Optical Aberrations Following Laser In Situ Keratomileusis (LASIK) Surgery

Xin Hong and Larry N. Thibos

School of Optometry, Indiana University, Bloomington, IN 47405, xhong@indiana.edu, thibos@indiana.edu

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ABSTRACT

We investigated the optical consequences of corneal refractive surgery by monitoring aberration changes during recovery for a patient who elected LASIK surgery to correct myopic astigmatism. A Shack-Hartmann aberrometer was used to measure aberrations of the whole eye and a corneal topographer (EyeSys) was used to measure aberrations of the cornea. Results showed a marked asymmetry in wave aberrations between vertical and horizontal meridians; increased spherical aberration near the pupil margin, good correspondence between topography and whole-eye aberrations, and a modest reduction of aberration magnitude 2 months after surgery.

OCIS codes: (330.0330) Vision and color; (330.5370) Physiological optics

INTRODUCTION

The aim of corneal refractive surgery to correct myopia is to flatten the central corneal, which decreases its refractive power. Unfortunately, large optical aberrations have been reported in eyes following surgery \(^1\) which suggests the need for a longitudinal study which documents the change in aberrations before and after surgery. To help guide the design of a large-scale clinical study for this purpose, we present a case report of the optical outcome of LASIK refractive surgery in a patient followed for a two month recovery period after elective surgery to correct a modest degree of myopic astigmatism. Preliminary results from this patient were reported previously \(^2\). Here we describe new results obtained from additional data analysis.

METHODS

Subject

The subject of this report was a 39 year old female who elected bilateral LASIK surgery to correct her myopic astigmatism. Results of cycloplegic refraction were: OD -4.00 +1.50X095, OS -5.25 +2.25X094. Laser surgery was performed over a nominal 6-mm optical zone After surgery, the manifest refractive error was OD -0.50, OS -1.25 +0.25X050. The patient was satisfied with the outcome for the right eye and reported only slight degradation of night vision. Subsequent to this study she underwent
additional treatment of the left eye to correct the residual refractive error. Similar results were obtained from both eyes. All data reported here were from the left (OS) eye.

**Procedure**

Ocular aberrations of the whole eye were measured with a Shack-Hartmann (SH) aberrometer which has been described in detail elsewhere. Sampling density in the pupil plane was 0.4 mm. Eye movements were controlled with a fixation target and head movement was suppressed by a bite-bar. The subject's line of sight was brought into coincidence with the optical axis of the aberrometer with the aid of an auxiliary alignment ring and pupil monitor. Ocular aberrations were measured under physiological conditions without mydriatic or cycloplegic drugs. Measurements were taken in a darkened room for which the natural pupil diameter was approximately 6 mm. A brief flash (200 ms) of He-Ne laser (632 nm, 0.01 mw at cornea) light was less than 1% of the maximum permissible exposure recommended by the American National Standards Institute.

Corneal aberrations were measured with a corneal topographer (EyeSys System 2000, EyeSys Technologies, Inc.). The instrument was calibrated against a set of known aspheric surfaces. Our previous experience indicated that the small correction associated with angle lambda between the pupillary axis and the line of sight has little effect on measured aberrations so was omitted for this patient.

Before surgery, the subject wore spectacle lenses to correct defocus and astigmatism when taking SH measurements. After surgery, any residual refractive error was left uncorrected in order to compare the optical quality of the post-surgical eye relative to the best-corrected optics of the pre-surgical eye. No spectacles were used when taking EyeSys measurements.

**Data analysis**

Raw data from the SH aberrometer were analyzed to obtain the centroid of each spot. The relative shift of spot locations with respect to the ideal position indicated the local slope of the aberrated wavefront over the lenslet aperture. These slope data were fitted with Zernike polynomials to determine aberration coefficients, from which the wavefront aberration function was reconstructed.

The sagittal heights of corneal locations were generated from raw curvature data using a utility function provided with the EyeSys instrument. The corneal aberration is an optical path length error computed as the product of difference of refractive indices (between cornea and air) and the physical path length between an aberration-free aspheric surface and the corneal surface. Corneal aberrations were corrected for systematic errors determined from instrument calibration prior to fitting with Zernike polynomials to obtain Zernike coefficients of the corneal aberration function.

Measures of optical qualities (e.g. modulation transfer function (MTF) and point spread function (PSF)) were calculated according to standard Fourier optics methods. All of the data analysis programs were written in Matlab (Mathwork, Inc.). Dioptric curvature maps were derived from wavefront aberration functions by applying the Laplacian operator (Matlab's del2 function).
**RESULTS**

*Figure 1* compares the aberrometer images obtained before surgery (with spectacle correction in place) and after surgery (without spectacle correction). Prior to surgery the corrected eye had excellent optical quality, as indicated by the regular matrix of well-formed spots. After surgery, the array of spots was not as regular, which indicated the presence of residual refractive errors and higher-order aberrations. Near the pupil margin the grid of spots was highly curved and spots were squeezed together, indicating markedly increased aberrations. If surgery achieved the optical effect of spectacles, then the spots would be in the same positions in *Figs. 1A and B*. Clearly this did not occur. The shift in spot locations before and after surgery, shown respectively by the tail and head of each arrows in *Fig. 1C*, indicates the difference in optical characteristics of the well-corrected pre-surgical eye compared to the uncorrected, post-surgical eye. The increase in arrow length near the pupil margin is indicative of the residual refractive error and unintended increase in higher-order aberrations.

Reconstructed wavefront aberration functions are shown as contour maps in *Fig. 2*. One interpretation of these maps is that they depict the shape of a wavefront of light reflected out of the eye due to a point source imaged on the fovea. Before and after surgery the wavefront was reasonably flat over the central 4-mm pupil area, which indicates good optical quality for a medium sized pupil. However, the wavefront becomes highly curved in the peripheral region of the pupil following surgery, which indicates the presence of significant aberration for large pupils. Zernike analysis indicated that most of the higher order aberrations were of the 4th order.

The change in wavefront aberration due to surgery was computed by subtracting the aberration function of the corrected eye prior to surgery from the uncorrected eye following surgery. The result was then converted to a dioptric power map using the Laplacian operator. The result, shown in *Fig. 3A*, is a pupil map showing the change in refractive power of the well-corrected eye prior to surgery relative to the uncorrected eye following surgery. If the surgery had the same optical effect as the patient's spectacles, then this power map would be zero everywhere. Clearly this was not the case for this patient. One component of the difference is the residual defocus and astigmatism which can be accounted by removing the second-order aberrations from the wavefront before computing the dioptric map. This result, shown in *Fig. 3B*, indicates that there is still a significant amount of higher-order refractive error in the outer portions of the pupil following surgery.
The impact of the change in optical aberrations on retinal image quality was assessed by computing the modulation transfer function (MTF) from the wavefront aberration functions (Fig. 4). The MTFs for large pupil diameter (6.4 mm) show a substantial loss of retinal contrast immediately after surgery and a modest recovery after 8 weeks. However the analysis for medium pupil diameter (4.5 mm) shows that the corneal surgery had little impact on image quality.

A similar conclusion may be drawn from a consideration of point-spread functions (PSF, Fig. 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 still much worse post-surgically. The shape of the post-surgical PSF for 6.0 mm pupil was typical of an optical system with positive spherical aberration. The wider spread along the vertical meridian corresponded to the higher residual refractive power in the superior and inferior pupil.

The change in higher-order wavefront aberrations caused by surgery was computed by subtracting the pre-surgical wavefront aberration function from the post-surgical aberration function. The result is shown in Fig. 6B. For comparison, we also computed the change in corneal aberrations and the result is shown in Fig. 6A. The shapes of these two aberration maps are similar, which indicates that the topographic distribution of changes in optical aberrations for the whole eye are mainly due to the changes in the cornea, as we would expect. However, the magnitude of the change in corneal aberrations is greater than the change in the whole eye. Possible reasons for the quantitative discrepancy are discussed below.
To reveal how the aberration structure of the eye changed during the 2 month recovery period, we analyzed the aberrations for a 6.0-mm pupil at different times. We chose the wavefront variance, which is the sum of squared Zernike coefficients, as a summary metric of the magnitude of aberrations. The square root of this quantity, called RMS wavefront error, is used for the left-hand ordinate in Fig. 7. To put this result into more clinical terms, we converted wavefront variance into its dioptric equivalent by computing the RMS error of spherical wavefronts of various curvatures. This allows us to plot dioptric equivalent on the right-hand ordinate. The results indicate that the magnitude of aberrations increased immediately after surgery and reached a peak value 3 days after surgery. A modest recovery then followed before optical quality stabilized.
Fig. 6 Change in wave aberration following surgery. (A) corneal aberration; (B) whole-eye aberrations. Units are micrometers. Contour interval is 0.5 micrometer. Second order terms not included.

Fig. 7. Recovery of wavefront error following surgery.

DISCUSSION

One of the more interesting features of the aberration structure of the patient's eyes following surgery was the large increase in 4th order aberration near the superior and inferior margins of the pupil evident in Figs. 2, 3. This asymmetry, which was evident in both eyes, may indicate some asymmetric healing following surgery. For example, the physical pressure of the upper and lower lids on the cornea during recovery may compress the weakened tissue and affect the way it heals. Alternatively, correction of with-the-rule astigmatism requires a greater degree of flattening in the vertical meridian than in the horizontal meridian. Since the depth of ablation in the pupil center is fixed, the vertical extent of the ablation will therefore be shorter than the horizontal extent. Consequently, a nominal 6 mm ablation zone may be significantly less than 6 mm in the vertical direction, which suggests that the highly aberrated regions near the superior and inferior pupil margins may be due to the myopic cornea outside the ablation zone but inside the pupil.

Despite good qualitative agreement between the topographic maps in Fig. 6 depicting change of aberrations of the cornea and that of the whole eye, significant quantitative differences were noted. Although it seems unlikely, we cannot rule out the possibility that the surgery affected more than just the corneal component of the eye's optical system. For example, the laser light not absorbed by the corneal tissue may have affected the patient's crystalline lens. Alternatively, perhaps the ablation generates an acoustic shock wave which affected the crystalline lens. Such laser-induced shock waves are known to occur when vaporizing metals with high-intensity laser pulses. Another possible explanation is that either the aberrometer or the corneal topographer is unreliable when measuring the highly aberrated eye of a surgically altered cornea. Although both instruments were calibrated with rotationally symmetric model eyes, this calibration may not be valid for eyes with large amounts of irregular aberrations. Yet another possibility is that an unusually large angle lambda, or poor fixation of gaze, induced errors into
the determination of the corneal aberrations along the line-of-sight reference axis. To determine which, if any, of these possibilities might account for the noted discrepancy will require further research.

ACKNOWLEDGMENTS

We thank Dr. Gerald Lowther and the staff of the Borish Center for Ophthalmic Research at Indiana University for performing corneal topography measurements. We also thank Dr. Arthur Bradley for helpful discussions and our patient for voluntary participation in the study. Supported by National Institutes of Health (National Eye Institute) grant R01-EY05109 to LNT. X. Hong is supported by the SOLA Graduate Fellowship in Ophthalmic Optics.

REFERENCES


