Longitudinal Evaluation of Optical Aberrations Following Laser in situ Keratomileusis Surgery

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ABSTRACT

Objective measurements of the optical aberrations of an eye were taken with a Shack-Hartmann aberrometer immediately before, immediately after, and at regular intervals over a two month recovery period following LASIK refractive surgery. Results indicate that the surgery induced large amounts of positive spherical aberration which regressed slightly during recovery. Computed point-spread functions for various pupil diameters indicate that retinal image quality was the same before and after surgery for small and medium sized pupils (<4 mm diameter) but was significantly degraded for large pupils (>4 mm). [*J Refract Surg* 2000;16:S647-S650]

The practice of corneal refractive surgery would benefit from routine measurement of ocular aberrations before and after surgery in order to document the optical consequences of the procedure. As currently practiced, corneal refractive surgery aims to correct defocus and astigmatism but in the process of correcting these lower-order aberrations the higher-order aberrations of the cornea typically increase as well.[1] Paradoxically, this increase in corneal aberrations is not necessarily detrimental to the patient's vision because aberrations of the whole eye could increase or decrease depending on the sign of the change in corneal aberrations compared to the sign of the aberrations from the rest of the eye. Consequently, unless measurements of the eye's aberrations are taken before and after surgery, disappointing visual outcomes might appear to be random variation when in fact they are understandable in simple optical terms. Alternatively, improvements in visual performance following refractive surgery which are ascribed to the reduction of defocus and/or astigmatism may in fact be due to reductions in higher order aberrations. The only way to resolve this uncertainty is to measure the eye's aberrations before and after surgery so that the optical outcome of the surgery is established empirically. With this motivation, we present the results of a case study on an individual who underwent laser in situ keratomileusis (LASIK) corneal surgery. Naturally the particular results of a single case cannot be generalized to the population at large, but the results are nevertheless of value because they demonstrate unequivocally how the aberration structure of an eye can be affected by the surgical procedure and how these changes are modified as the wound heals during the recovery period.

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Published previously in the February, 2000 Technical Digest of the Optical Society of America, and reprinted here with permission of the Optical Society of America.

Supported by National Institutes of Health (National Eye Institute) grant R01-EY05109. X. Hong is supported by the SOLA Graduate Fellowship in Ophthalmic Optics.

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METHODS

Procedure

The patient was a 35-year-old female who elected bilateral LASIK surgery over a 6 mm optical zone to correct the following refractive error (cycloplegic refraction): OD -4.00 +1.50 x 95°, OS -5.25 +2.25 x 94°. Subsequent to that decision she volunteered to participate in our study. We measured ocular aberrations with a Shack-Hartmann (SH) aberrometer which has been described in detail elsewhere.[2] Following informed consent the patient was fitted with a dental bite bar to aid alignment of the patient's eye with the SH aberrometer. The day before surgery we measured aberrations of the patient's eye plus spectacle correction. Following surgery her refractive error was OD -0.50 DS, OS -1.25 + 0.25 x 50° which was left uncorrected when taking aberration measurements. A single, 200 msec exposure of a 10 µw beam (at the cornea) from a helium-neon laser (633 nm) was sufficient to capture a SH data image. This was less than 1% of the maximum permissible exposure recommended by American the National Standards Institute.[3] The use of a brief exposure in a darkened room avoided the need to dilate the pupil pharmacologically and thus allowed us to measure aberrations

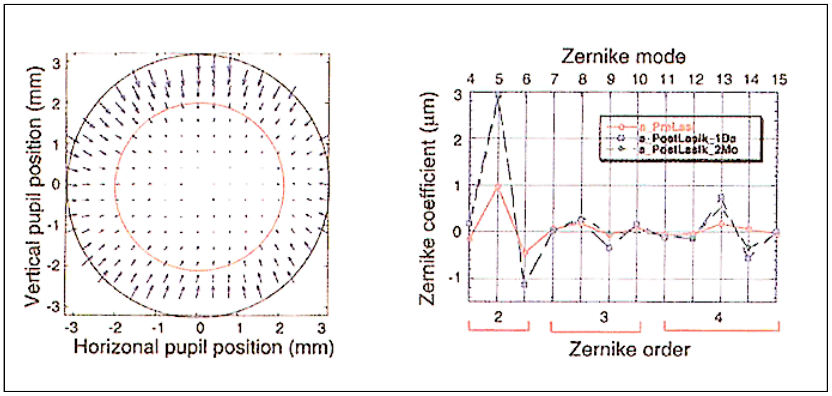

Figure 1. Left: Change in spot locations due to refractive surgery. Tail of each arrow shows location of spot the day before surgery, head indicates spot location the day after surgery. **Right:** Zernike aberration coefficients the day before, the day after, and two months after surgery. Left eye (OS).

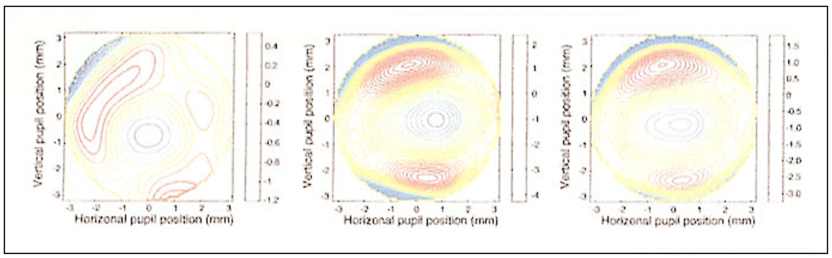

Figure 2. Wavefront aberration functions **(left)** the day before surgery), **(middle)** the day after surgery, and **(right)** after 8 weeks of recovery. Second order aberrations not included. Left (OS) eye. Note difference in scales (units are micrometers). Contour interval is 0.5 wavelengths of 633 nm light.

over the full extent of a physiologically natural pupil (6.4 mm diameter).

Data Analysis

Raw data from the SH aberrometer consists of a two-dimensional array of approximately 200 spots which are images of a single point of light reflected from the patient's fovea. The location of each spot was specified by its centroid, from which we inferred the local slopes of the wavefront aberration function at each pupil location sampled by the aberrometer. These slope data were fit with Zernike polynomials[4] to determine aberration coefficients, from which the wavefront aberration function was reconstructed. To derive aberration coefficients for pupil diameters smaller than 6.4 mm, the raw data images were masked to include only the data inside the smaller pupil before proceeding with Zernike analysis. Measures of optical image quality (eg, optical transfer function, point spread function) were derived from an aberration function by standard Fourier optics methods.[5] Computer algorithms were written in Matlab (Mathworks, Inc.).

RESULTS

The movement of spot locations in the SH data image before and after surgery is shown in Figure 1. Over the central 4 mm of the pupil the spots shifted only slightly, which implies that the refractive characteristics of the uncorrected eye after surgery were the same as the corrected eye prior to surgery. However, over an outer annular zone extending from 2 to 3 mm radius the spots shifted by increasingly large amounts towards the pupil center, which indicates increasing amounts of positive refractive power of the surgical eye compared to the corrected normal eye. This suggests that refractive surgery induced positive spherical aberration, which was confirmed by Zernike analysis. As shown in Figure 1, the aberration coefficient for mode 13 was significantly larger the day after surgery, less so after 8 weeks of recovery. Mode 14 also increased in amplitude following surgery, indicating a difference between the 4th order aberration along the vertical and horizontal meridians.

Wavefront aberration functions reconstructed from the Zernike coefficients of Figure 1 are shown as contour maps in Figure 2. One interpretation of these maps is that they depict the shape of the wavefront of light reflected out of the eye from a point source on the retinal fovea. Before and after surgery the wavefront is reasonably flat over the central 4 mm pupil area, but becomes highly curved in the peripheral region of the pupil following surgery. This is the effect of the increased amount of spherical aberration (mode 13) noted in Figure 1. The asymmetry in shape between the vertical and horizontal meridia associated with mode 14 is also

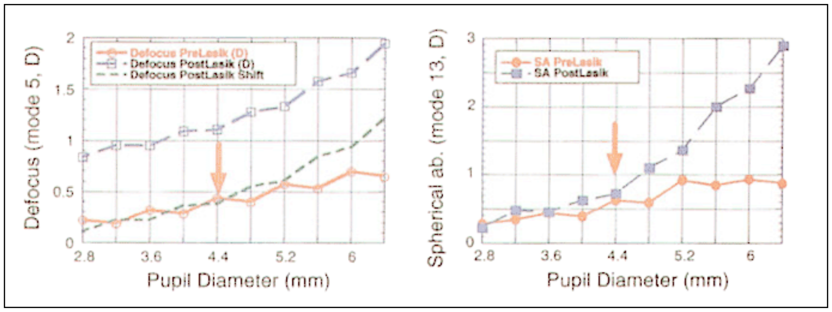

Figure 3. Variation of defocus **(left)** and spherical aberration **(right)** in diopters with pupil diameter. Left eye (OS). Arrow shows the maximum pupil diameter for which the aberrations of eye after surgery match those of the eye before surgery.

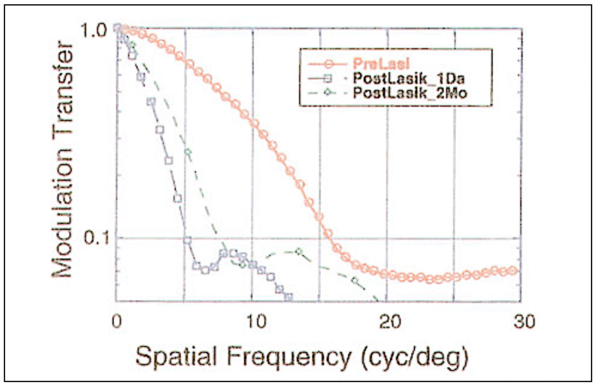

Figure 4. Modulation transfer function for 6.4 mm pupil, second order aberrations not included.

clearly evident in the aberration functions of Figure 2. Vertical coma (mode 9) also increased immediately after surgery, but this was resolved after 8 weeks of recovery.

To systematically investigate the change in aberrations with pupil diameter, we re-computed aberration coefficients for a variety of pupil diameters. Figure 3 shows the results for the two most prominent Zernike modes, defocus (Z5) and spherical aberration (Z13). Overall the defocus curve after surgery is displaced upwards by about 0.75 diopters, which corresponds to the mean spherical equivalent of the residual refractive error. To compensate for this residual error, and to enable a closer visual comparison, the data were shifted downward to match the curve before surgery. Now we can see that the curves match well over the central portion of the pupil but begin to diverge for larger pupils because of the influence of spherical aberration. Likewise, the spherical aberration of the eye after surgery matches that of the eye before surgery for the smaller pupil diameters (<4.4 mm) but then grows rapidly as pupil diameter increases.

The impact of the change in optical aberrations on retinal image quality were assessed by computing the modulation transfer function from the wavefront aberration functions of Figure 2. The result, shown in Figure 4, shows a substantial loss of retinal contrast immediately after surgery and a modest recovery of image contrast after 8 weeks. A similar conclusion may be drawn from a consideration of point-spread functions shown in Figure 5. For a medium pupil size (4.5 mm) image quality was nearly normal after 8 weeks recovery, but for a large pupil (6.0 mm) image quality was much worse after surgery.

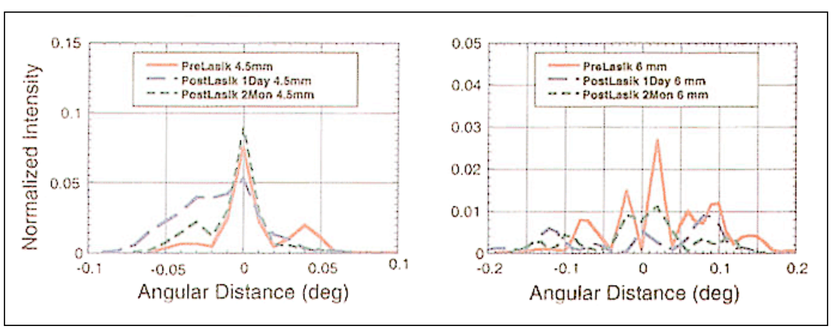

Figure 5. Point-spread functions for a medium-sized pupil (left) and a large pupil (right), second order aberrations not included

DISCUSSION

Although the intended ablation zone of the refractive surgery on this patient was 6 mm in diameter, the optically clear zone of low aberrations was only 4.4 mm in diameter. This difference is not due to regression since it was present the day after surgery and persisted for another 2 months without major changes.

Since this patient had insignificant amounts of higher-order aberrations prior to surgery, the surgically induced 4th order aberrations had a deleterious effect on retinal image quality. If the patient's natural eye had had positive amounts of Zernike mode 14, then it is conceivable that the same surgery would have again induced negative amounts of this aberration, thereby correcting this particular aberration and improving retinal image quality.

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