

Ocular Aberrations before and after Myopic Corneal Refractive Surgery: LASIK-Induced Changes Measured with Laser Ray Tracing

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PURPOSE. To determine objectively the changes in the ocular aberrations (3rd order and above) induced by myopic LASIK refractive surgery and its impact on image quality.

METHODS. The ocular aberrations of 22 normal myopic eyes (preoperative refraction ranged from -13 to -2 D) were measured before (2.9 ± 4.3 weeks) and after (7.7 ± 3.2 weeks) LASIK refractive surgery using a laser ray tracing technique. A set of laser pencils is sequentially delivered onto the eye through different pupil locations. For each ray, the corresponding retinal image is collected on a CCD camera. The displacement of the image centroid with respect to a reference provides direct information of the ocular aberrations. Root-mean-square (RMS) wavefront error was taken as image quality metric.

RESULTS. RMS wavefront error increased significantly in all eyes but two after surgery. On average, LASIK induced a significant ($P = 0.0003$) 1.9-fold increase in the RMS error for a 6.5-mm pupil. The main contribution was due to the increase (fourfold, $P < 0.0001$) of spherical aberration. The increase in the RMS for a 3-mm pupil (1.7-fold) was also significant ($P = 0.02$). The modulation transfer (computed for 6.5-mm pupil) decreased on average by a factor of 2 for middle-high spatial frequencies.

CONCLUSIONS. (1) Laser ray tracing is a well-suited, robust, and reliable technique for the evaluation of the change of ocular aberrations with refractive surgery. (2) Refractive surgery induces important amounts of 3rd and higher order aberrations. The largest increase occurs for spherical aberration. Decentration of the ablation pattern seems to generate 3rd order aberrations. (3) This result is important for the design of customized ablation algorithms, which should cancel existing preoperative aberrations while avoiding the generation of new aberrations. (*Invest Ophthalmol Vis Sci.* 2001;42:1396-1403)

Refractive surgery has become a popular procedure to treat refractive errors, alternative to conventional spectacle or contact lens wear. The development of new surgical techniques and the improvements in the laser systems have run parallel to a tremendous increase of the number of patients undergoing refractive surgery. Narrow-beam (flying-spot) laser

systems and the incorporation of eye trackers for compensation of eye movements during surgery have lead to better results and to a higher degree of satisfaction by the patients (although complaints of seeing glare and halos at night are not uncommon). The most recently developed LASIK¹ (laser-assisted in situ keratomileusis) technique overcomes many of the problems of the older techniques of radial keratotomy (RK) and photorefractive keratectomy (PRK), such as refraction stability or painful recovery. Other advances include the increase of the diameter of the optical zone (from the initial 4 mm up to 6 mm or higher²) or the ablation of a wider transition zone of 8 or 9 mm to smooth out the steep edges at the border of the ablation zone.

In contrast to the fast evolution of refractive surgery, there has not been such an update of the clinical methods used to evaluate objectively the impact of refractive surgery on the overall optical quality. Routine postoperative evaluation consists mainly of measuring, under photopic conditions (small pupil sizes), subjective refraction, visual acuity, and, in some cases, contrast sensitivity (CSF). Some visual acuity loss, particularly for low contrast charts and dilated pupils has been reported after surgery.^{3,4}

Most of the analysis reported in the literature is based on corneal topography data.⁵⁻⁸ Corneal aberrations are computed from corneal height maps, which provide information on the imaging-forming capability of the cornea alone. Results from different authors indicate that corneal aberrations increase substantially after refractive surgery, which suggests a degradation of the overall image quality.^{5,9}

Although the optical changes induced in refractive surgery occur on the cornea and the anterior corneal surface provides the main contribution to refraction, corneal aberrations are not sufficient to describe the overall optical quality of the eye, because other parameters (position, thickness, and refractive index of the lens, axial length, or pupil centration) also play an important role in image formation. Predictions of the overall optical quality have been made using virtual ray-tracing in model eyes provided with measured¹⁰ or theoretical¹¹ surgical corneal shapes. Nevertheless, the experimental measurement of the overall ocular aberrations is the most direct and accurate way to evaluate the effects of refractive surgery on global image quality, and it can be directly related to visual performance. Several objective techniques are available for the measurement of ocular aberrations,¹²⁻¹⁵ some of which have already been used to measure the effect of refractive surgery on image quality. Campbell et al.¹⁶ collected data in PRK patients and in a control group, using a Hartmann-Shack wavefront sensor, and found a degradation of image quality after PRK. The image analysis was limited to the computation of the aberration at the edge of the pupil, probably because of indexing problems of the particular implementation of the Hartmann-Shack technique used in that study or to the degraded quality of the postsurgical data. Thibos and Hong¹⁷ presented data on one eye measured with a Hartmann-Shack aberrometer both before and on the day after LASIK refractive surgery to

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demonstrate the applicability of the technique and reported the limits to the technique for highly aberrated eyes. To our knowledge, there is only one published quantitative study by Seiler et al.¹⁸ studying in detail the change in the overall ocular aberrations induced by conventional refractive surgery (PRK), for which they used a video-aberroscope of the Tscherning type.¹⁴ This study shows that the overall aberrations increase significantly after surgery especially for large pupils, the spherical aberration becoming the dominant aberration.

In the present article, we show the change of the individual ocular aberrations induced by standard myopic LASIK corneal refractive surgery, by measuring the aberration pattern before and after surgery with a laser ray tracing (LRT) technique.¹⁵ The sequential nature of the LRT (as opposed to the parallel nature of other techniques) permits one to measure large amounts of aberrations and seems especially suitable for pathologic eyes. As concluded by previous studies, we found that with the current standard corneal refractive surgery procedures, the compensation of low-order refractive errors (such as myopia) is associated with the generation of high-order aberrations.

The next generation of refractive surgery procedures is heading toward a customized ablation, aiming at the cancellation of not only low-order aberrations, but also of the individual high-order aberrations.¹⁹⁻²¹ Algorithms to produce an aberration-free eye should also avoid the generation of high-order aberrations (as we show in this article) inherent to standard ablation patterns.⁹

METHODS

Patients and Procedures

We measured the ocular aberrations of 22 eyes from 12 patients (2 men and 10 women), before and after LASIK refractive surgery. Average age was 28 ± 5 years. Preoperative refraction ranged from -13 D to -2.5 D, and preoperative astigmatism was <2.5 D. Besides corneal surgery, all eyes were normal (no corneal or lens opacities and no retinal condition). Postoperative recovery was normal for all patients, and no eye was re-treated. Inclusion in the study did not involve any modification in the surgical procedure. All volunteers were appropriately informed before their participation in the study and gave written informed consent in accordance with institutional guidelines, according to the Declaration of Helsinki.

We analyzed left and right eyes independently for two reasons: (1) recent work indicates that the pattern of aberration is not necessarily symmetric between left and right eyes of the same subject,²² and (2) surgery is conducted independently for left and right eyes. Postoperative measurements were conducted between 24 and 103 days (average, 54 ± 23 days), because recent studies report healing process duration of less than 1 month.³ Surgery and follow-up study of the patients was performed at the Instituto de Oftalmobiología Aplicada, University of Valladolid (Spain). The equipment used for LASIK was a narrow-beam (flying spot) excimer laser (Chiron Technolas 217-C-LASIK; Bausch & Lomb Surgical), with an emission wavelength of 193 nm, a fixed pulse repetition rate of 50 Hz, and a radiant exposure of 400 mJ. The hinged flap, set to 180- μ m depth and 8.5-mm diameter, was cut with a Hansatome microkeratome and was always superior. All patients underwent photoablation of a 6-mm optical zone, with a 9-mm transition zone. The surgery was assisted by the eye tracker in 20 of the 22 eyes.

LRT Measurements

Ocular aberrations were measured using LRT, which is an objective technique developed at the Institute of Optics in Madrid (Spain).^{15,23,24} Subjects' pupils were dilated by instillation of 1 drop of tropicamide 1%, and typically both eyes were measured in a single session. Stabilization was achieved by means of a dental

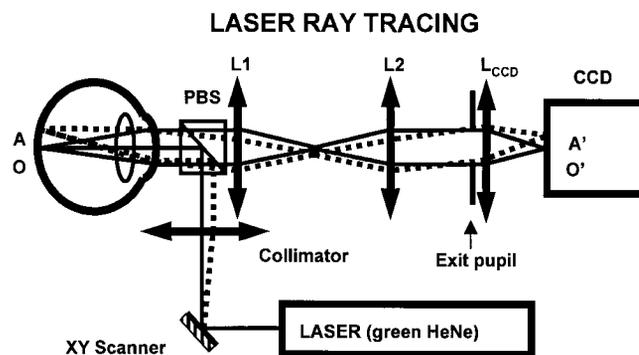


FIGURE 1. Basic setup of the laser ray tracing technique. An unexpanded laser beam is scanned so that it enters the eye sequentially through different pupil locations. One marginal (*dotted line*) and the principal ray (*solid line*) are shown. Each retinal image (A, O) is projected onto a CCD camera (A', O'). The displacement of the image with respect to a reference (A'O'), is proportional to the local derivative of the wave aberration. PBS, polarizing beam splitter.

impression. Each individual run, consisting of 37 rays, lasted between 4 and 14 seconds (depending on the CCD camera used). An entire session (including consent form explanation, dental impression fabrication, pupil dilation, and the recording of five successive runs in similar conditions for each eye) lasted around 45 minutes. Defocus was corrected by means of a trial lens placed in the front of the eye in the manner of spectacles. For patients for whom the trial lens could not be placed closer than 40 mm because of the face anatomy or for spherical errors <5 D, the subject was left uncorrected, because the system allows to perform measurements in eyes with ± 10 D of spherical error without compensation. The eye's pupil is centered to the optical axis of the system by means of a XYZ positioner on which the dental impression is mounted. The eye's pupil is viewed on a TV monitor to ensure a correct centration throughout the experiment.

The basic setup of the LRT technique is depicted in Figure 1. A set of parallel laser pencils is delivered sequentially onto the eye's pupil. The pupil was sampled at steps of 1-mm and by following a hexagonal pattern (37 rays for a 6.5-mm effective pupil). The laser source was a green (543 nm) HeNe laser. Irradiance was at least one order of magnitude below safety standards.²⁵ Each retinal image (associated to a given pupil location) is projected onto a CCD camera and recorded. We compute subsequently the displacement (A'O') of the image's centroid with respect to a reference position, taken as the centroid for the image associated to the center of the pupil (chief ray). This geometrical distance (A'O') is equal (in angular units) to the displacement between the corresponding retinal images (AO).²⁶ AO is proportional to the slope (or derivative) of the wavefront at the pupil position sampled.²⁷ The combined plot of all the image centroids is called "spot diagram," which is a good approximation to the shape of the retinal PSF.²⁸ In the spot diagram associated to an aberration-free eye, all the spots would overlap. As an example, Figure 2A shows the series of 37 images recorded for eye 17 after surgery. Images are arranged according to the associated entry pupil position. Figure 2B shows the corresponding retinal spot diagram. Five runs (each consisting of 37 images) were collected per eye both in the pre- and in the post-LASIK session.

Data Analysis

The wave aberration is described as a Zernike polynomial expansion up to the 7th order.²⁹ The raw data (derivative of the wave aberration for a series of pupil locations) are fitted to the derivatives of the Zernike polynomials to obtain the Zernike coefficients, which describe the aberrations of the eye under test. The average set of Zernike coefficients was computed by fitting all the raw data available from the

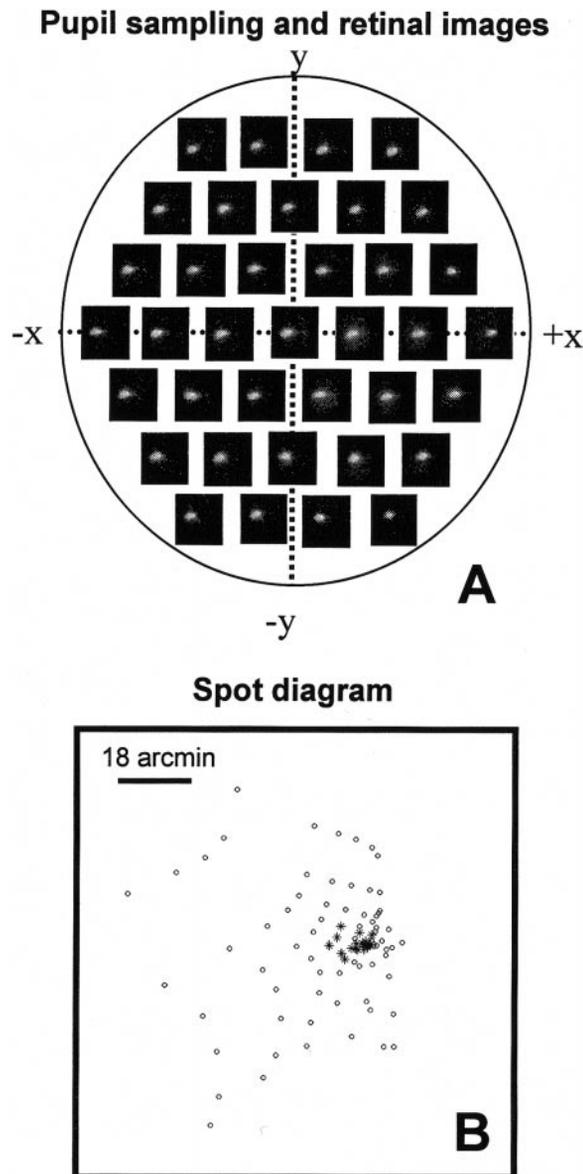


FIGURE 2. (A) Series of images on the CCD, for a single run in a laser ray tracing session on a post-LASIK eye. The position of each image indicates the corresponding entry pupil position. X and y indicate pupil coordinates. Pupil diameter is 6.5 mm. (B) Spot diagram for data set in (A). Symbols represent the centroid of each aerial image (*, entry pupils within a 3-mm pupil; \circ , entry pupils within 6.5-mm pupil). The extent of the retinal field represented is 1.5° .

five individual runs, together with the SD of the coefficients from each run as an estimation of the repetitivity of the measuring technique. The root-mean-square (RMS) wavefront error was used as metric of global image quality, isolating the contribution of the different aberration orders or of the different types of aberrations. With the notation used in this study, the RMS for a particular radial order is computed as the square root of the sum of the squared coefficients for that radial order. Unless otherwise noted, the contribution of the first- (prism) and second-order (defocus and astigmatism) aberrations has not been included, because the main goal was to assess 3rd and higher order aberrations induced by the surgical procedure. The measurements were carried out for a 6.5-mm pupil, but the Zernike coefficients were also recalculated for a smaller, 3-mm pupil. This permits to estimate the contribution of the different pupil regions, neglecting diffraction effects at the optical zone's edge.

RESULTS

Spot Diagrams and Wave Aberration Patterns

Figures 3 and 4 show the spot diagrams (top panels) and contour plots of the wave aberration (bottom panels) before (left panels) and after (right panels) LASIK surgery, for two different eyes (eye 14 for Fig. 3 and eye 9 for Fig. 4; both right eyes). Asterisks stand for data corresponding to a 3-mm pupil diameter, and circles for data up to a 6.5-mm pupil. Positive horizontal coordinates indicate nasal retina for right eyes and temporal for left eyes. Pupil diameter for the wave aberration plots is 6.5 mm and the contour line step is $0.5 \mu\text{m}$. Only 3rd and higher order aberrations have been considered (i.e., we assume best correction of defocus and astigmatism, which can be achieved with conventional lenses). Compensation for the residual defocus and astigmatism (present in both pre- and postsurgery measurements) has been done computationally before generating the spot diagrams and the wave aberration, by canceling the corresponding Zernike coefficients (all Z_1^i and Z_2^j).

In both eyes (which have been selected among those showing most different outcome), preoperative spherical error was similar (-6.86 D for eye 14 and -6.1 D for eye 9). In both cases, LASIK-surgery induces a degradation in optical quality, much more pronounced for eye 14 (Fig. 3) than for eye 9 (Fig. 4). The spot diagrams show this image quality decrease in terms of the spread of the spots (directly related to the spread of the retinal image). For both 3- and 6.5-mm pupil diameters, postoperative spot diagrams appear more spread than preoperative spot diagrams. Increasing the pupil size causes a spread of the spot diagrams, but the impact is much more pronounced in postoperative eyes. In both eyes, wave aberration maps

Best-corrected optical quality of eye #14

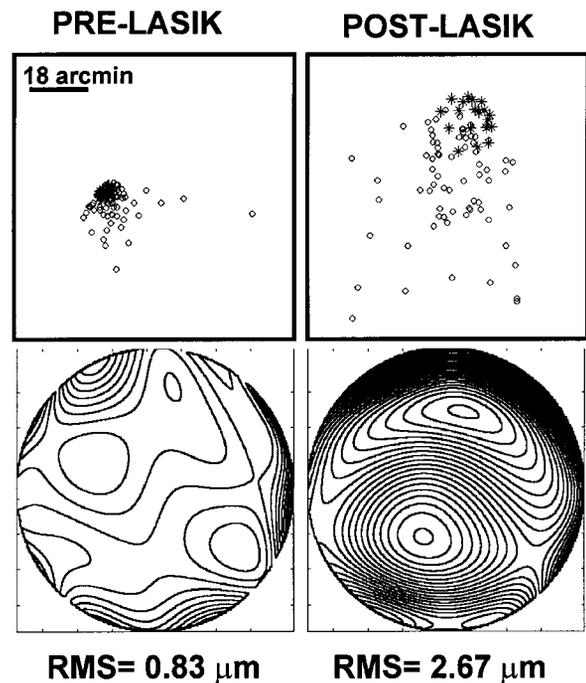


FIGURE 3. Example of preoperative (left) and postoperative (right) results for eye 14. Top: simulated spot diagrams from the fitted Zernike coefficients for a 6.5-mm pupil (\circ) and for a 3-mm pupil (*). Retinal extent, 1.5° . Bottom: wavefront aberration contour plot. Contour line step, $0.5 \mu\text{m}$; pupil diameter, 6.5 mm.

Best-corrected optical quality of eye #9

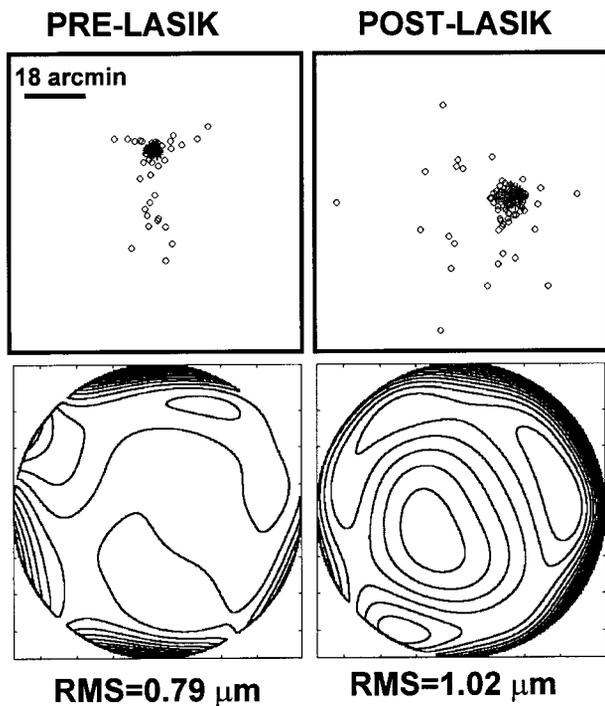


FIGURE 4. Example preoperative (left) and postoperative (right) results for eye 9. See Figure 3 caption and text for explanations.

show an increase in the number of contour lines after surgery, reflecting an increase of the aberrations. Postoperative wave aberration patterns present a characteristic circular region of constant wavefront error, displaced slightly temporally and inferiorly for both eyes. RMS wavefront error associated with 3rd and higher order aberrations is shown before and after surgery in both figures for the 6.5-mm pupil. RMS error for eye 14 increased by a factor of 3.2, whereas eye 9 had a 1.3-fold increase. Spherical aberration increased similarly in both eyes (by a factor of 4.5 for eye 14 and of 3.7 for eye 9). Surgery caused a drastic increase in coma terms for eye 14 (by a factor of 4.2), much higher than for eye 9 (by a factor of 1.2), which is likely to be associated with a decentration of the ablation pattern.

Change in Overall Image Quality (RMS Wavefront Error)

Figure 5 shows the RMS (for 3rd and higher order aberrations), for all 22 eyes, before (white bars) and after (black bars) LASIK

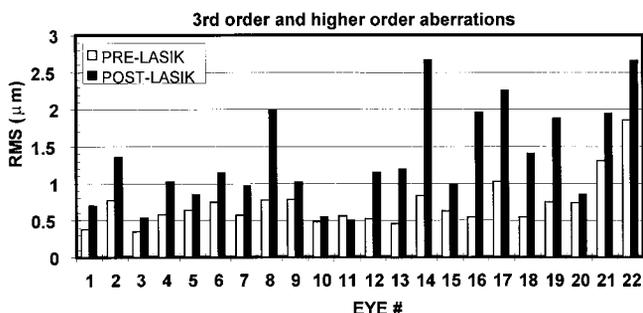


FIGURE 5. RMS wavefront error for 3rd and higher order aberrations, for the 22 participant eyes, before (□) and after (■) LASIK refractive surgery. Data are sorted by ascending preoperative defocus.

surgery, for a 6.5-mm pupil. Eyes are sorted by preoperative spherical error. Eyes 1 to 12 had preoperative myopic spherical errors below 6.5 D, whereas eyes 13 to 22 had errors between 6.5 and 13 D.

There is a great intereye variability, greater for postoperative RMS values (SD, 0.66 μm) than for preoperative values (SD, 0.33 μm). There is some dependence of RMS with preoperative refraction error³⁰: 66% of the low and moderate myopic eyes (eyes 1-12) had preoperative RMS > 0.5 μm, whereas 100% of the high myopic group (eyes 13 through 22) exceeded 0.5 μm. Also, the largest postoperative RMSs are found in the more myopic group. For all subjects except two (10 and 11), postoperative RMS is significantly higher than preoperative RMS, although there is also a great intereye variability. The increment in RMS ranged from -0.06 to 1.84 μm. Mean measurement variability (SD) was 0.12 μm, so that this increase is significant in all but the two mentioned eyes. In terms of ratios, postoperative RMS/preoperative RMS ranged from 0.9 to 3.6.

Table 1 (first row) shows the average (±SD) preoperative and postoperative RMS wavefront error and average increase in RMS ratio (post-RMS/pre-RMS) with LASIK surgery for this group of patients, for a 6.5-mm pupil (columns 1-3) and for a 3-mm pupil (columns 6-8). The increase in aberrations induced by surgery is smaller for 3 than for 6.5 mm. If we exclude 2nd order aberrations (defocus and astigmatism), the average increase of the wavefront error is approximately 67%. The increase of RMS for a 6.5-mm pupil is highly statistically significant ($P < 0.0003$) and marginally statistically significant for a 3-mm pupil ($P = 0.0212$), as shown in columns 4 and 9, respectively.

Spherical Aberration

Figure 6 shows preoperative (white bars) and postoperative (black bars) values of the RMS spherical aberration, for a 6.5-mm pupil. It appears as positive in all cases, because it is given in terms of the RMS corresponding to Z_4^0 and Z_6^0 .²⁹ Eyes are sorted by increasing myopic spherical error, as in Figure 5. There is a dramatic increase in spherical aberration after LASIK in all but three eyes (1, 10, and 11). The spherical-aberration RMS increase ranged from 0.002 to 0.97 μm. Table 1, row 5, shows the average increase of spherical aberration (by a factor of 3.99) in this group of eyes, which is highly statistically significant ($P < 0.0001$). For a 3-mm pupil, the RMS corresponding to spherical aberration increases by a factor of 7.48 on average, and this increase is again significant ($P = 0.002$). The increase of 4th order aberration terms (Table 1, row 3) is mostly due to the increase in spherical aberration. The fact that the asphericity of the cornea changes with surgery (from a prolate to an oblate shape or from negative to positive asphericity) is reflected in a change of spherical aberration toward

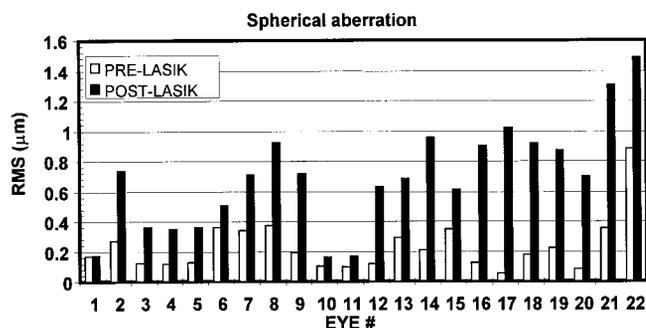


FIGURE 6. Root-mean-square wavefront error (RMS) for spherical aberration (Z_4^0 and Z_6^0), before (□) and after (■) LASIK refractive surgery. Data are sorted by ascending preoperative defocus.

TABLE 1. Preoperative and Post-LASIK Average RMS Wavefront Error

RMS (μm)	6.5-mm Pupil				3-mm Pupil				
	Preoperative*	Post-LASIK*	Average Ratio (Post/Pre)†	P‡	Seiler's Ratio (Post/Pre)§	Preoperative*	Post-LASIK*	Average Ratio (Post/Pre)†	P‡
3rd to 7th order ($Z_3^i, Z_4^i, Z_5^i, Z_6^i, Z_7^i$)	0.72 ± 0.33	1.34 ± 0.66	1.91	0.0003	4.20 (>0.0001)	0.081 ± 0.035	0.136 ± 0.1	1.74	0.0212
3rd order (Z_3^i). Coma-like	0.54 ± 0.30	1.01 ± 0.62	2.10	0.0028	4.7 (0.007)	0.076 ± 0.036	0.127 ± 0.10	1.78	0.0308
4th order (Z_4^i)	0.33 ± 0.18	0.77 ± 0.34	2.51	<0.0001	4.11 (0.008)	0.025 ± 0.009	0.041 ± 0.02	1.69	0.0026
5th and higher orders (Z_5^i, Z_6^i & Z_7^i)	0.28 ± 0.13	0.34 ± 0.14	1.32	0.1698	3.90	0.011 ± 0.006	0.017 ± 0.01	1.77	0.0408
Spherical aberration (Z_4^0 and Z_6^0)	0.23 ± 0.18	0.69 ± 0.35	3.99	<0.0001		0.013 ± 0.01	0.028 ± 0.02	7.48	0.002

* Values are means ± SD.

† Computed as the average of the RMS increase-factor of each individual eye.

‡ Paired t-test.

§ Seiler et al. compute the variance of the wavefront error, which is equivalent to the squared-RMS. What is shown in the table is the square root of the values reported by this group. Values in parentheses are P values.

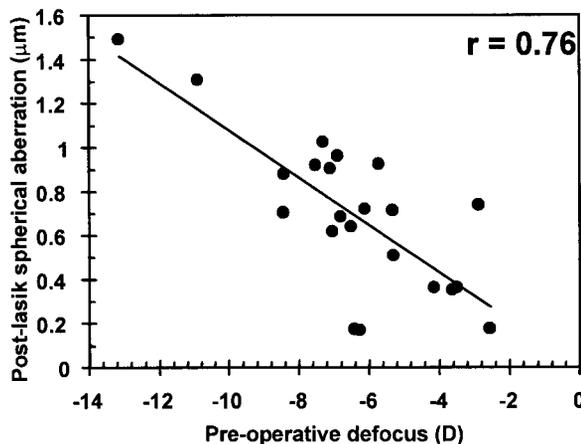


FIGURE 7. Correlation between preoperative spherical error and induced postoperative spherical aberration (RMS). The solid line represents the linear regression of the data ($r = 0.76, P < 0.0001$).

more negative values, i.e., more myopic at the pupil edges (mean $Z_4^0 = -0.13$ preoperatively and -0.68 postoperatively). Figure 7 shows that the increment of spherical aberration is directly related to the preoperative refraction: the larger the correction, the larger amount of spherical aberration is induced by LASIK. Symbols represent individual data, and the solid line denotes a linear regression to the data. The increase is highly statistically significant ($r = 0.76; P < 0.0001$). A slightly higher correlation coefficient ($r = 0.88$) is found when the spherical equivalent correction programmed in the laser system (i.e., attempted correction) is used in the calculation. However, there is a good agreement between the preoperative spherical error derived from the Zernike polynomial expansion and the value used in the surgery ($r = 0.98$ D, average difference = 1.02 D). Two eyes (10 and 11) do not seem to follow the mentioned trend; they have postoperative spherical-aberration RMS below $0.2 \mu\text{m}$ while having a preoperative myopia of >6 D.

Coma and Higher Order Aberrations

Although the increase in spherical aberration is very systematic, there is a high intereye variability in the amount of coma induced. Increase in coma is not correlated with preoperative spherical error. Figures 3 and 4 illustrated two eyes (9 and 14) with similar preoperative refraction, similar induced postoperative spherical aberration and very different outcomes in terms of coma. Table 1, row 2 shows the average RMS preoperative and postoperative values corresponding to 3rd order (coma-like terms), along with the SDs and average increase. For a 6.5-mm pupil, coma-like terms increase on average by a factor of 2.1 ($P = 0.0028$). For a 3-mm pupil, the increase is marginally significant. Excluding the two eyes operated without the assistance of an eye tracker, 3rd order aberrations increase by a factor of 1.8 ($P = 0.0026$).

We did not find any significant increase in high order terms (5th and higher), either for a 6.5- or a 3-mm pupil. The corresponding pre- and postoperative values, SDs, average increase and P values are shown in Table 1, line 4.

Modulation Transfer Function

Modulation Transfer Functions (MTF; contrast loss as a function of spatial frequency) before and after surgery was computed for each eye from the corresponding wave aberration, assuming a 6.5-mm pupil and ignoring apodization imposed by the Stiles-Crawford effect. Contribution of tilts, defocus, and astigmatism (all Z_1^i and Z_2^j)²⁹ was cancelled.

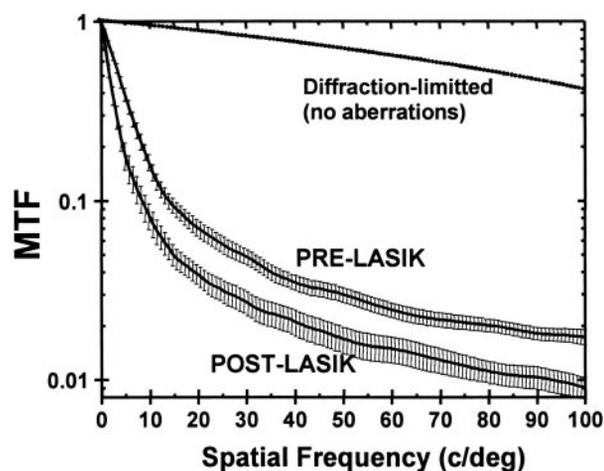


FIGURE 8. Average MTF (radial profile) before and after LASIK, computed from the wave aberration, and for a 6.5-mm pupil diameter and 543 nm. The *solid lines* are the average across 22 eyes, and the *bars* are the SE for selected frequencies. The diffraction-limited MTF is included for comparison purposes.

Figure 8 shows the average MTF (logarithmic scale, radial profile) for the pre- and the post-LASIK eyes, together with the corresponding diffraction-limited MTF (6.5-mm pupil diameter and 543-nm wavelength) for comparison purposes. Error bars represent \pm SE across eyes. There is a significant contrast loss for all spatial frequencies. As an example, the MTF for 30c/deg decreases by a factor of 2, on average.

DISCUSSION

As in previous studies, most based on psychophysical measurements or on corneal topography, we found that the best-corrected image quality degrades after corneal refractive surgery. Because we measured aberrations of the entire optical system, these results can be more directly related to image quality and visual performance. In the following subsections, we compare our results with those previously reported in the literature and discuss the potential sources of aberrations and the implications of our results.

Comparison with Previous Studies

Although a direct comparison across studies is limited by the particular surgical procedures and the group of patients under test, we can get some insight on (i) the average differences in the optical quality and visual performance outcomes provided by the different surgical techniques and (ii) the complementary information provided by the different methods of evaluation (corneal topography, visual performance, and overall aberration measurements).

Differences in the surgical procedures include the following: (1) type of surgery (RK, PRK, or LASIK); (2) ablation zone and transition zones diameters; (3) type of laser (wide beam with a variable-size diaphragm or narrow-beam flying spot laser); (4) presence or not of an eye tracker to compensate for eye movements; (5) surgeon's choice of reference axis; and (6) type of microkeratome and flap cutting procedures. Differences in the population under test include the following: (1) different age groups; (2) different preoperative spherical error range; and (3) different preoperative astigmatism and higher order aberration pattern.

Studies Based on Corneal Aberrations. Our results agree well with previous studies based on corneal topogra-

phy data, which also report that corneal aberrations increase substantially after refractive surgery, suggesting a degradation of overall image quality. Applegate et al.⁸ reported an increase of corneal aberrations of RK patients at large pupil sizes, which was highly correlated with the decrease of visual performance (CSF). Verdon et al.⁴ found similar results for PRK patients. Oshika et al.⁵ found an increase of 3rd and higher order corneal aberrations (2.7-fold for LASIK and 2.3-fold for PRK), with respect to preoperative values in the same eyes, comparable with the 1.91-fold increase found in the present study for overall aberrations after LASIK surgery. We found a greater relative contribution of spherical aberration, which increases with the level of attempted correction. The correlation between preoperative refraction and induced spherical aberration agrees with results by Schwiegerling,⁹ by Martinez et al.,⁶ and by Applegate et al.⁸ for corneal aberrations alone or by Hersh et al.³¹ based on postoperative corneal asphericity.

Studies Based on Wave Aberration Measurements. To our knowledge, there is only one published quantitative study¹⁸ on the changes in individual optical aberrations induced by standard refractive surgery (PRK). In this study the total wavefront error (RMS), excluding first- and second-order aberrations, increases by a factor of 4.2 on average ($P < 0.001$). However, such increase was found to be statistically significant ($P < 0.05$) only for large pupils (6–7 mm), whereas we find it significant for both large (6.5-mm) and small (3-mm) pupils. Although in preoperative eyes third-order aberrations are dominant, Seiler et al. found that 4th-order aberrations (spherical-type) dominated on postoperative eyes. We found that 3rd order aberrations are still dominant after surgery, despite the fact that the patients in our study presented higher preoperative myopia (−6.5 D on average, as opposed to −4.8 D in Seiler's), which tends to induce larger amounts of spherical aberration. This difference might be due to higher induction rates of spherical aberration for a given attempted correction in the surgical procedure used on the patients from Seiler's study. Table 1 displays the increase ratios obtained in this study and by Seiler et al. Note that they fitted 27 Zernike coefficients (up to 6th order), whereas we fitted 35 (up to 7th order). Although both studies show a significant degradation of best-corrected optical quality after refractive surgery, we found an average RMS increase half of that found by Seiler et al. Intersubject variability is smaller in our group of patients (lower P values). Differences between the surgical techniques (PRK in Seiler et al. study, LASIK in our study) may be the main reason for the discrepancy. Although some authors have reported better outcome for PRK in terms of optical quality from corneal topography data,⁵ we believe that part of the difference is due to the improved system used in the surgery reported here (i.e., incorporation of an eye tracker device and flying spot laser).

Studies Based on Visual Performance. The change in visual performance after LASIK surgery has been frequently assessed in terms of visual acuity (usually number of lines lost), which, in general, does not suffer a significant decrease. Recent data indicate that most changes occur in contrast sensitivity (CSF), low contrast visual acuity, and visual acuity measured under low illumination (i.e., with large pupils). A decrease in the MTF for large pupils, as that shown in Figure 8 must be directly correlated to a decrease in CSF at low light levels. This is in agreement with findings by Applegate et al.⁸ on RK patients, who observed a good correlation between the increase in the variance of the corneal wave aberration and the decrease of the area under the CSF.

Causes for the Increase of Ocular Aberrations after Surgery

Corneal Asphericity. Our results show that spherical aberration is the aberration that has the largest increase after refractive surgery. Also, as found in previous studies, induced spherical aberration is highly correlated with preoperative refraction.^{7,9} This indicates that the change in the asphericity of the cornea³¹ induced by current ablation algorithms is the main cause of retinal image quality degradation after conventional LASIK surgery.

Decentration. There seems to be a direct relation between the amount of coma induced and the decentration of the ablation pattern. In many cases the ablation pattern appears slightly decentered. The laser system used in this study was provided with an eye tracker, which maintains centration by compensating for involuntary eye movements. Two eyes (14 and 17) for which the eye tracker was off during surgery had an increase in coma-like aberrations (4.2 and 2.3, respectively) above the average (2.1-fold). The use of an eye tracker might explain the fact that the average increase in coma-like aberrations in our study is less than half the increase found by Seiler et al.¹⁸ (4.7- versus 2.1-fold). Nevertheless, despite the improvement in centration achieved in eye-tracker-assisted surgeries, it seems to be a factor that can be still further improved and that could reduce considerably the impact of surgery on image quality. In agreement with Tsai et al.,³² our results suggest that an eye tracker helps to avoid severe decentration but does not ensure a perfect centration.

Corneal Irregularities. We have found a slight increase of 5th and higher order aberrations, not statistically significant ($P = 0.17$), which is in agreement with Seiler et al.¹⁸ In their study, 5th and higher order aberrations had an average 3.9 increase, but the increase was significant only for 2 of the 13 coefficients. It seems that the impact of surgery occurs on 3rd and 4th order aberrations, whereas 5th and higher remain almost unaffected. This might suggest that PRK and LASIK do not induce microirregularities in the cornea (at least of sizes larger than the measurement beam size, which is 0.5 mm in our study).

Haze. Corneal haze is due to the presence of stromal opacities induced by refractive surgery (probably caused by an increased reflectivity of anterior stromal wound healing keratocytes),³³ which produces a loss of corneal transparency, and to increased scattering. The LRT technique is unable to quantify effects operating at scale below the beam size, and therefore an objective evaluation of the contribution of corneal haze should be addressed by other methods.

Wound Healing. Histologic experiments have shown that wound healing is a major cause of refractive instability and intersubject variability outcomes. Although stromal reaction seems to be less extensive in LASIK than PRK, it is still one of the main concerns on the operation outcomes.^{34,35} Wound healing is expected to be similar in left and right eyes of the same patient, and therefore its impact on the aberration pattern should not change between eyes of the same subject. The correlation between the left and right RMS wavefront does not decrease significantly after surgery (coefficient of correlation: preoperative, $r = 0.65$; postoperative, $r = 0.58$). The major difference comes from coma-like terms ($r = 0.45$ and $r = 0.41$, respectively), which depends on centration during surgery (and therefore is independent between eyes), whereas the correlation between left and right eyes for spherical aberration remains unchanged ($r = 0.84$ and $r = 0.84$, respectively). The fact that the two eyes not following the trend in Figure 7 (those who experienced little increase in spherical aberration despite having >6 D of preoperative myopia) correspond to the same subject may suggest a potential role of wound healing on the surprisingly good outcome for this patient.

Time after Surgery. Wave aberration measurements were conducted from 24 to 103 days after surgery. Although refractive stability after LASIK seems to be achieved in a short period, one may argue that differences in the recovery time across eyes may be influencing the results. For a group of eyes with close preoperative spherical errors (-5.25 through -7.5 D), we did not find any correlation between time after surgery and RMS wavefront error ($r = 0.11$).

Implications of Our Results

Our results confirm that standard refractive surgery procedures induce considerable amounts of 3rd and higher order overall aberrations. Their impact increases notably for large pupil sizes, which explains reported experience of night vision problems, such as halos.³⁶ The decrease in contrast modulation predicted by our measurements explains a decrease of the CSF under low light levels or of the low contrast visual acuity.³ The presence of asymmetrical aberrations affects not only the modulus of the optical transfer function (MTF), but also its phase. A phase change can cause ghost or double images, contrast reversals, and halos, which are not necessarily detected during clinical routine measurements. Thus, the objective measure of overall aberrations results on a fast and valuable method to evaluate the outcomes of refractive surgery, in many ways more complete than standard clinical subjective procedures.

Our results show the lowest reported degree of image quality degradation after conventional (non-wavefront-guided) myopic LASIK surgery, which suggests that procedures, laser systems, and algorithms have improved over the years. However, the amount of spherical aberration induced, inherent to the ablation profile, suggests that further improvements are needed. Schwiegerling⁹ computed the ideal ablation pattern for a particular eye that would minimize the impact of spherical aberration while correcting the spherical error. He found that this ideal pattern would require a deeper ablation of the central cornea and a more abrupt transition at the edge of the optical zone, which is a drawback, particularly for higher attempted corrections.

The knowledge of the individual aberration pattern before surgery has attracted surgeons to the idea of surgically canceling not only conventional refractive errors, but also the higher order aberrations naturally occurring in each eye (customized ablation). The first wavefront-guided refractive surgeries have already been carried out,^{19,20} with variable results. From ours as well as from previous data in the literature, it becomes clear that, before the cancellation of existing high-order aberrations, design of optimal ablation algorithms and procedures avoiding new aberrations while attaining the desired refractive error correction is essential. The impact of wound healing on a fine corneal topography-sculpture still remains unclear, and other alternatives (such as customized intraocular lenses) are being suggested.³⁷

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References

1. Pallikaris IG, Papatzanaki ME, Siganos DS, Tsimilbaris MK. A corneal flap technique for laser in situ keratomileusis: human studies. *Arch Ophthalmol*. 1991;109:1699-1702.
2. Gartry DS, Kerr MG, Marshall J. Excimer laser photorefractive keratectomy—18-month follow-up. *Ophthalmology*. 1992;99:1209-1219.
3. Holladay JT, Dudeja DR, Chang J. Functional vision and corneal changes after laser in situ keratomileusis determined by contrast

- sensitivity, glare testing and corneal topography. *J Cataract Refract Surg.* 1999;25:663-669.
4. Verdon W, Bullimore M, Maloney RK. Visual performance after photorefractive keratectomy. A prospective study. *Arch Ophthalmol.* 1996;114:1465-1472.
 5. Oshika T, Klyce SD, Applegate RA, Howland HC, El Danasoury MA. Comparison of corneal wavefront aberrations after photorefractive keratectomy and laser in situ keratomileusis. *Am J Ophthalmol.* 1999;127:1-7.
 6. Martinez C, Applegate R, Klyce S. Effects of pupillary dilation on corneal optical aberrations after photorefractive keratectomy. *Arch Ophthalmol.* 1998;116:1053-1062.
 7. Oliver K, Hemenger R, Corbett M. Corneal optical aberrations induced by photorefractive keratectomy. *J Refract Surg.* 1997;13:246-254.
 8. Applegate RA, Howland HC, Sharp RP, Cottingham AJ, Yee RW. Corneal aberrations and visual performance after radial keratotomy. *J Refract Surg.* 1998;14:397-407.
 9. Schwiegerling J, Snyder RW. Corneal ablation patterns to correct for spherical aberration in photorefractive keratectomy. *J Cataract Refract Surg.* 2000;26:214-221.
 10. MacRae S, Schwiegerling J, Snyder SW. Customized and low spherical aberration corneal ablation design. *J Refract Surg.* 1999;2(suppl):246-248.
 11. Klonos GG, Pallikaris J, Fitzke FW. A computer model for predicting image quality after photorefractive keratectomy. *J Refract Surg.* 1996;12:S280-S284.
 12. Walsh G, Charman WN, Howland HC. Objective technique for the determination of monochromatic aberrations of the human eye. *J Opt Soc Am A.* 1984;1:987-992.
 13. Liang J, Grimm B, Goelz S, Bille JF. Objective measurement of wave aberrations of the human eye with the use of a Hartmann-Shack wave-front sensor. *J Opt Soc Am A.* 1994;11:1949-1957.
 14. Mierdel P, Krinke HE, Wiegand W, Kaemmerer M, Seiler T. Measuring device for determining monochromatic aberration of the human eye. *Ophthalmologie.* 1997;94:441-445.
 15. Navarro R, Losada MA. Aberrations and relative efficiency of light pencils in the living human eye. *Optom Vis Sci.* 1997;74:540-547.
 16. Campbell MW, Haman H, Simonet P, Brunette I. Dependence of optical image quality on refractive error: eyes after excimer laser photorefractive keratectomy (PRK) versus controls [ARVO Abstract]. *Invest Ophthalmol Vis Sci.* 1999;40(4):S7. Abstract nr 34.
 17. Thibos LN, Hong X. Clinical applications of the Shack-Hartmann aberrometer. *Optom Vis Sci.* 1999;76:817-25.
 18. Seiler T, Kaemmerer M, Mierdel P, Krinke H-E. Ocular optical aberrations after photorefractive keratectomy for myopia and myopic astigmatism. *Arch Ophthalmol.* 2000;118:17-21.
 19. Mrochen M, Kaemmerer M, Seiler T. Wavefront-guided Laser in situ Keratomileusis: Early results in three eyes. *J Refract Surg.* 2000;16:116-121.
 20. Liedel KK, Campin JA, Petit GH, McDonald MB. Patient treatments based on wavefront-guided custom cornea corrections [ARVO Abstract]. *Invest Ophthalmol Vis Sci.* 2000;41(4):S689. Abstract nr. 3667.
 21. Alessio G, Boscia F, La Tegola MG, Sborgia C. Topography-driven photorefractive keratectomy: results of corneal interactive programmed topographic ablation software. *Ophthalmology.* 2000;107:1578-1587.
 22. Marcos S, Burns SA. On the symmetry between eyes of wavefront aberration and cone directionality. *Vision Res.* 2000;40:2437-2447.
 23. Moreno-Barriuso E, Navarro R. Laser Ray-Tracing versus Hartmann-Shack. Sensor for measuring optical aberrations in the human eye. *J Opt Soc Am A.* 2000;17:974-985.
 24. Moreno-Barriuso E, Marcos S, Navarro R, Burns SA. Comparing Laser Ray Tracing, Spatially Resolved Refractometer and Hartmann-Shack sensor to measure the ocular wavefront aberration. *Optom Vis Sci.* 2001;78:152-156.
 25. American National Standard Institute. *American National Standard for the Safe Use of Lasers, Standard Z-136.1-1993.* Orlando, FL: The Laser Institute of America; 1993.
 26. Navarro R, Moreno E, Dorronsoro C. Monochromatic aberrations and point-spread functions of the human eye across the visual field. *J Opt Soc Am A.* 1998;15:2522-2529.
 27. Born M, Wolf E. *Principles of Optics*, 6th ed. Oxford, UK: Pergamon Press; 1993.
 28. Navarro R, Losada MA. Aberrations and relative efficiency of light pencils in the living human eye. *Optom Vis Sci.* 1997;74:540-547.
 29. Thibos LN, Applegate RA, Schwiegerling JT, Webb RH. Members VST Standards for reporting the optical aberrations of eyes. *Vision Science and its Applications TOPS Volume.* 2000;35.
 30. Marcos S, Moreno-Barriuso E, Llorente L, Navarro R, Barbero S. Do myopic eyes suffer from larger amount of aberrations? In: Thorn F, Troilo D, Gwiazda J, eds. *Proceedings of the 8th International Conference on Myopia*, Boston, MA. 2000:118-121.
 31. Hersh PS, Shah SI, Holladay JT. Corneal asphericity following excimer laser photorefractive keratectomy. Summit PRK Topography study group. *Ophthalmic Surg Lasers.* 1996;27:S421-28.
 32. Tsai YY, Lin JM. Ablation centration after active eye-tracker-assisted photorefractive keratectomy and laser in situ keratomileusis. *J Cataract Refract Surg.* 2000;26:28-34.
 33. Moller-Pedersen T, Cavanagh HD, Petroll WM, Jester JV. Stromal wound healing explains refractive instability and haze development after photorefractive keratectomy: a 1-year confocal microscopic study. *Ophthalmology.* 2000;107:1235-1245.
 34. Wachtlin J, Langenbeck K, Schrunder S, Zhang EP, Hoffmann F. Immunohistology of corneal wound healing after photorefractive keratectomy and laser in situ keratomileusis. *J Refract Surg.* 1999;15:451-458.
 35. Park CK, Kim JH. Comparison of wound healing after photorefractive keratectomy and laser in situ keratomileusis in rabbits. *J Cataract Refract Surg.* 1999;25:842-850.
 36. Brunette I, Gresse J, Boivin J, et al. Functional outcome and satisfaction after photorefractive keratectomy: Part 2: survey of 690 patients. *Ophthalmology.* 2000;107:1790-1796.
 37. Werbling TP. Multicomponent intraocular lenses. *J Refract Surg.* 1996;12:187-189.