Temporal evolution of ocular aberrations following laser in situ keratomileusis

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Keywords: Laser in situ keratomileusis, ocular aberrations, spherical aberration

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Received: 13 May 2010; Accepted: 28 April 2011

Abstract

\textbf{Purpose:} To study the temporal evolution of ocular aberrations after standard LASIK to correct myopia.

\textbf{Methods:} The ocular, corneal and internal aberrations for a 6-mm pupil were measured in 22 young myopic eyes (n = 12 subjects; range \(-2.0\) to \(-7.6\) D) before and during a 9-month follow-up after standard myopic LASIK. Ocular aberrations were measured with a Hartmann-Shack wavefront sensor, while corneal aberrations were estimated from the elevation data obtained by corneal topography. For every patient and condition the eye’s modulation transfer function (MTF) and Strehl ratio (SR) were calculated.

\textbf{Results:} Compared to preoperative results, we found that standard myopic LASIK produced a significant increase of ocular high-order aberrations at 1 month after surgery. During the next 8 months, we found a small increase of ocular and corneal positive spherical aberration (SA), although with a large inter-subject variability. However, all eyes treated for myopia higher than \(-5\) D showed a significant increase of positive SA during the first 6 months after surgery.

\textbf{Conclusions:} Standard myopic LASIK decreases ocular optical quality. For most subjects, the increase in aberrations induced by the surgery was stable during the next 9 months after LASIK. However, further changes of the ocular SA after myopic LASIK are possible in patients treated for higher amounts of myopia. The changes in aberrations mainly appeared between the first and the sixth month after surgery, which suggests the need to wait at least 6 months after myopic LASIK before comparing outcomes, especially for patients treated for higher myopias.

Introduction

The anterior surface of the cornea is the major refracting element in the human eye, with about two-thirds of the total eye’s optical power. It can be approximately described as a rotationally symmetric ellipsoidal conoid that tends to flatten from its apex towards the periphery.\textsuperscript{1} The spherical aberration (SA) of the cornea is on average positive and usually well compensated by the lens in young subjects. However, this compensation tends to be reduced with age, as the lens’ negative SA tends towards positive values in the older eye.\textsuperscript{2,3} A relationship between the kappa angle of the eye and compensation of the corneal lateral coma by the lens has also been reported.\textsuperscript{4}

Laser in situ keratomileusis (LASIK) has been the most popular refractive surgery for the correction of myopia during the last two decades. Its main advantages are the less severe wound healing response, and faster visual recovery compared to other techniques such as Photorefractive Keratectomy.\textsuperscript{5} Disadvantages of refractive surgery have included unwanted optical effects, such as night vision problems\textsuperscript{6} or perceived halos.\textsuperscript{7} Most problems, especially under mesopic or scotopic conditions\textsuperscript{8} are related to a decrease in optical quality due to a significant increment of ocular aberrations after surgery.\textsuperscript{9–12} The increase of spherical-like aberrations after LASIK is due to the ablation profile and corneal reflection losses of the laser beam,\textsuperscript{13–15} while the increase of coma-like aberrations seem to be
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mainly related to ablation decentrations. An increase of ocular aberrations may not be always related to an increase of corneal aberrations, but to a disruption of the fine balance of the aberrations of the corneal and the lens.

These optical problems have been alleviated by a more detailed patient selection and technical refinements as using a flying-spot laser combined with eye-tracking, or using a femtosecond laser instead of microkeratome to create the flap. Ablation profiles have been also improved by using asphericity or customization based on wavefront sensing that reduced the induced aberrations. However, wavefront-guided LASIK is not able to avoid an increase of ocular high-order aberrations after surgery, although the increase is lower extent than associated with standard treatments.

There are some other specific problems related to LASIK that cannot be easily avoided, including a postoperative dry eye sensation, and corneal biomechanical changes. Uncontrolled corneal changes after surgery could lead to myopic regressions, or in extreme cases it could actually induce corneal ectasia. Factoring addition, the nature and type of the optical changes after refractive surgery due to healing process and corneal biomechanics, is still not completely understood.

In this context, the aim of the present study was to establish the changes of ocular optical quality during the 9 months after standard myopic LASIK. We were also interested in identifying the origin of these postoperative optical changes.

Methods

In a consecutive case series study we measured the ocular, corneal and internal aberrations in young subjects treated with standard myopic LASIK, before and during a postoperative follow-up. Twelve myopic subjects (n = 22 eyes; mean age 29.5 ± 5.2 years; mean sphere -3.6 ± 1.7 D; mean cylinder -1.3 ± 1.1 D), were enrolled in the study. The LASIK procedures included cutting the flap by means of a microkeratome (Hansatome; Bausch & Lomb, St Louis, Clara, CA, USA, http://www.bausch.com). The optical zone (OZ) diameter was selected by the surgeon (one of the authors, MR), according to patients’ refraction and corneal central thickness. The OZ was 6.5-mm in all but two eyes, which had an OZ of 6 mm. An 8-mm blending zone (-1 D ablation), was performed on 17 eyes. Astigmatism correction was obtained by selecting an elliptical OZ, varying between 6.5/6.3 mm (maximum OZ/minimum OZ), and 6.5/5.0 mm. After a complete ophthalmic exam, we excluded those patients showing any ocular pathology. Informed consent was obtained from each patient, following the tenets of the Declaration of Helsinki. All treatments were considered uneventful, with only a few cases of dry eye symptoms, which remitted during the length of the study.

We measured the ocular and corneal wavefront aberrations for a 6-mm pupil in every session, represented as a Zernike polynomials expansion up to the sixth-order, before and at 1 week, and 1, 3, 4, 6 and 9 months after surgery. Ocular wavefront aberrations were obtained under natural viewing conditions, using our own developed near-infrared Hartmann-Shack (HS) wavefront sensor adapted to the clinical environment. The system is quite robust with nearly 300 microlenses sampling a 6-mm pupil area, and a high-dynamic range. Corneal aberrations were obtained for the same pupil size from corneal elevation maps (with more than 2000 points in a 6-mm area) provided by videokeratography (Atlas; Carl Zeiss-Meditec, Dublin, CA, USA, http://www.meditec.zeiss.com), by using custom ray-tracing with optical software (Zemax Development Corp., San Diego, CA, USA, http://www.zemax.com). We measured the position of the centre of the pupil for each eye by measuring the distance from the corneal reflex at the Placido disk image recorded by the corneal topographer. The ocular aberration data were the average from four different HS images acquired during the same session, and corneal aberrations were the average of three consecutive measurements. Internal aberrations were estimated by subtracting corneal aberrations from those of the eye, when the pupil centre was used as reference for registration in each set of data.

We analyzed the possible changes of high-order aberrations in terms of the root mean square (RMS) of the aberrations commonly induced by standard myopic LASIK: fourth-order spherical aberration (c4; SA) and third-order coma (coma = \( \sqrt{(c_1^4)^2 + (c_3^4)^2} \)).

We also computed the eye’s modulation transfer function (MTF), which represents the loss of contrast produced by the eye on a sinusoidal grating as a function of the spatial frequency, and the Strehl ratio (SR).

To determine the influence of the surgical procedure in ocular aberrations, a Student t-test was performed to compare the preoperative values with those obtained at 1-month after LASIK. We also performed a one-way ANOVA test to determine the significance of the possible changes within the studied population during the 9 months follow-up after standard myopic LASIK.

Results

We studied the evolution of the aberrations after surgery in 22 eyes from 12 subjects and measured both eyes in 10 subjects, considering them as providing independent
 information. Although there is a random variation in the eye’s aberrations from subject to subject, in normal subjects the aberrations in one eye tend to be correlated with those in the contralateral eye. The aberrations that are mostly correlated are second and third order terms, with a slight tendency towards mirror symmetry between eyes. We performed a statistical analysis of the postoperative data from the left and right eyes of each subject, to determine if data obtained from both eyes of the same subject could be considered as independent after standard myopic LASIK. The one-way ANOVA test performed revealed that there was no relationship for the ocular high-order aberrations RMS for all of subjects. Similar analyses comparing results from both eyes for post-op ocular coma, showed a relationship in one subject, while for post-op ocular SA, we found a relation between both eyes in two subjects.

We also compared data from the right and left eyes of the same subject using Pearson correlations (r); while for ocular coma we found that r was lower than –0.50 in seven subjects, the opposite occurred for ocular SA, with r higher than 0.50 in six subjects. The temporal evolution of ocular SA found after standard myopic LASIK in some subjects, seemed to be related to the amount of dioptric correction and the ablation properties, but changes in ocular coma seemed to depend on other factors, such as differences in the surgical procedure performed on each eye. We considered that this allowed us to use data obtained from both eyes of the same subject for 10 patients.

Compared to the preoperative status, we found a statistically significant increase of high-order aberrations (RMS) at 1 month after LASIK (Figure 1a): we found an average twofold increase of ocular RMS, from 0.33 ± 0.12 μm up to 0.63 ± 0.25 μm; a similar increase was found for average corneal RMS, from 0.40 ± 0.08 μm up to 0.76 ± 0.25 μm. Myopic LASIK is known to increase ocular and corneal positive SA and coma. When comparing the SA measured at 1 month after LASIK with pre-operative values (Figure 1b), we found a small but statistically significant increase of SA for both the eye (0.084 ± 0.075 μm; p = 0.016) and the cornea (0.153 ± 0.056 μm; p < 0.001), with no significant change in internal SA (–0.036 ± 0.079 μm; p = 0.18). We also found a statistically significant increase of average ocular (0.172 ± 0.107 μm; p < 0.01) and corneal (0.148 ± 0.133 μm; p = 0.016) third-order coma. Post-op average third-order trefoil was also higher than pre-op values for the cornea (0.123 ± 0.060 μm; p < 0.001) but not for the eye (0.011 ± 0.060 μm; p = 0.35).

The study of optical changes during the follow-up revealed no significant changes of high-order aberrations RMS (p = 0.07) or coma (p = 0.58) after standard myopic LASIK. However, there was a small but statistically significant increase of both ocular (0.091 ± 0.058 μm; p < 0.01) and corneal (0.062 ± 0.045 μm; p < 0.01) SA. This supposed a posterior increase of the comparatively low average ocular (0.163 ± 0.219 μm) and corneal (0.366 ± 0.131 μm) SA found at 1 month after myopic LASIK. No change in internal SA over time was found. These results were the same when including only one eye per subject (n = 12 instead of 22 eyes), for the whole follow-up, with no significant temporal variation of ocular high-order aberrations RMS (p = 0.16) or ocular coma (p = 0.45), but a significant change of ocular SA (p = 0.02).

We compared the average ocular MTF, considering only the high-order aberrations, to determine the possible contributions to the small changes in the eye’s optical quality. Figure 2 shows a noticeable decrease of the MTF due to LASIK that remained maintained stable during the rest of the follow-up. Results on related Strehl ratio (SR) are shown on Figure 3. We found a statistically significant decrease from pre-op values in SR 1 month after LASIK (–0.063 ± 0.034; p < 0.001), showing no significant

**Figure 1.** Mean ocular (circles), corneal (triangles) and internal (squares) aberrations, measured before and 1, 4, 13, 17, 26 and 39 weeks after standard myopic LASIK for a 6 mm pupil size. (a) High-order aberrations RMS (green). (b) Fourth-order spherical aberration (c; blue). Dashed line indicates surgical treatment. Bars represent standard deviation.
change during the rest of the follow-up (0.003 ± 0.013; p = 0.31).

Although on average, patients did not suffer changes in aberrations after standard myopic LASIK, except for a minor increase of SA, our results show a large inter-subject variability (Figure 1b) that indicates different patterns of variation of the SA depending for each specific patient. Figure 4 shows pre-op, 1 month post-operative and 6 month post-op ocular SA for all eyes included in the study. Eyes included on the left graph (n = 16) showed a significant increase of ocular SA after myopic LASIK (0.139 ± 0.078 μm; p < 0.001), but remained nearly stable during the following months after the surgery (0.025 ± 0.033 μm; p = 0.06). The values for the rest of the eyes are depicted in the right graph (n = 6). In this case, they did not exhibit significant changes in the ocular SA after LASIK, but they had a significant increase of ocular SA during the next 5 months (0.257 ± 0.093 μm; p < 0.001). This increase remained at the ninth month after LASIK (0.236 ± 0.040 μm). These six eyes also presented a comparatively higher increase in coma after LASIK (0.446 ± 0.231 μm; p = 0.002) than the rest of the group (0.062 ± 0.072 μm; p = 0.04). However, coma did not significantly change during the rest of the follow-up (p = 0.41). Figure 5 shows the 6-mm ocular wavefront aberration, along with the values of SA and coma, before (left) and during the first 6-month post-op follow-up (right) for the three subjects showing a significant increase in ocular SA during the follow-up. Myopic LASIK increased ocular coma, which could be due to a small ablation decentration. The temporal evolution of coma after surgery did not follow a clear trend. For example, the right eye of subject MCAG, showed an increase of ocular positive SA between the first and the sixth month, followed by a slight decrease of ocular coma; while for the left eye (LE), with a similar increase of positive SA, there was nearly a 50% increase in ocular coma; these eyes had a higher pre-op refraction (mean sphere: 5.79 ± 0.81 D; range: 5.00 to 7.00 D; mean cylinder: 0.67 ± 0.34 D; range: 0.25 to 1.25 D), compared to the rest of eyes (n = 16; mean sphere: 3.02 ± 1.27 D; range: 0.5 to 5.00 D; mean cylinder: 0.55 ± 1.14 D; range: 0.25 to 3.00 D).

Discussion

Increased ocular high-order aberrations after myopic LASIK decreased the overall optical quality in terms of the ocular MTF, without significant changes during the 9-month follow-up. Related average SR showed a clear decrease due to myopic LASIK, showing little changes during the follow-up. The changes in mean values and dispersion of the SR during the postoperative follow-up (Figure 3) were related to small changes in ocular aberrations during this period, but without a significant trend. Previous studies reported slight improvement in contrast sensitivity after standard myopic LASIK. With a MTF stable over time after the surgery, the role of neural adaptation could account for this increase in contrast sensitivity.

We found an average twofold increase of ocular and corneal high-order aberrations RMS from preoperative values to those found at 1 month after myopic LASIK. The increase affected mainly third-order coma and fourth-order SA, although the latter to a lower extent than in previous studies. This lower increase of aberrations could be due to the selected group of patients
with low or medium myopic pre-op refractive errors. We found a slight increase of the aberrations of the internal media. However, results of internal media aberrations should be considered with caution as the method used to estimate the internal aberrations, suppose that both the corneal and ocular aberrations are calculated.

**Figure 4.** Example of changes on ocular aberrations after standard myopic LASIK. Most measured eyes suffered a small or moderate increase of positive ocular SA at 1 month after myopic LASIK, showing little or no change during the next 5 months after surgery (left). But we also found six eyes showing no increase or even an inversion of ocular SA after myopic LASIK that clearly grew towards positive values during the follow-up (right).

**Figure 5.** Temporal changes of ocular wavefront aberration after myopic LASIK in three subjects (ABSM, JGS and MCAG), for a 6 mm pupil size. Values of ocular SA (blue) and coma (magenta) at 1 week and at 6 months after myopic LASIK are shown.
using the pupil centre as reference for registration, considering a similar pupil size and pupil centre location. This would not be true when corneal topography and ocular aberrometry are obtained for different pupil sizes, as the pupil centre location change with pupil size.\textsuperscript{39} In order to minimize this source of error, we measured with both instruments under similar viewing conditions. When using the HS, we minimized the room illumination in order to obtain a natural pupil size of 6 mm or higher. Corneal aberrations were calculated using the pupil position obtained from the ring image provided by the corneal topographer. Using these images we found that the average pupil diameter was 5.6 ± 0.49 mm, only around 0.5 mm smaller than the pupil size used as reference for ocular aberrations, so that both ocular and corneal aberrations were obtained using nearly the same reference. Corneal aberrations also suffered from the calculation method, as the elevation surface provided by Placido-type topographers may lack accuracy for pupil sizes larger than 4 mm.\textsuperscript{32} Although we found slight changes in internal optics, the limited accuracy of the procedure followed made us to consider such small change as negligible. In this group of patients, most of the ocular optical changes were due to changes on the corneal anterior surface. Apart from the amount of surgically-induced aberrations, which could be reduced by using more advanced laser platforms, our main interest was to understand the possible evolution of the aberrations after surgery and in particular to know the type and nature of the optical changes after refractive surgery that could affect the visual outcome. Our results show that on average, the high-order aberrations remained stable during the 9-month follow-up, although with large inter-subject variability. We only found a minor increase of the average ocular positive SA during the first 9 months, due to the increase found in six eyes (Figure 4; right graph).

In 68% of eyes included in the study the OZ was elliptical, with a major axis of 6.5 mm and a minor axis with a reduction ranging from 0.2 to 1.5 mm, related to the preoperative cylinder ($r^2 = 0.76$). Elliptical OZ was used to save corneal tissue, as it allowed a reduction in ablation along the corneal meridian that needed a higher correction. Most eyes (72%) were treated with a blending zone of $-1$ D of defocus correction over an 8 mm corneal area. According to the Munnerlyn formula,\textsuperscript{40} the corneal ablation depth for the six eyes showing a significant change on their ocular SA (mean was 91.9 ± 12.2 $\mu$m; range was 78.3–108.3 $\mu$m), was equal or higher than the rest of the cases studied. This suggests that a larger ablation depth was related to corneal anterior surface changes during the corneal healing process.

The average increase of coma was not large, and remained stable during the length of the study. We found that the eyes treated for higher preoperative myopia, were those showing larger increases of ocular coma.\textsuperscript{9} Average results during the follow-up suppose little change in ocular, corneal or internal coma during the following 9 months. However, postoperative changes in ocular coma were frequent and subject-dependent. For example (Figure 5), subject ABSM showed a large initial increase of coma in both eyes, that remained during the following months; subject JGS showed a clear reduction of ocular coma, but just in one eye; the right eye of subject MCAG showed a reduction of coma over time, while his left eye showed a nearly 50% increase during follow-up.

Seidel defocus for the whole eye can be obtained from the measured Zernike terms $c_4$, $c_{12}$ and $c_{24}$.\textsuperscript{41} On the other hand, defocus changes associated only with the cornea could also be determined by applying the ray-tracing procedure to the corneal elevations to obtain a defocus difference between cases. We compared the results obtained for the first 6 months after LASIK in the six patients with clear change of ocular SA and found no statistically significant change of ocular defocus towards hyperopia ($-0.56 \pm 0.62$ D; $p = 0.079$). Corneal defocus also showed no significant change also towards hyperopia ($-0.21 \pm 0.68$ D; $p = 0.48$). A change towards hyperopia is consistent with an increasing positive SA. These results have to be considered with caution since the changes were small and showed large inter-subject variability. In addition, the changes in ocular defocus could be affected by minor changes in accommodation during the wavefront sensor measurements.

To our knowledge, there is no previous publication studying the temporal evolution of ocular optics, with detailed measurements of both ocular and corneal aberrations before and after standard myopic LASIK. Although a relatively small sample of 22 eyes may not be sufficient for definitive conclusions regarding the temporal changes of ocular aberrations after myopic LASIK, these results clearly showed the nature and variability of the optical temporal changes. Our results suggest that changes in optical aberrations after myopic LASIK are frequent for the range of myopias and optical zones diameters studied. The increase in ocular positive SA over time could mean that the cornea tend to increase its symmetry during the first months after myopic LASIK. The changes in ocular coma are quite difficult to explain, as we found different behaviours even in the two eyes of the same subject. But overall changes in ocular aberrations seemed a consequence of the natural corneal healing process, modified by ablation depth and centration.

One other important finding of this study is that reported changes in aberrations mainly appeared between the first and the sixth month after surgery. This may suggest the need to wait at least 6 months after myopic
LASIK before comparing outcomes, especially for patients treated for higher myopias.

Acknowledgements

We thank Bart Jaeken for his help on statistical analysis. The authors have no proprietary interest in the present study. Supported by 'Ministerio de Educación y Ciencia', Spain (grants nº FIS2004-2153, FIS2007-64765) and 'Fundación Séneca', Murcia, (grant 04524/GERM/06). None of the authors have commercial relationships related to the subject of this manuscript.

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