either the cornea ($p=0.99$) or the ocular eye ($p=0.67$). Time after surgery ranged from about 1 month to five months in our group of subjects. Within this sample of eyes, no correlation between post-operative SA ($p=0.54$ for the cornea, $p=0.58$ for the ocular eye) and time after surgery was found.

7.4.4.- COMPARISON BETWEEN THE CHANGES IN OPTICAL ABERRATIONS AFTER MYOPIC AND AFTER HYPEROPIC LASIK

Figure 7.7 A and B show ocular and corneal SA, respectively, induced by myopic (black circles) and hyperopic (white circles) LASIK as a function of absolute attempted spherical correction. As previously described, ocular and corneal induced SAs were always positive in myopes and negative in hyperopes. Induced ocular SA (post minus pre-operative values for Z_4^0) ranged from 0.22 to 1.64 μm (0.63±0.45μm, on average), and induced corneal SA ranged from -0.02 to 1.72 μm (0.74±0.57 μm on average) for myopic eyes. For the hyperopic eyes, induced SA ranged from -0.39 to -1.13 μm (-0.76±0.26 μm) for the whole eye and from -0.1 to -1.68 μm (-0.85±0.48 μm) for the cornea. The induced corneal and ocular SA were correlated with attempted spherical correction for both myopic (r=-0.87, p<0.0001 and r=-0.81, p<0.0005, respectively) and hyperopic eyes (r=-0.81, p<0.0005 and r=-0.85, p<0.05, respectively). The rate of ocular SA increment per dioptre of attempted spherical correction tended to be higher for the myopic procedure (+0.13 µm/D of myopic error and -0.07 µm/D of hyperopic error). For the purpose of comparison between groups, a subgroup of myopic (n=4) and a subgroup of hyperopic (n=4) eyes of similar absolute attempted correction (1.5 to 3.00 D) were selected. For these subgroups, ocular and corneal HOA increased a factor of 1.62 and 1.58 in myopes, respectively, compared to 2.33 and 1.81 in hyperopes. The average induced ocular SA was, in absolute value, 3.3 times higher for the hyperopic than for the myopic eyes (-0.66 ± 0.28 µm and 0.20 ± 0.06 µm, respectively). The average induced corneal SA for the previous subgroups was -0.78 ± 0.40 µm for hyperopes and 0.13 ± 0.14 µm for myopes (i.e., six times more for hyperopic than for myopic LASIK). The rate for the corneal spherical error increments was higher for the hyperopic procedure (-0.28 µm/D) than for the myopic procedure (0.17 µm/D). The amount of absolute SA after surgery (both myopic and hyperopic) was lower in the ocular eye (-0.38 ± 0.36 µm and 0.40 ± 0.09 µm for the previous hyperopic and myopic subgroups, respectively) than on the cornea alone (-0.46 ± 0.34 µm and 0.43 ± 0.12 µm for the previous hyperopic and myopic subgroups, respectively).

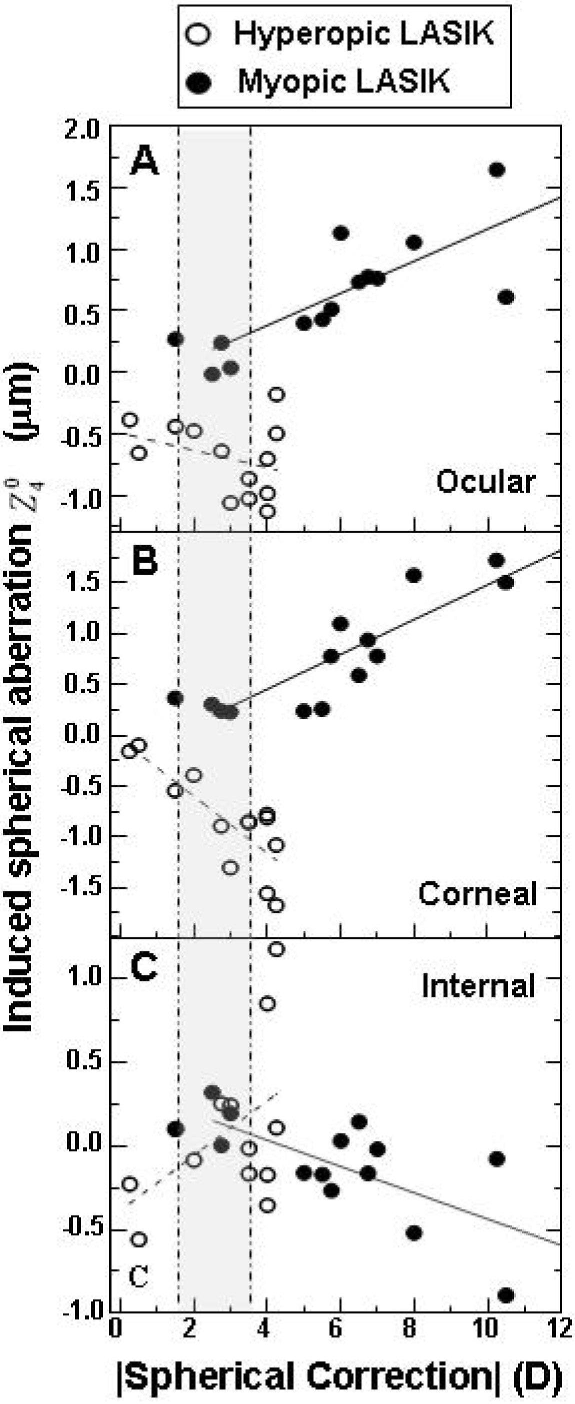


Figure 7.7. Total (A), corneal (B) and internal (C) SA induced by myopic (black circles) and hyperopic (open circles) LASIK as a function of absolute spherical correction, for a 6.5-mm pupil. Shaded areas indicate eyes included in the averages reported in the text comparing the results from both hyperopic and myopic techniques.

7.4.5.- CHANGE OF INTERNAL ABERRATIONS WITH LASIK

Figure 7.7 C shows the internal SA (Z_4^0) induced by hyperopic (white circles) and myopic (black circles) LASIK as a function of absolute attempted spherical correction. As seen in Figure 7.7 A and B, induced ocular SA is generally smaller in absolute value than the induced corneal SA (average SA induced was 0.74 µm and -0.85 µm for the cornea versus 0.61 µm and -0.76µm for the whole eye across myopic and hyperopic subjects, respectively; ocular slope was -0.13 and -0.11 versus -0.19 and -0.30 for the whole eye, for myopic and hyperopic eyes, respectively). In the myopic group, induced internal SA tended to decrease towards negative values with spherical correction (r=0.57, p=0.04). In the hyperopic group the trend was for induced internal SA to increase towards positive values with spherical correction (r=0.52, p=0.06). This indicates that internal SA, of opposite sign than induced corneal SA is reducing the impact of the corneal changes and its magnitude increases with attempted correction as does the induced corneal SA. Since the LASIK surgery is a corneal procedure (i.e. no change is happening on the crystalline lens) changes in internal aberrations must account for changes on the posterior surface of the cornea in this case. No similar behaviour was found for induced third-order aberrations, indicating that third-order aberrations do not seem to be induced in the posterior corneal surface.

Experiments in control subjects (who had not undergone a surgical procedure) performed in two different experimental sessions (separated by at least one 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 recentration algorithm) cannot account for the observed differences in the internal optics found between pre- and post-LASIK results. Therefore these changes must be attributable to surgery.

7.5.- DISCUSSION

Ocular and corneal aberrations increased after LASIK surgery for myopia and after LASIK surgery for hyperopia. The higher the preoperative ametropia (and therefore, the surgical correction to be applied), the higher the increase. In general, although the trends are similar when looking at ocular and corneal HOA, the induced SA in the anterior corneal surface was greater than that of the entire eye in absolute value, for both groups. In the following sections, several other factors that indicate that anterior corneal aberrations alone are not sufficient to explain surgical outcomes will be discussed. In addition, our findings will be related to those in current biomechanical models of corneal response to surgery and previous observations. Finally, the implications of these results in the evaluation of refractive surgery outcomes and aberration-free ablation procedures will be discussed.

7.5.1.- CHANGE IN ABERRATIONS WITH MYOPIC AND HYPEROPIC LASIK

Corneal aberrations were expected to change with the procedure, and this change was expected to implie a change in ocular aberrations. However, the fact that the amount of absolute SA after surgery (both myopic and hyperopic) was lower in the ocular eye than on the cornea alone (-0.38 ± 0.36 µm and 0.40 ± 0.09 µm for ocular versus -0.46 ± 0.34 µm and 0.43 ± 0.12 µm for corneal SA for the previous hyperopic and myopic subgroups, respectively) suggests a compensation by internal aberrations (see section 7.4.5.-). Part of this compensation was due to aberration of the crystalline lens. The role of the preoperative internal SA (primarily aberrations of the crystalline lens) in hyperopes, compared to myopic eyes, will be discussed in the next section. The posterior surface of the cornea seems to play also a compensatory role, which will also be discussed.

As expected, major changes occurred on the anterior corneal surface for both myopic and hyperopic LASIK. The causes of a change in corneal Q leading to important changes in SA found clinically are not well understood (Gatinel et al., 2001, Anera et al., 2003). It has been shown analytically (Gatinel et al., 2001), computationally (Marcos et al., 2003) and experimentally (Dorronsoro et al., 2006) that those changes are not inherent to the Munnerlyn ablation algorithm, or at least to the exact application of it. Radial changes of laser efficiency across the cornea, due to angular changes of reflectivity and laser fluence, have been shown to be responsible for at least part of the discrepancies of postoperative asphericities with respect to predictions (Anera et al., 2003, Mrochen and Seiler, 2001). These effects are expected to be much more relevant in hyperopic LASIK than in myopic LASIK, since in the hyperopic procedure corneal tissue is removed primarily in the periphery where the effects of laser efficiency losses are more important (Berret et al., 2003).

The biomechanical response, presumably responsible for some of the Q changes found with LASIK (Roberts and Dupps, 2001), is probably also higher in hyperopic LASIK. In the myopic LASIK profile, there is only one inflection zone per hemimeridian (located at the border between the treated and the untreated peripheral cornea) for purely spherical corrections, or at the steepest meridian for astigmatic myopic correction, as shown in Figure 7.8 A (see arrows), and two inflection zones in the flattest hemimeridian (located at the junctions between the ablation optical zone and the transition zone (1), and between the transition zone and the untreated peripheral cornea (2), respectively) for myopic astigmatic correction, as shown in Figure 7.8 B (MacRae, 1999). However, the hyperopic profile shows three inflection zones per hemimeridian, as represented in Figure 7.8 C: (1) located at the centre of the ablation (some high hyperopic treatment plans treat the central cornea optical zone); (2) at the deepest portion of the ablation, which is at the boundary border between the ablation optical zone and the transition zone; and (3) at the boundary between the transition zone and the untreated peripheral cornea. The increased number of inflection zones may result in a larger biomechanical response than occurs for myopic LASIK, although the actual mechanisms still need to be worked out. This has also been considered to reduce the maximum amount of treated hyperopic refractive error to about one-third of the treated myopic error (MacRae, 1999). In addition, ocular third order aberrations were found to increase slightly more in hyperopic than in myopic LASIK eyes (factor of 2.2 and 1.7, respectively), in agreement with the report by Oliver et al. (2001) and Kohnen et al. (2004). However, no correlation was found between induced third order aberrations and attempted spherical correction. This result suggests that coma was primarily associated with decentration of the ablation pattern, and the amounts of decentration were rather variable

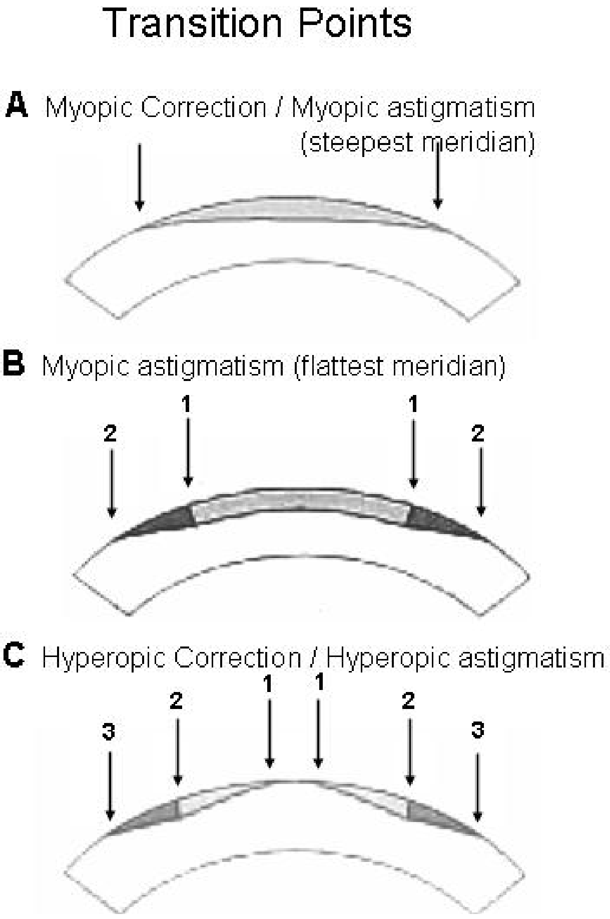


Figure 7.8. Diagrams showing corneal transition points after ablation for correction of myopia or myopic astigmatism on the steepest meridian (A), myopic astigmatism on the flattest meridian (B), hyperopia or hyperopic astigmatism (C). Modified from (MacRae, 1999)

across eyes, both myopic and hyperopic.

7.5.2.- ROLE OF PREOPERATIVE INTERNAL OPTICS

Ocular aberrations result from the combination of corneal and internal aberrations and their inter-relationships. According to the study described in Chapter 6 of this thesis, this combination may be different for myopic and hyperopic eyes. Therefore, different outcomes between both groups of eyes after surgery may be expected due to different combinations of ocular, corneal and internal aberrations, in addition to differences attributable to the LASIK procedures.

In general, before myopic surgery, both components contributed to the whole aberration with comparable amounts of aberrations—in some cases even balancing each other. Figure 7.1 A and Figure 7.3 A (white bars) show that whereas before surgery the cornea dominated the ocular wave aberration pattern in some eyes (eye M1 or M7 for example), in some others there was little similarity between ocular 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 high degree of balance between corneal and internal aberrations in normal young eyes has been reported in previous studies (Artal et al., 2002, Marcos et al., 2002). A discussion on the percentage of balance for hyperopic and myopic eyes depending on the age group can be found in Chapter 6 , section 6.5.2.- of this thesis. Before surgery, a term-by-term balance of at least 50% of the aberration was found in 28% of the 14 myopic eyes of this study. For SA, this balance increased to 57% of the eyes. In 78% of the eyes, the SA of the anterior corneal surface and the internal optics had a different sign, resulting in less positive ocular SA (Figure 7.3 B, white bars). Furthermore, it is not uncommon (35%) that the amount of negative internal SA - likely from the crystalline lens (Artal and

Guirao, 1998, Elhage and Berny, 1973) - exceeds the amount of positive SA of the anterior corneal surface.

Figure 7.9 illustrates one of these cases (eye M6), with a corneal preoperative SA (Z_4^0) of 0.38 µm and internal preoperative aberration of -0.48 µm. The upper row shows the pre-operative measured ocular and corneal and the computed internal aberration patterns. The negative internal aberration dominates the central area ocular aberration pattern. After LASIK (lower row), positive SA is induced on the anterior corneal surface, which cancels (actually overcompensates) the preoperative negative SA of the internal optics. For this reason, the post-LASIK ocular aberration pattern for this eye is much better than predicted from corneal aberrations alone. Unlike other subjects with similar preoperative myopia and similar corneal topography after LASIK, this subject did not show any loss of contrast sensitivity (actually improved at two spatial frequencies) (Marcos, 2001). An individual comparison of pre and post-surgical ocular and corneal aberration can be invoked to explain the surprisingly good surgical outcomes in this patient.

In general, the possible balance between corneal and internal aberration gets disrupted with refractive surgery. In this group, compensation of more than 50% of the corneal SA by the preoperative internal aberrations decreased from eight eyes before surgery to four eyes after surgery and only happened in eyes with the lowest preoperative spherical errors (eyes M2, M3, M5, and M6). However, at least in these eyes, these interactions are relevant in determining the ocular wave aberration pattern. The counteracting effects of the crystalline lens may be accounted for by adding the induced corneal SA and internal preoperative SA (which accounts mainly for crystalline lens SA), and then dividing this number by the induced corneal aberration to provide a relative value. A value between 0 and 1 will be indicative of compensation by the crystalline lens, a value close to 1 indicative of no compensation, and a

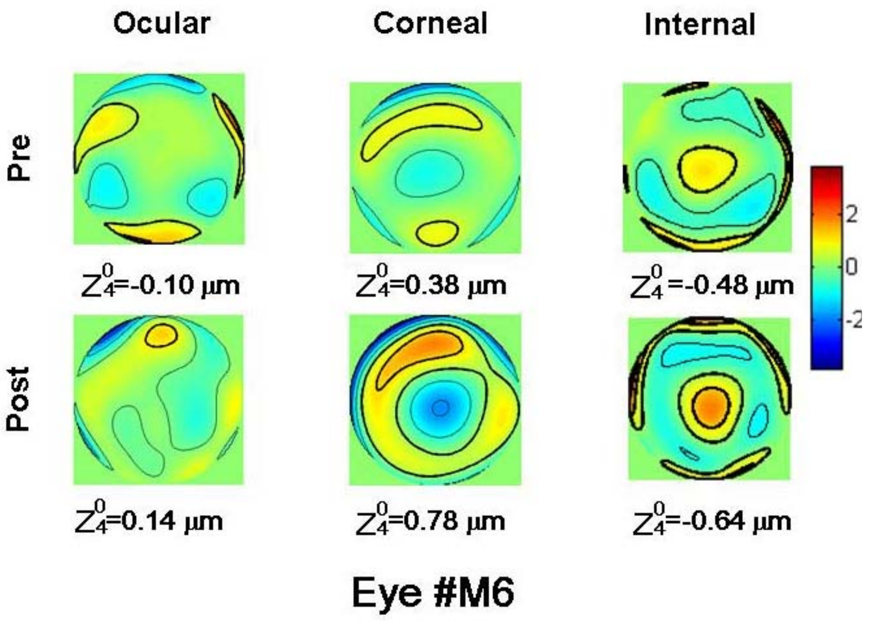


Figure 7.9. Ocular (left), corneal (middle) and internal (right) HOA maps before (top) and after (bottom) myopic LASIK for eye M6 (with a particularly good surgical outcome). Before surgery, the negative internal aberration dominates the total pattern. After surgery, the positive SA induced on the anterior corneal surface partially cancels the preoperative negative SA of the internal optics. Contour lines were plotted every 1 µm, and pupil diameter was 6.5 mm.

value higher than 1 indicative of additional contribution of the crystalline lens to the degradation. In the myopes from our study, where attempted spherical error correction ranged up to -10.50 D, a counteracting value of 0.375 was found.

In our hyperopic group, a dominance of preoperative corneal aberrations (particularly SA) in the preoperative ocular aberration pattern in several of the eyes (see Figure 7.1 B and Figure 7.5) was found. When the eyes of this study were sorted by age, younger eyes (H6, H10 and H12; 24 through 25 years old) showed negative internal SA, while older eyes, showed less negative SA (eyes H13, H5, H7, H8, H3, 25 through 43 years old), which turned into positive for the oldest eyes (H4, H1, H2, H9, H11, 43 through 54 years old), disrupting the balance of the positive SA of the cornea by the crystalline lens. This balance between internal and corneal aberrations observed in our younger hyperopic eyes has been reported in previous studies in normal young eyes (Artal et al., 2002) and myopic eyes

(Marcos et al., 2002), as well as the loss of this compensation with age (from 45 years) in normal eyes (Marcos et al., 2002). In the age and absolute refractive error matched comparison of hyperopic and myopic eyes reported in Chapter 6 of this thesis, an early loss (at approximately 30 years of age) of corneal to internal balance in hyperopic eyes was found. This loss was not present in the myopic group of the same study, which did not show a significant trend of balance at this age.

These findings may be relevant to understanding the outcomes of hyperopic LASIK and to predicting possible changes in performance with age. Given that corneal SA shifts to negative values after a hyperopic procedure (Figure 7.5 B), the fact that the crystalline lens contributes with additional negative SA is disadvantageous in young hyperopic eyes, whereas for myopic eyes the negative SA of the crystalline lens subtracts from the induced positive corneal SA (Figure 7.9). However, since SA of the crystalline lens becomes more positive with age, patients who undergo hyperopic LASIK will experience an absolute decrease of SA with age (and potentially an increase in optical quality), whereas for myopic eyes, SA will increase with aging (Marcos, 2002). Aberrations of the crystalline lens therefore play a significant role in the evaluation of the individual surgical outcomes and in the prediction of long-term optical performance. In this group, compensation of more than 50% of the corneal SA by the preoperative internal aberrations was present in 3 of the 13 hyperopic eyes, which were the youngest eyes (H6, H10 and H12; 24, 24 and 25 years old). After the surgery, compensation of more than 50% was found in four eyes, which were the oldest eyes of the group (H1, H2, H9 and H11; 48, 48, 54 and 54 years old). For this group a counteracting value of 1.04 was found.

Possible effects of preoperative corneal aberrations on postoperative outcomes were also studied. For myopic eyes, no correlation between preoperative and postoperative SA was found. Although a slight correlation for hyperopic eyes (r=-0.42) was found, this was not significant (p=0.16), and could be driven by the correlation between spherical error and corneal SA in preoperative hyperopic eyes (r=0.76, p=0.002), which was not found for preoperative myopic eyes (see Chapter 6).

7.5.3.- CHANGES IN INTERNAL ABERRATIONS AND BIOMECHANICAL RESPONSE

Absolute value of induced ocular SA (Figure 7.7 A) was generally smaller than induced corneal SA (Figure 7.7 B) in absolute value for both, myopic and hyperopic groups. This indicates that induced internal SA (Figure 7.7 C), of opposite sign to induced corneal SA, reduces the impact of corneal changes. The effect was larger as the preoperative spherical refractive error (and therefore attempted correction) increased and did not depend on the preoperative internal aberrations. There was a significant correlation between induced internal SA and spherical attempted correction (r=0.57, p=0.04) in the myopic group. In the hyperopic group the correlation (r=0.52) is on the limit of significability (p=0.06), probably due to higher variability and a limited refractive range. The effect is only present for SA, but not for other terms.

Since LASIK surgery is not likely to induce changes in the crystalline lens, one might think that the changes occur in the posterior corneal surface. This hypothesis is consistent with some studies using scanning slit-lamp corneal topography in myopic subjects that reported a forward shift of the posterior corneal surface after PRK for myopia (Naroo and Charman, 2000) and LASIK (Seitz et al., 2001, Baek et al., 2001, Bruno et al., 2001). They suggested that the thinner, ablated cornea may bulge forward slightly, steepening the posterior corneal curvature. This effect has been thought to account for the regression towards myopia that is sometimes found after treatment, particularly in the patients with highest preoperative myopia (Naroo and Charman, 2000).

Using a simple corneal model with aspherical surfaces developed by Sergio Barbero (Barbero, 2004), the observed mean changes of internal SA were found to be consistent with the changes in power (from -6.28 to -6.39 D) and Q (from 0.98 to 1.14) of the posterior corneal surface reported by Seitz et al. for a group of eyes undergoing LASIK with preoperative spherical refractive error similar to those in our study (range: -1.00 to -15.50 D, mean, -5.07±2.81 D) (Seitz et al., 2001). The induced SA of the posterior corneal surface computed using the model (-0.103 μm) was very similar to the change in internal SA measured experimentally in this study (-0.110 μm, on average).

To our knowledge, equivalent changes in posterior corneal curvatures and asphericities after hyperopic LASIK have not been studied. Ma et al. (2004) compared internal aberrations after hyperopic LASIK eyes with a control group of eyes and found more positive internal SA in the operated eyes, consistent with a shift of the posterior corneal surface towards more positive values. In both myopic and hyperopic eyes, the shift of internal SA resulted in slight compensation of the aberration induced on the anterior surface of the cornea. On the other hand, recent studies using Scheimpflug imaging report that no changes are found in the topography of the posterior cornea after LASIK for myopia (Ciolino and Belin, 2006, Ciolino et al., 2007). Early studies reporting disagreement in pachymetry measured with slit-lamp corneal topography and ultrasound (Yaylali et al., 1996, Chakrabarti et al., 2001, Modis et al., 2001) have lead to the application of correction factors (acoustic factor) to slit-lamp topography to minimise this discrepancy. Although with the correction factor this discrepancy decreased for measurements in normal corneas, slit-lamp topography has been reported to underestimate central corneal thickness for post-LASIK eyes (Prisant et al., 2001, Iskander et al., 1999). Studies comparing Scheimpflug imaging and slit-lamp topography find differences between both techniques (Quisling et al., 2006), specially in post surgery eyes (Matsuda et al., 2008). Therefore, the question of the changes on the posterior corneal surface induced by LASIK remains unclear.

In summary, using a combination of aberrometry and anterior corneal topography, the change in the posterior corneal shape was found to produce a decrease of ocular SA in comparison with that predicted from anterior corneal aberrations alone, and the effect is rather variable across eyes. Our results confirm that this effect is correlated with the amount of preoperative refractive error (or, equivalently, with the depth of corneal ablation).

7.5.4.- COMPARISON WITH OTHER STUDIES

Direct comparison among studies is usually hampered by differences in surgical technique (type of surgery, optical and transition zone diameters, type of laser, use of an eye-tracker) and the characteristics of the study population (age range, preoperative correction, preoperative HOA, etc). In this section our results are compared with those in literature.

The change of corneal aberrations with LASIK for myopia found in this study - increase of coma, SA and HOA (by a factor of 2.73, 3.94 and 3.72, respectively) - agrees with results reported by Oshika (1999b) (increment factor of 2.48, 5.11 and 3.24, for coma, SA and HOA, respectively) and Oliver et al. (1997) (increment factor of 2.11 and 2.38, for coma and SA respectively). The correlation between induced corneal SA and attempted correction found in this study ($r=-0.81$, $p<0.0005$) agrees with the results reported by Schwiegerling and Snyder (2000) for PRK patients ($r=-0.84$).

As expected from the results for corneal SA, and in agreement with published studies on LASIK for myopia (Hersh et al., 2003, Holladay et al., 1999b), anterior corneal Q increased (more oblate corneas) with the surgery (from -0.14 to 1.09, compared to from -0.17 to 0.92 by Hersh et al. (2003), and from -0.16 to 0.47 by Holladay et al. (1999b)). Holladay et al.'s post-surgical mean value was smaller than Hersh et al.'s and ours, maybe due to differences in the pre-surgical refraction, and therefore the attempted correction (-2.50D through -13D for this work, -3.75D through -10.75D for Hersh et al., -2.25D through -10.12D for Holladay et al.) used, or the specific laser platform.

The significant increase in ocular aberrations found in this work after myopic LASIK agrees with those reported by other studies (Seiler et al., 2000, Yamane et al., 2004). However, the values reported by Seiler et al. are greater than ours: RMS_{post}/RMS_{pre} ratios (Moreno-Barriuso et al., 2001) for 3rd order, 4th order, and HOA (3rd through 6th order) were 4.7, 4.11 and 4.20 compared to our 1.98 μm, 2.54 μm and 1.92 μm). This could be attributed to the different surgical techniques (PRK vs LASIK, broad beam vs flying spot), and the slightly greater pupil they use (7 mm vs 6.5mm in diameter). The ratio values from Yamane et al. were slightly smaller than ours, probably because the pupil diameter they used was smaller (4 mm): 1.46 for 3rd, 1.63 for 4th and 1.70 for 3rd through 5th RMSs.

Recent studies report a decrease in the aberrations induced by LASIK procedures that use modified laser algorithms such as wavefront-guided or wavefront-optimised compared to standard algorithms. For example, Kim et al. (2004) reported post surgery RMS values of 0.34 μm, 0.23 μm and 0.47 μm for 3rd order, 4th order and HOA RMSs (increase factors 1.93, 2.00 and 2.16), respectively, for the standard procedure, compared to 0.29 μm, 0.22 μm, and 0.38 μm (increase factors 1.65, 2.32 and 1.84), respectively for the wavefront-guided procedure for corrections ranging from -2.75 to -8D. However, differences were not statistically significant.

Our findings on the increase of corneal aberrations with hyperopic surgery, and particularly the change in corneal SA towards negative values, are in general agreement with the findings previously reported (Oliver et al., 2001, Wang, 2003, Ma et al., 2004) Changes reported by Oliver et al. were greater (postoperative mean corneal SA of -0.44 ± 0.43

µm and third-order corneal RMS of 0.91 ± 0.39 µm) than those found in the present study in spite of using a slightly smaller pupil probably due to inclusion of higher hyperopes (+2.50 to +7.50 D) and differences between surgical procedures (PRK versus LASIK). They also found a statistically significant increase in coma RMS (from 0.64 ± 0.24 µm to 1.76 ± 1.39 µm after 12 weeks). Also, our values were greater than Wang et al.'s pre- and postoperative values for corneal SA (0.27 ± 0.08 µm and -0.058 ± 0.16 µm, respectively) and RMS for HOA (0.49 ± 0.09 µm and 0.56 ± 0.20 µm, respectively).

Regarding corneal Q, the relative changes that found in this study were similar to those (-0.32 versus average of -0.39) in Chen et al.'s (2002) study, even though our pre (-0.21 ± 0.12) and postoperative (-0.54 ± 0.19) mean Q were less negative. In agreement with Chen et al, correlation between the postoperative Q and the attempted spherical correction was found, although it was not statistically significant (r=-0.47, p=0.1), as well as some correlation between pre and postoperative corneal Q (r=-0.40, which was statistically significant; r=-0.76, p=.005, without eye #H5). Unlike reported by Chen et al, a good correlation between the preoperative corneal radius of curvature and the postoperative Q (r=-0.68, p=.008) was found in the current study.

Ocular aberration postoperative values reported by Ma et al. on LASIK for hyperopia were comparable to those found in this study (1.18 µm and 0.86 µm for ocular and corneal HOA RMS for a 6-mm diameter pupil, as opposed to our 1.23 and 1.18 µm for a 6.5-mm-diameter pupil; and -0.41 and -0.24 µm for ocular and corneal SA for 6-mm, as opposed to our -0.44 µm and -0.33 µm for 6.5-mm), in spite of the differences between preoperative spherical error ranges in both studies (+0.75 to +7.25 D in Ma et al versus +2.50 to +5.50 D in our study). However, their study reported larger changes in internal SA, which they attributed partly to reshaping of the posterior surface of the cornea and partly to possible errors in their techniques.

7.5.5.- IMPLICATIONS

Our results have important implications for the evaluation of the outcomes in standard LASIK surgery as well as for the design of wavefront-guided ablation procedures (designed to individual cancelling preoperative aberrations). It has been shown that the combination of corneal and ocular aberrations is necessary to understand individual surgical outcomes and their impact on visual performance. In general, both corneal and ocular aberrations increased with surgery, but the particular increment depended on the individual subject. This is particularly critical in any aberration-free procedure, which cannot rely on the mean population response, but must be adapted to the individual patient. Moreover, ocular wavefront aberration measurements complement corneal topography information to gain insight into the biomechanical corneal response. Although the ablation is applied on the anterior corneal surface, our analysis revealed changes in the shape of the posterior corneal surface, assessed by the modification of its SA.

In the last years, the induction of aberrations with surgery, specifically SA, has driven the advance of corneal refractive surgery due to its impact on postsurgical visual quality. Different approaches have been followed to avoid the induction of aberrations (Kohnen, 2006, Mrochen, 2006). Technological advances and experience in wavefront-guided procedures have resulted in an improvement of the outcomes of this surgery reported by more recent studies (Kim et al., 2004, Zhang et al., 2008). Some studies report less aberrations induced during the wavefront-guided procedure compared to standard procedures (Schallhorn et al., 2008, Kim et al., 2004). However, the differences reported in terms of optical aberrations or impact on visual functions are not always statistically significant (Chisholm et al., 2004, Netto et al., 2006, Kim et al., 2004). Wavefront-optimised laser profiles aim at not altering pre-surgical ocular aberrations, and specifically at avoiding the induction of SA reported for the standard procedure (Mrochen et al., 2004), whereas aspheric ablation patterns have been designed to optimise the corneal Q (Schwiegerling and Snyder, 2000, Manns et al., 2002). Nevertheless, the results reported for these techniques are not better than those reported for wavefront-guided procedures (Padmanabhan et al., 2008, Koller et al., 2006). Different studies (Jimenez, 2004b, Jimenez, 2004a, Dorronsoro et al., 2006, Kwon et al., 2008, Arba-Mosquera and de Ortueta, 2008, Dupps and Wilson, 2006, Hersh et al., 2003) have been carried out with the purpose of identifying the different factors that contribute to the induction of the aberrations during the surgery. All these different works reflect the influence of the findings of the work presented in this chapter.

7.5.6.- CONCLUSIONS

1) High order aberrations (3rd through 7th order) increase with standard LASIK treatment, particularly SA, which changes towards positive values with myopic LASIK and towards negative values with hyperopic LASIK.

2) However, the increase in the anterior corneal SA is slightly counteracted by the posterior corneal SA, resulting in an increase of the whole eye SA smaller than that of the anterior cornea. This indicates that corneal biomechanics play a role in the surgery outcomes.

3) Preoperative aberrations play also an important role in the outcomes of the surgery, due to the disruption of the balance existing between the corneal and the lens aberrations resulting from aberrations induced by LASIK. The fact that aberrations change with time, should also be considered.

4) The combined use of ocular and anterior corneal aberrations is essential to asses the outcomes of refractive surgery as well as to select the

individuals suitable for the surgery. In the first case, the combined use of both devices allowed us to gain insight into the biomechanical corneal response. In the second case, the study of the relationship between anterior corneal and internal aberrations before surgery may allow to predict the outcomes of the procedure.

5) These results have important implications for wavefront-guided procedures. Ocular wavefront aberration measurements complement corneal topography information to gain insight into the biomechanical corneal response. Although the ablation is applied on the anterior corneal surface, our analysis revealed changes in the shape of the posterior corneal surface, assessed by the modification of its SA.