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Susana Marcos

Institutions: Spanish National Research Council

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Aberrations and Visual Performance Following Standard Laser Vision Correction

Susana Marcos, PhD

ABSTRACT

PURPOSE: To relate the change of ocular aberrations with the change of visual performance produced by standard laser in situ keratomileusis (LASIK) for myopia.

METHODS: Aberrations and visual performance were measured before and after surgery in 22 eyes. Total aberrations were measured using a laser ray tracing technique. Corneal aberrations were obtained using a commercial videokeratoscope and custom software. Visual performance was evaluated in terms of best spectacle-corrected contrast sensitivity and high-contrast visual acuity.

RESULTS: The amount of total and corneal aberrations increased with LASIK in all except two eyes. In general, the total and corneal aberration patterns were well-correlated after LASIK. However, the anterior corneal surface alone did not capture all the information (ie, possible changes induced on the posterior corneal surface or interactions between the different ocular components), which suggests that total aberrations are better predictors of visual performance. The decrease of the modulation transfer function (both in terms of area under the curve or as a function of spatial frequency) with LASIK accounted for most of the decrease in contrast sensitivity. High-resolution visual acuity was not very sensitive to the LASIK-induced changes in image quality.

CONCLUSION: Wavefront and total aberration measurements, and in particular a combination of the two techniques, provide useful information for understanding the optical changes induced by standard refractive surgery. Predictions of the change in modulation transfer function derived from wave aberrations matched measurements of change in contrast sensitivity. [*J Refract Surg* 2001;17: S596-S601]

The development of videokeratoscopes capable of recording corneal shape in detail, and aberrometers that measure the wave aberration of the optics of the entire eye, have revealed that although standard laser refractive surgery eliminates conventional refractive errors, higher order errors (particularly spherical aberration) are typically induced.[1-3] Numerous reports in the literature evaluate visual performance after laser in situ keratomileusis (LASIK)[4,5], but only a few attempt to characterize the correlation between visual performance and optical aberrations (in particular, the aberrations of the anterior corneal surface) induced by refractive surgery.[6] We compared corneal and total aberrations as well as visual performance before and after standard LASIK for myopia in a group of patients. Although most of the changes induced by LASIK occur on the anterior corneal surface, the total wave aberration captures possible changes of the posterior corneal surface and interactions between the different optical components, and therefore should predict visual outcomes more accurately. We report a good correlation between the decrease of contrast sensitivity function after LASIK and the decrease in the modulation transfer function (computed from the total wave aberration).

PATIENTS AND METHODS

Total Aberrations: Laser Ray Tracing

Wave aberrations were measured using laser ray tracing, a technique developed by Navarro and colleagues at the Instituto de Optica, Madrid, Spain.[7]

From the Instituto de Optica "Daza de Valdés," Consejo Superior de Investigaciones Científicas, Madrid, Spain.

The author has no proprietary interest in the methods presented herein.

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The author acknowledges Dr. Esther Moreno-Baniuso for her inestimable contributions to the total aberration measurements; Mr. Sergio Barbero for invaluable work in generating custom software for topographic analysis; Ms. Lourdes Llorente for data analysis; Ms. Guadalupe Rodríguez and Mr. Raúl Martín for clinical data collection, and collaborative refractive surgeon, Dr. Jesús Merayo-Lloves, from the Instituto de Oftalmobiología Aplicada, Universidad de Valladolid; Carl-Zeiss Spain for the loan of Atlas Humphrey Corneal Topography System and partial funding of a research fellowship; and CAM08.7/0010.1/2000 and Convenio de Cooperación USA-Spain for research funding.

Correspondence: Susana Marcos, PhD, Instituto de Optica, Consejo Superior de Investigaciones Científicas (CSIC), Serrano 121, 28006 Madrid, Spain. Tel: 34.915616800 x2306; Fax: 34.915645557; E-mail: susana@io.cfmac.csic.es

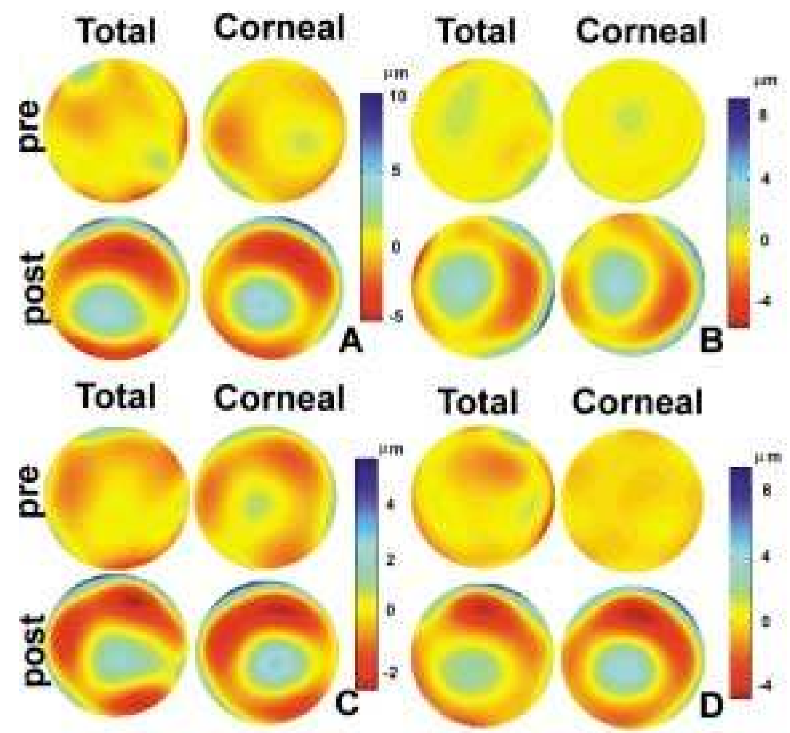

Figure 1. Total and corneal wave aberration maps, before and after standard LASIK for myopia for **A)** eye #14, **B)** eye #16, **C)** eye #18, and **D)** eye #19. Total aberrations measured with laser ray tracing. Corneal aberration measured using a commercial corneal videokeratoscope and custom software. Tilts, defocus, and astigmatism were cancelled. Pupil diameter = 6.5 mm.

This technique provides similar results to Shack-Hartmann and the Spatially Resolved Refractometer in normal eyes, and is appropriate in highly aberrated eyes.[8] In this technique, a set of parallel rays is projected sequentially through 37 different pupil positions (forming a hexagonal array that samples a 6.5-mm pupil). The corresponding aerial retinal images are collected on a high-resolution CCD camera. The deviation of each centroid from the principal ray is proportional to the local slope of the wave aberration. The wave aberration is obtained from the derivatives using a least-mean-squares procedure and described as a seventh order Zernike polynomial expansion. Measurements were performed on dilated pupils. The patient fixated foveally and the eye's pupil was aligned to the optical axis of the instrument. Figure 1 (A, B, C, and D, left panels) shows examples of total wave aberrations for four patients before and after LASIK. Root-mean-square (RMS) wavefront error is typically used as an optical quality metric.

Corneal Aberrations From Corneal Topography

Corneal aberrations were estimated using a placido-disk-based videokeratoscope (Atlas Mastervue Corneal Topography System, Humphrey Instruments-Zeiss, San Leandro, CA) and custom software developed by Sergio Barbero[9] (Instituto de Optica, CSIC, Madrid, Spain) in Matlab (Mathworks, Nathick, MA) and Zemax (Focus Software, Tucson, AZ). In brief, the slopes of the corneal wave aberration were calculated by virtual ray tracing on the corneal elevation, and corneal aberrations were then obtained using a similar procedure to that described for the total aberrations. Since corneal aberrations use the corneal reflex as a reference and total aberrations are measured with respect to the pupil center, a realignment algorithm was applied to allow a direct comparison of corneal and total aberration maps. The small tilt between the videokeratographic axis and the line of sight was not considered. A series of corneal aberration maps were obtained over 6.5 mm, shifting the center at 0.1-mm steps. The difference, total – corneal RMS, was then computed as a function of pupil location. These maps are smooth and show a well defined minimum, slightly decentered from the corneal reflex, which was used as a common axis. Figure 1 (A, B, C and D, right panels) shows examples of corneal wave aberrations for four patients before and after LASIK.

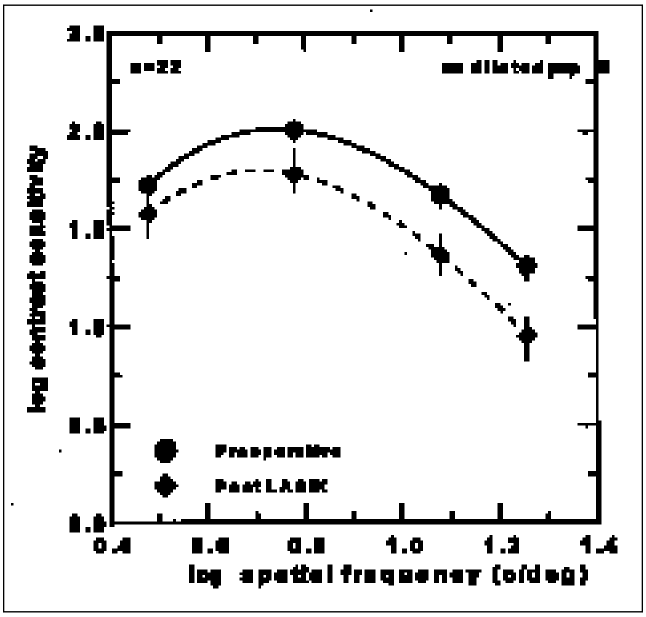

Figure 2. Contrast sensitivity function (average of 22 eyes) before and after LASIK, measured with the CSV-1000E chart. Lines are third order polynomial fits to the data, error bars represent standard error of the mean, with best spectacle-correction and undiluted pupil.

Visual Performance: Contrast Sensitivity Function and Visual Acuity

Visual performance was assessed by means of contrast sensitivity function (with best spectacle correction) and best spectacle-corrected high-contrast visual acuity. Contrast sensitivity was measured using a standard CVS-1000E chart (Vector Vision, Arcanum, OH). This chart uses vertical sinusoidal grids (at 3, 6, 12, and 18 c/deg), a forced double-alternative choice paradigm, and a calibrated luminance of 85 cd/m^2. Figure 2 shows the average contrast sensitivity function (22 patients) before and after LASIK. High contrast visual acuity was measured using a conventional Snellen chart.

Patients and Procedures

Twenty-two eyes from 12 patients (mean age, 28 ± 5 yr; preoperative spherical error, -2.50 to -13.00 diopters [D]) participated in the study. LASIK was performed using a narrow-beam, flying-spot excimer laser (Chiron Technolas 217-C; Bausch & Lomb, Surgical, Dornach, Germany), assisted by an eye-tracker. The flap diameter (performed with a Hansatome microkeratome) was 8.5-mm and the intended depth 180 µm. Photoablation was applied to a 6-mm optical zone, with a transition zone of 9 mm. The LASIK procedures were conducted at the Instituto de Oftalmobiología Aplicada, Universidad de Valladolid, Spain, by Dr. Jesús Merayo-Lloves.

Total aberrations were measured about 1 month before and between 1 and 3 months after LASIK at the Instituto de Optica, Madrid, Spain. Data were typically the average of five sets of measurements. Corneal topography was performed during the same examination session. Visual performance measurements were conducted at the Instituto de Oftalmobiología Aplicada, Universidad de Valladolid, by Raúl Martín and Guadalupe Rodríguez, before and between 6 months and 1 year after LASIK.

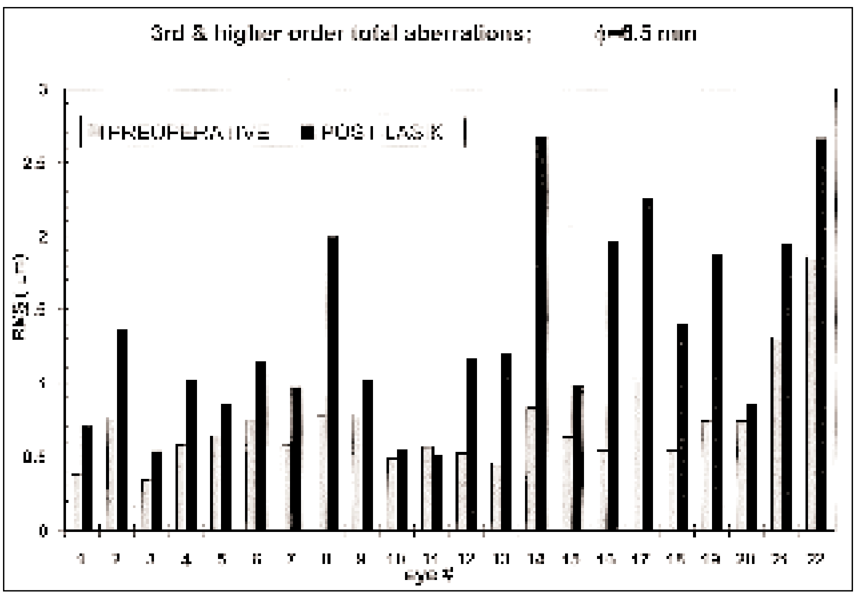

Figure 3. Root-mean-square (RMS) wavefront error before (gray bars) and after (black bars) LASIK, for total third and higher order aberrations. Pupil diameter = 6.5 mm. Eyes are sorted by increasing preoperative spherical error. Adapted from Moreno-Barriuso et al.[3]

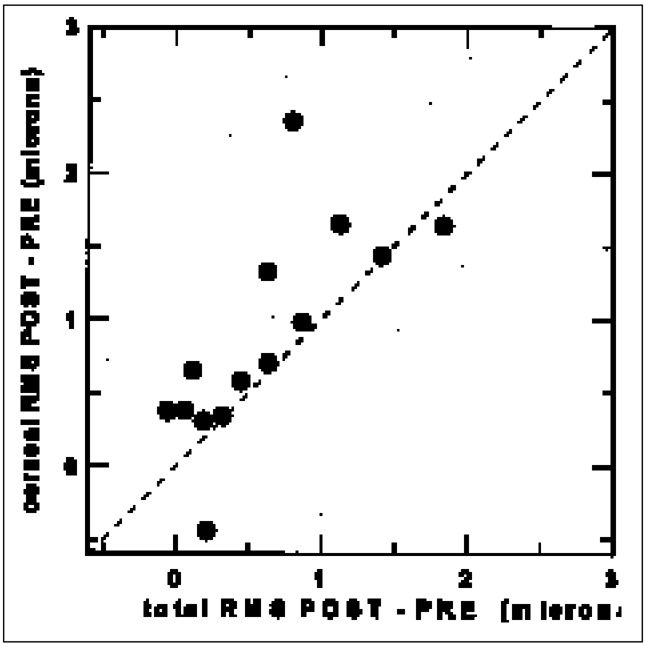

Figure 4. Increment of total aberrations (third order and higher) with LASIK versus increment of corneal aberrations. The dotted line indicates a linear function through the origin (y=x). Most data points are above this line, indicating a higher increase of corneal aberrations. Coefficient of correlation r=0.73, *P*=.0024.

RESULTS

Change of Total Aberrations With LASIK

As has been reported, total aberrations increase following standard LASIK for myopia.[3] Figure 3 shows the root-mean-square (RMS) wavefront error before and after LASIK for third order and higher aberrations (ie, excluding tilt, defocus, and astigmatism), for a 6.5-mm pupil. Eyes are sorted by increasing preoperative refraction. The average increase was 1.9 times, and the effect was more pronounced for the highest preoperative myopes. Spherical aberration increased by a factor of 3.9.[3] As shown in Figure 1, this was a common trend in most eyes (central area of positive aberrations surrounded by a ring of negative aberration). Third order terms (including coma)[1] increased by a factor of 2, and were likely associated with a decentration of the ablation pattern (the central area appeared decentered in some cases, as shown in Figure 1).[3] Aberrations increased significantly in all eyes except for two (eyes #10 and #11).

Do Corneal Aberrations Change Similiar to Total Aberrations After LASIK?

Figure 1 shows that although corneal and total aberrations are in general different in normal eyes (prior to surgery), they show a high degree of similarity after surgery.[10] Although there is a good correlation between corneal and total aberrations after surgery (r=0.97, $P < .0001$), a direct comparison demonstrates the following[10]: 1) The spherical aberration induced in the anterior surface of the cornea significantly exceeds that induced in the whole eye. This attenuation is likely produced by a spherical aberration of negative sign induced on the posterior surface of the cornea (related to the reported forward shift of the posterior corneal surface following refractive surgery). 2) The correlation of the increment of total aberration with the increment of corneal aberrations (Fig 4) is lower (r=0.73, $P = .0024$) than the correlation of postoperative total and postoperative corneal aberrations. This suggests a significant role of the interaction of corneal and internal aberrations prior to surgery, and in some cases relevant after surgery. For example, the relative amount of corneal and internal (probably crystalline lens) aberrations prior to surgery explains the surprisingly good outcome encountered in eyes #10 and #11.[10] In general, total aberrations should be better related to visual performance than aberrations of the anterior corneal surface alone, since they take into account possible changes of the posterior corneal surface and interaction with other ocular components (crystalline lens and pupil).

Predictions From Aberrometry and Psychophysical Measurements of Visual Performance

Contrast sensitivity function represents the contrast degradation imposed by the optics and posterior visual processing as a function of spatial frequency. Since only the optics are modified with LASIK, one expects any change induced in contrast sensitivity function to be due to a change only in the optical system, and more specifically in the modulation transfer function (MTF) of the eye. The Strehl ratio (normalized volume under the MTF) is an alternative global image quality parameter to the root mean square error. Both metrics are, in general, well-correlated. The MTF can be obtained easily from the wave aberration using Fourier optics. For better comparison with the one-dimensional contrast sensitivity function (for vertical gratings), we used the horizontal section of the MTF. We computed the MTF for a 3-mm diameter pupil, to simulate a closer condition to the contrast sensitivity function measurement, performed with an undilated pupil. The area under these curves was computed, using linear units for both spatial frequency and contrast units, a linear interpolation, and integrating

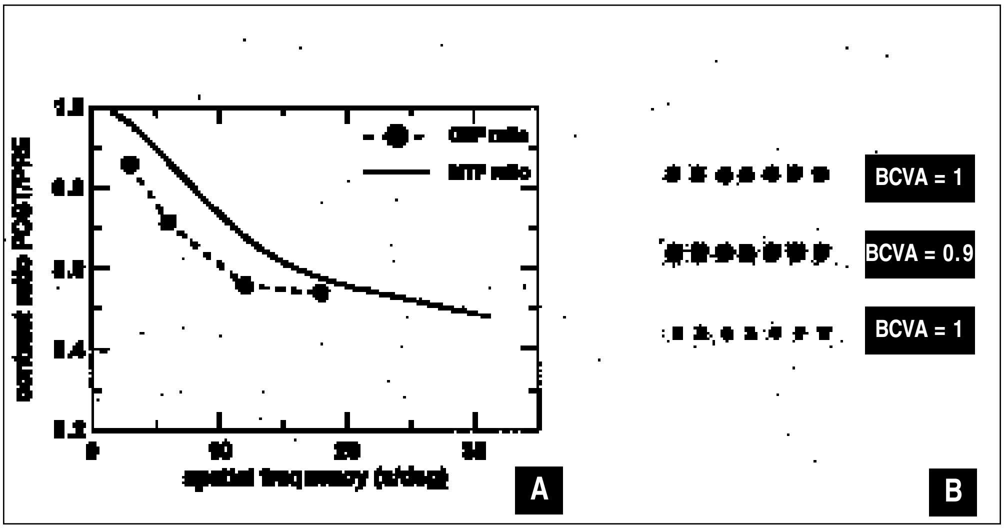

Figure 5. A) Modulation transfer ratio postoperative/preoperative (solid line) and contrast sensitivity ratio postoperative/preoperative (circles and dashed line) as a function of spatial frequency. Data are average of 22 eyes. Pupil diameter = 3 mm for the modulation transfer function (MTF), and undilated for the contrast sensitivity function (CSF). **B)** Simulation of retinal image quality (obtained by convolution of the 20/20 line on a Snellen chart and the corresponding point spread function) and clinical measurements of best spectacle-corrected visual acuity, for three eyes (#14, #21, #11) with different surgical outcomes.

between 3 and 18 c/deg. The area under the MTF (average of 22 eyes) decreased by a factor of 1.38 after LASIK, and the area under the contrast sensitivity function (average of 22 eyes) decreased by a factor of 1.51 after LASIK. This indicates that the average image contrast degradation estimated from wave aberration data accounts for most of the decrease in contrast sensitivity in this spatial frequency range. Figure 5 shows the average contrast ratio before and after surgery for both modulation transfer and contrast sensitivity as a function of spatial frequency. Again, both functions tend to decrease similarly with LASIK. The fact that contrast sensitivity function seems to suffer a slightly larger degradation could be due to the fact that pupils were larger than 3 mm during the contrast sensitivity function measurements, that the visual performance and aberration measurements were not collected on the same day, that MTF computations were based on monochromatic aberrations whereas contrast sensitivity function was measured in polychromatic light, or that other factors apart from the aberrations (such as haze) may also contribute to contrast degradation. The eye in which the root mean square decreased (although not significantly) after LASIK experienced a slight increase in the MTF postoperative/preoperative ratio, as well as a contrast sensitivity improvement at certain spatial frequencies (3 and 12 c/deg).

We also compared visual performance (best spectacle-corrected visual acuity [BSCVA]) with simulations of retinal images of a Snellen chart. These were generated by convolution of point-spread-functions (computed from the wave aberrations) with images of the Snellen chart. These simulations do not represent vision of patients, but provide an idea of the image quality on the retinal plane. Figure 5B shows simulations of the 20/20 line of a Snellen chart for three eyes (#14, #21, #11) after LASIK. Clinical BSCVA measurements for these eyes are reported. In many cases, such as eye #14, a clear degradation of retinal image quality is not associated with a line loss, indicating that unlike contrast sensitivity, high-contrast visual acuity is not a very sensitive measurement to evaluate the changes induced by refractive surgery.

From measurements of total and corneal aberrations, contrast sensitivity and visual acuity measured in a group of eyes before and after surgery, we conclude that:

1) Both total and corneal aberrations increase significantly following standard myopic LASIK.

2) Total aberrations should be better correlated to visual performance than corneal aberrations alone. Although most of the changes occur on the anterior corneal surface, in general corneal aberrations are not sufficient to understand the changes induced by refractive surgery. Preoperative interaction of the corneal and internal optics, and possible changes induced on the posterior corneal surface also contribute to the total aberration pattern.

3) Most of the decrease in contrast sensitivity can be accounted for by the decrease in the modulation transfer function (computed from the total wave aberration)

4) High contrast visual acuity is not a very sensitive measurement of image quality.

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