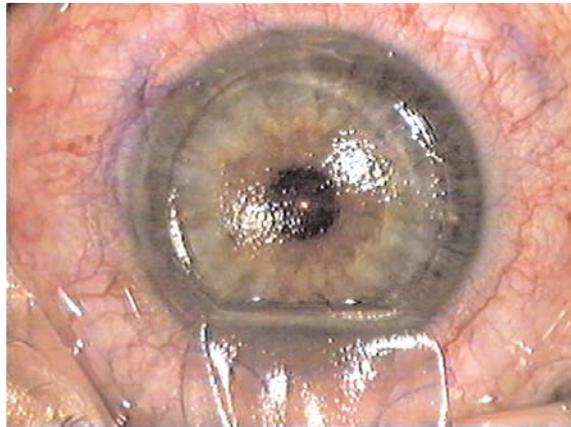


Refractive Surgery and Optical Aberrations

Susana Marcos

For more than a century there has been awareness of the fact that the eye is not a perfect optical system and that it suffers from defects or optical aberrations other than defocus and astigmatism. Attempts to measure the wave aberration of the human eye, i.e., phase distortions at the plane of the pupil, date back to 1894. In recent years, new terminology and new technology have invaded the field of refractive surgery and changed the way ophthalmologists and optometrists look at the image-forming capabilities of ocular optics. Wave-front-sensing, aberrometers, high-order aberrations, and Zernike polynomials are only a few of the novelties that have recently entered the field.

Over the past two decades, several new methods have been developed to assess the



Courtesy of Jesús Merayo and Raúl Martínez.

optical quality of the human eye.¹ Only recently, however, as these procedures have begun reaching a clinical population, has the instrumentation involved captured the attention of refractive surgeons. For the compensation of refractive errors (myopia, hyperopia, and astigmatism), corneal refractive surgery has become a popular alternative to wearing glasses or contact lenses: the operation and recovery are rapid and the procedures are constantly being perfected. The surgery alters the curvature of the central area of the cornea, reducing it in myopes and increasing it in hyperopes. From the lens designer's point of view, it is clear that a change in only part of the front surface of the cornea (the most refractive element of the ocular optical system) must modify the aberration pattern of the entire optical system. Particularly in the case of large pupils, an increase in optical aberrations—despite the correction of defocus and astigmatism—can frequently be associated with complaints of halos and visual loss at night. Understanding the change in aberrations induced by standard refractive surgical procedures is important for assessment of how vision can be compromised after surgery. It is essential to develop new ablation algorithms to overcome such problems, and perhaps even improve vision.

Measuring refractive-surgery-induced change of corneal aberrations

Computerized videokeratography—which measures the shape of the cornea, typically by analysis of the distortion of concentric rings projected on it—is routinely used in clinics to evaluate surgical results (i.e., centration and location of the treatment zone and characteristic patterns of what is known in clinical terms as irregular corneal astigmatism). Applegate *et al.*² and Oliver *et al.*³ used corneal elevation maps from commercial corneal topographers to measure the changes induced in the cornea by different types of refractive surgery; their findings show that refractive surgery is generally followed by an increase in the amount of and an alteration in the distribution of aberrations.

The corneal surface and the pattern of aberrations associated with any optical system are typically described as a polynomial expansion. The first-order terms correspond to a prismatic error; the second-order terms to defocus and astigmatic errors; third-order aberrations include coma, in which a point source appears as a comatic shape; fourth-order aberrations include spherical aberration, or increased focusing error as the pupil dilates. Studies based on corneal topography show that, for large pupils, corneal aberrations increase by approximately a factor of 3. In addition, the distribution of aberrations shifts from third-order dominance (comatic) to fourth-order dominance (spherical). The dramatic increase in spherical aberration is caused by a surgery-induced change in corneal asphericity. Figure 1 shows the distribution of aberrations (in terms of variance) in normal eyes, and one-year after radial keratotomy (RK), photorefractive keratectomy (PRK), and laser *in situ* keratomileusis (LASIK). In general, there is an increase in both third- and fourth-order aberrations, and the increase is correlated to a decrease in contrast sensitivity.

PRE-OP vs 1 YR POST-OP

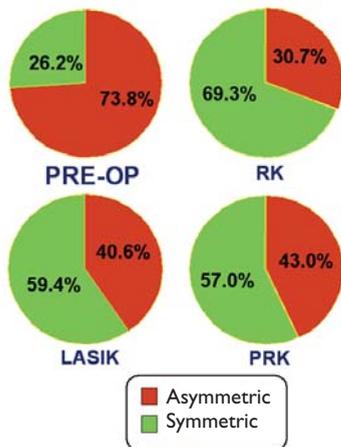
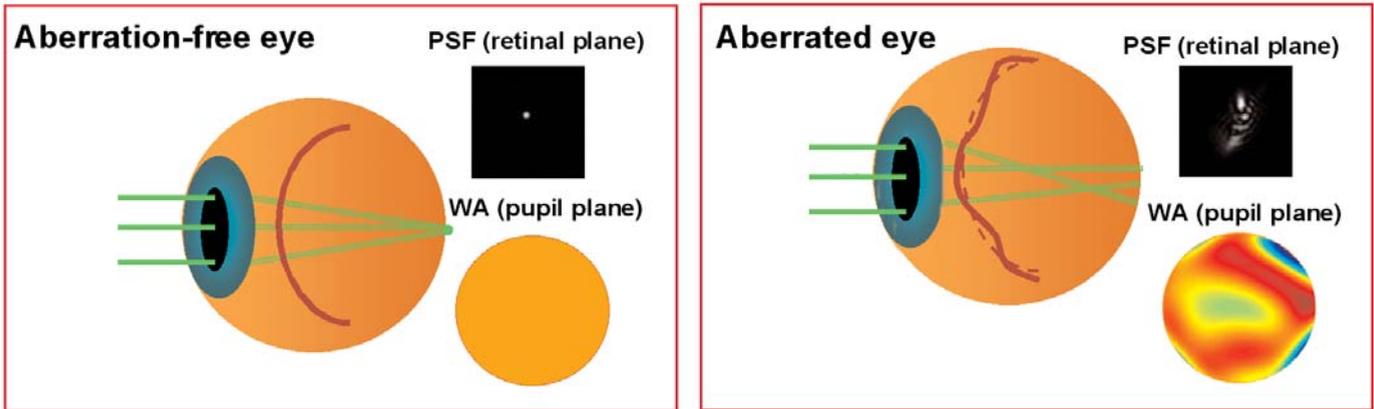


Figure 1. Distribution of corneal aberrations (symmetric versus asymmetric) for eyes before (pre-op) and one year after myopic RK, PRK and LASIK. (Adapted from R. A. Applegate, H. C. Howland, and S. D. Klyce, *Corneal Aberrations and Refractive Surgery in Customized Corneal Ablation: The Quest for Super Vision*, Slack, Inc., N.J., in press. Courtesy of R.A. Applegate.)



Measuring the aberrations of the entire optical system

Although refractive-surgery-induced optical changes 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.

Experimental measurement of total ocular aberrations is the most direct and accurate way to evaluate the effects of refractive surgery on global image quality, and it can be more directly related to visual performance. Figure 2 shows the underlying principle of most methods for measurement of the wave aberration of the eye. If the eye were perfect, or in other words only limited by diffraction (Fig. 2, upper panel), rays that enter the eye through any pupil position would converge on the same retinal location. But in the presence of aberrations, rays that enter the eye through different pupil positions deviate from the ideal location (or principal ray), as indicated in Fig. 2, lower panel. These deviations are proportional to the local derivatives of the wave aberration; in other words, the rays are normal to the wave front that travels toward the retina. A perfect eye would have a wave aberration of zero; for an aberrated eye, the wave aberration is the deviation of the distorted wave front from the ideal sphere (see Fig. 2). With knowledge of the wave aberration, and therefore also of the pupil function of the entire optical system, we can compute the point-spread-function (an Airy disk for the ideal system, but in general, an asymmetric shape for the eye) and simulate the degradation of any visual scene projected on the retina (Fig. 2).

Several wave-front-sensing methods have been used to measure the ocular aberrations associated with refractive surgery. Figure 3 shows raw data from four of them:

- Laser ray tracing (LRT) system, in which a series of aerial images of a

point source are imaged sequentially as a laser beam scans the pupil through different positions, and the deviations of each image from the principal ray are analyzed⁴⁻⁶;

- Dresden wave-front analyzer (DWA), in which the distortions of an array of points projected in the pupil are analyzed⁷⁻⁹;
- Spatially resolved refractometer (SRR), a sequential procedure like the LRT, which differs from it in that the retinal displacements are assessed psychophysically by the subject, who aligns the spots to a reference cross¹⁰;
- Hartmann-Shack wave-front sensor, in which the wave front is sampled as it exits the eye by a microlens array conjugate to the pupil, and the deviations of the multiple images from the ideal focal points are analyzed.¹¹⁻¹³

Figure 4 shows some examples of overall wave aberrations (third- through seventh-order in the Zernike polynomial expansion) from a recent study by Moreno-Barriuso *et al.*⁶ The results are for the same patients before and approximately one month after myopic LASIK surgery. The measurements were made with a laser ray-tracing system developed by Rafael Navarro and colleagues at the Consejo Superior de Investigaciones Científicas (CSIC) in Madrid, Spain. For each patient, the scale used to plot the wave aberration is the same before and after surgery, and in all cases pupil diameter is 6.5-mm. Preoperative myopia ranged between -13 and -2 diopters (D), and preoperative astigmatism was less than 2.5 D. Preoperative aberration patterns showed a large intersubject variability in terms of both amount and distribution, but in general no deep valleys or high peaks were found. After surgery, a typical central island (associated with the ablation pattern) appears in all cases, with variable

Figure 2. In an ideal aberration-free eye, rays through any pupil location would converge onto the same retinal location. The wave aberration would be flat, and the image of a point source viewed through a large pupil would be an Airy disk. Real eyes are aberrated. Therefore, rays that enter the eye through different pupil locations will hit the retina at different locations. The deviations from the ideal are proportional to the local slope of the wave aberration, which is distorted. The retinal image of a point source, (which can be simulated from the wave aberration), is in general asymmetric. Most instruments that measure the aberrations of the living human eye measure these deviations by projecting light beams through the pupil and by analyzing the light returned from the retina, or by psychophysical methods.

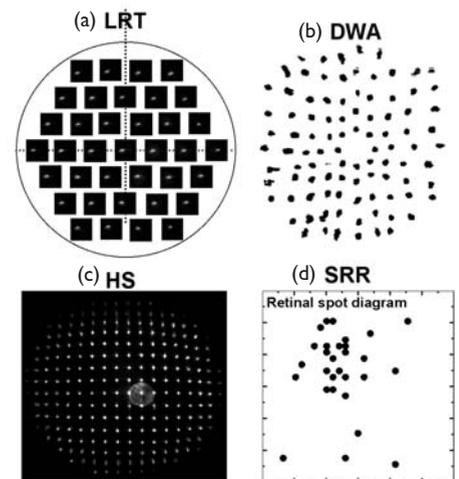


Figure 3. Raw data using different methods to assess aberrations following refractive surgery. (a) LRT: series of retinal images of a point source through different entry locations. This is a one-month post-LASIK eye (Moreno-Barriuso *et al.*). (b) DWA: image of a grid distorted by the ocular aberrations (courtesy of M. Mrochen). (c) Hartmann-Shack wave-front sensor: image of a point source projected on the retina through a lenslet array in a two-month post-LASIK patient (courtesy of X. Hong and L. Thibos). (d) Spatially resolved refractometer: sets of alignments (in the form of a retinal spot diagram) from a post-LASIK patient (courtesy of K. Thompson and S. A. Burns).

amounts of decentration. Root-mean-square (rms) wave-front error is used as a global image quality metric. We observed that the rms increased in all cases after standard LASIK surgery.

Figure 5 shows the average results for 22 eyes (6.5-mm pupil) from the study by Moreno-Barriuso *et al.*: the green bars represent data before surgery and the red bars represent data after surgery. The rms for all

nonconventional terms (third order and higher) increases on average by a factor of 2. Data are also classified by orders: third- and fourth-order terms increase significantly after surgery, whereas the higher-order terms do not show a significant increase. The largest increase occurred for spherical aberration (the main contributor to the fourth-order terms), which in this group of subjects increased by a factor of 4.

The spherical aberration induced is correlated with the attempted myopic correction, indicating that the larger the decrease in central corneal curvature needed and the more tissue removed, the more dramatic the change in asphericity and spherical aberration. The generation of third-order terms is associated with decentered ablation zones. These results agree with the findings from the study by Seiler *et al.*⁸ of patients following standard PRK surgery. By use of the Dresden wave-front analyzer, they found an even larger increase in the amount of overall aberrations, probably because of differences in the ablation algorithms and the fact that an eye-tracker system was not used during surgery.

With knowledge of the wave aberration, it is possible to simulate how any visual scene looks on the subject's retina by convolving the point-spread function with the original image. Figure 6 shows the effect of aberrations on the retinal image of a Snellen card (a test commonly used by doctors to assess visual acuity). In this chart, the bottom line

retinal image results after standard LASIK because of an increase in third- and higher-order aberrations. The image quality deterioration occurs for both small (3-mm) and large (6-mm) pupil sizes, but is more dramatic for dilated pupils. Along with a decrease in contrast, halos and ghost images appear after surgery because of the presence of asymmetric aberrations that affect phase information. Although these simulations represent only those images projected on the retina and cannot be considered by any means as an exact rendition of what the patient actually perceives after processing by the entire visual system, they are indicative of the blur caused by high-order aberrations, not obvious to practitioners until recently.

Toward a perfect ablation

To compensate for ametropias refractive surgery has improved over the years, with the result that these operations are fast and generally uneventful. Visual outcomes have been improved by the combined effects of experience accumulated by practitioners and the incorporation of technical improvements such as active eye-tracking systems to ensure proper centration. Until recently, because the main goal has been to compensate for refractive errors, little attention has been paid to retinal image degradation caused by nonconventional aberrations. We have already shown that, when we compensate for myopia with current techniques, the amount of aberrations increase, particularly spherical ones. To avoid causing spherical aberration, new ablation profiles are needed. Schwiegerling and Snyder¹⁴ proposed ideal ablations aimed at reducing the amount of induced spherical aberration, although a caveat with this model is the requirement of a deeper ablation pattern and a more abrupt transition zone.

Until recently, excitement about and interest in refractive surgery have overshadowed the problem of new aberrations in the eye; now, however, attention is turning toward compensating for individual preoperative high-order aberrations, as well as for conventional refractive errors. The idea is to apply a customized corneal ablation during the surgical procedure, which has been adapted to the patient's own aberration pattern. Several companies have started incorporating aberrometers (either based on corneal topography or overall wave aberration measurements) into their laser systems to guide ablation.¹⁵ The first results of wave-front-guided

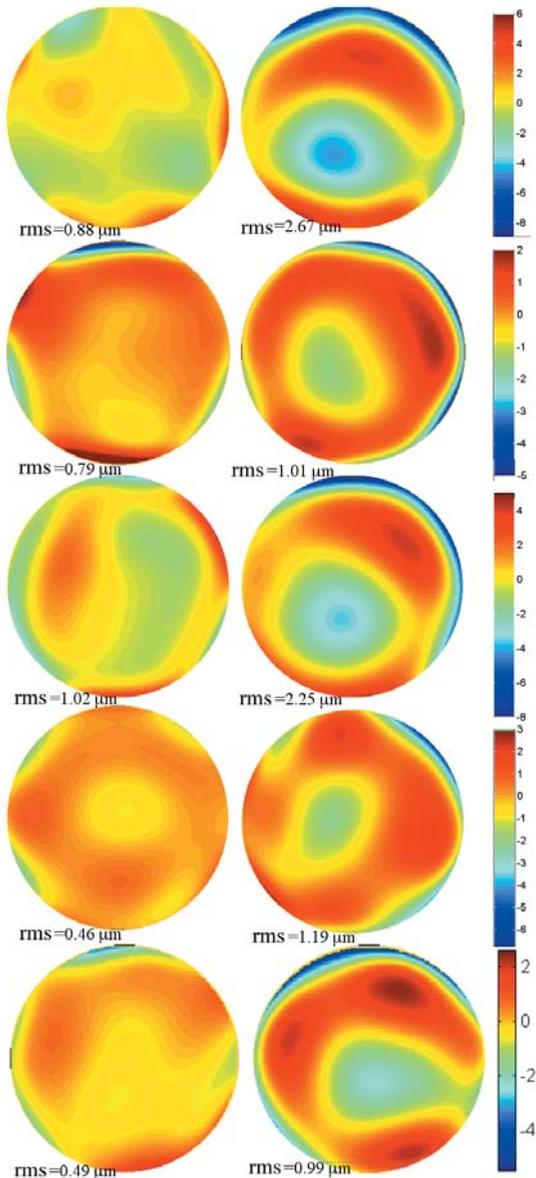


Figure 4. Wave aberration of five eyes before and after standard myopic LASIK surgery (Moreno-Barriuso *et al.*), with a laser ray-tracing method. Only third-order and higher terms are shown (i.e., best correction for defocus and astigmatism is assumed). Root-mean-square wave-front error is taken as an image quality metric.

corresponds to a visual acuity of 20/20 (assumed to be the highest resolving power of a normal eye, equivalent to 30 c/deg). Preoperative and postoperative results for one patient are shown, assuming best correction for defocus and astigmatism in all cases. A degradation of the

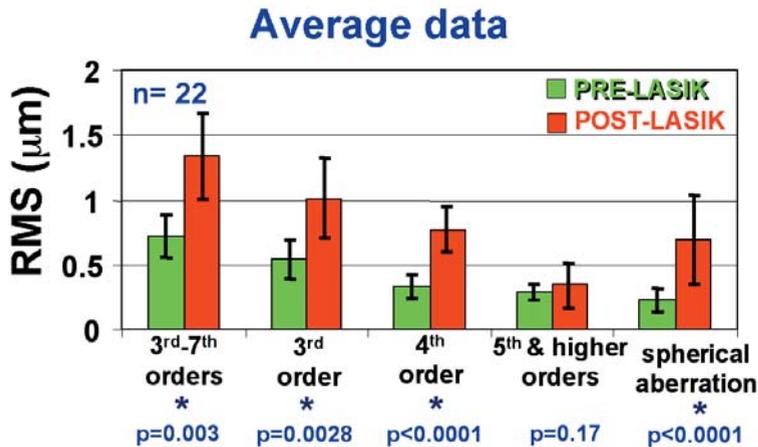


Figure 5. Root-mean-square wave-front error in a group of 22 patients before and after standard LASIK surgery. Average data from Moreno-Barriuso *et al.* Data are shown for all nonconventional (third-order and higher) aberrations together and by orders of a Zernike polynomial expansion. All terms (except the highest orders) register a significant increase following surgery. The largest increase (by a factor of 4) occurs for spherical aberration.

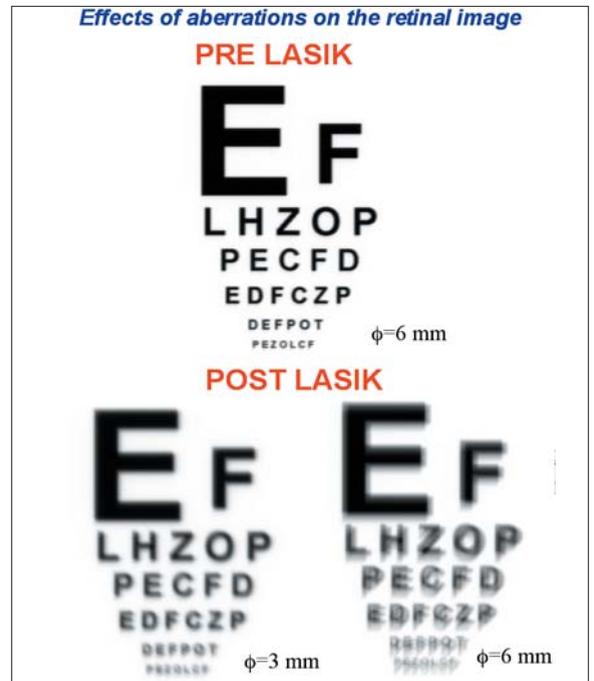


Figure 6. Retinal image of a visual acuity card for an eye before and after standard LASIK surgery, obtained by convolution of the original card with the ocular point-spread-function. This simulation does not represent what the subject really perceives, but the appearance of the image projected on the retina. Contrast loss, halos and ghost images (frequent complaints for night vision after surgery) appear particularly for a large (6-mm) pupil.

LASIK show improvements in some eyes over standard LASIK.^{9,16}

There are still several limits to the achievement of an aberration-free eye:

- the wound healing process can modify the final corneal thickness and shape;
- overall aberrations depend on the patient's accommodative state (near or far vision) because of a change of the aberrations of the crystalline lens¹⁷;
- aberrations change with age^{18,19};
- compensation is attempted for a single wavelength, although polychromatic aberrations are equally important.²⁰

On the other hand, the final limit to spatial resolution is imposed by retinal and neural factors, even if the optics are perfectly corrected. All these aspects need to be taken into account to achieve a perfect correction and can be used to determine whether other approaches (such as custom-made intraocular lenses) would be better alternatives than corneal refractive surgery. It is extremely significant, however, that contributions from different fields including optics and astronomy are providing new insights into refractive surgical procedures. Patient care will undoubtedly benefit.

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