# **Operative Correction of Ocular Aberrations to Improve Visual Acuity**

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#### ABSTRACT

PURPOSE: Optical aberrations of the human eye degrade the quality of the retinal image and may, therefore, represent a major limit of visual acuity.

METHODS: In 15 eyes, ocular aberrations were corrected in addition to myopia and astigmatism by means of wavefront-guided laser in situ keratomileusis (LASIK).

**RESULTS:** At 1 month after surgery, a supernormal visual acuity of 20/10 and better was obtained in 4 eyes (27%). The increase in root mean square wavefront error ranged from 0.6 to 2.3 and was significantly correlated with the increase in visual acuity ( $R^2 = 0.79$ ; P = .03).

CONCLUSION: Although the correction of aberrations was not yet optimal, these results show that ocular optical aberrations limit visual acuity in humans and supernormal visual acuity can be achieved by operative correction. [*J Refract Surg* 2000;16:S619-S622]

The optical quality of the human eye suffers from ocular monochromatic aberrations that have long been recognized, as early as middle of 18th century.<sup>1</sup> Shape factors of the refractive surfaces, such as the cornea and lens and their decentrations result for large pupils in wavefront errors that degrade the retinal image quality and, therefore visual acuity. Hitherto, the ocular aberrations could not be corrected by spectacles and contact lenses. Ocular wavefront errors are increased during corneal surgery and in detail during corneal refractive surgery. Increase factors of 10-fold to 20-fold have been reported for large pupil sizes.<sup>2-4</sup> The first attempt to compensate for ocular optical aberrations was performed by means of adaptive optics but this approach was considered impractical for clinical use. $^{5}$ 

Since the introduction of scanning spot excimer lasers to reshape the corneal surface for correction of refractive errors such as myopia, hyperopia, and astigmatism, monochromatic aberrations may now be individually treated.<sup>6</sup> As a first step, the wavefront error of the individual eye is measured preoperatively. The wavefront error may then be expressed numerically in terms of a surface irregularity at the level of the outer corneal surface which can be remodeled by means of the excimer laser, with submicron precision.

An improved quality of the retinal image does not necessarily result in improved vision. It has been speculated that evolution has optimized the human eye to reach an optical quality that matches or exceeds the mosaic of the photoreceptors of the retina.<sup>7</sup> It was one of the purposes of this study to investigate whether a reduction in ocular aberrations may lead to supernormal vision, defined as a visual acuity of 2.0 (20/10 Snellen scale) or better.

#### **PATIENTS AND METHODS**

#### **Patients**

Fifteen eyes of 15 patients that were scheduled for laser in situ keratomileusis (LASIK) to correct myopia and astigmatism were included in the study. Mean patient age was  $32 \pm 13$  years. Eight left and seven right eyes were operated. The baseline spherical equivalent refraction was  $-3.90 \pm 2.80$  diopters (D) and ranged from -1.90 to -7.80 D. The manifest refractive cylinder ranged from 0 to -3.00 D with an average of  $-1.00 \pm 0.70$  D. Written informed consent was obtained from each patient after a thorough discussion of benefits and known risks of the procedure. The protocol was approved by the ethical committee of the Universitätsklinikum CGC Dresden, Dresden, Germany.

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Figure 1. A) Preoperative and B) 1 month postoperative wavefront maps of one eye. Maps do not include tilt, defocus (spherical error), and astigmatism but only coma-like and spherical-like optical aberrations to facilitate comparison. The demonstrated optical zone corresponds to the ablation zone of 7 mm in diameter.

## **Examinations**

Preoperatively and at 1 month after surgery, a complete ophthalmic examination was performed including uncorrected and best spectacle-corrected visual aquity, low contrast visual acuity (Model 595, Humphrey, San Leandro, CA), corneal topography (c-Scan, Technomed, Baesweiler, Germany), aberrometry, applanation tonometry, slit-lamp and fundus inspection.

## **Wavefront Analysis**

The aberrations were measured by means of a wavefront analyzer of the Tscherning type that has been described.<sup>2,6</sup> In brief, a matrix of 13 x 13 collimated parallel beams of a green frequency doubled Nd:YAG laser (l = 532 nm) with a diameter of 0.3 mm each were shined onto the cornea. The entrance pupils of the patients were dilated to diameters of at least 7 mm and the patients fixated a target in the center of the laser spot grid. The alignment and centration with respect to the line of sight was achieved by a video camera. The spot pattern at the retina was imaged onto the sensor array of a high sensitive CCD camera (LH 750 LL, Lheritier SA, Clermont-Ferrant, France) using the principle of indirect ophthalmoscopy. The measurement itself took 60 milliseconds. Using a mathematical model<sup>8</sup>, the wavefront aberrations are approximated by means of Zernike polynominals and root mean squared wavefront errors (rms) including only 3rd and 4th-order aberrations as a measure for the

higher order optical aberrations. The increase in root mean square wavefront error was correlated with the increase in visual acuity with a nonparametric test and this correlation was tested for statistical significance.

## Treatment

The operation was performed under topical anesthesia. After insertion of the lid speculum, central corneal thickness was measured ultrasonically (DGH 500, Technomed, Baesweiler, Germany). The surface parallel keratotomy to obtain the lamella was done by means of a microkeratome (Supratome, Schwind, Kleinostheim, Germany) with scleral suction. After flipping the flap over the hinge the laser treatment was performed with a scanning spot excimer laser (Allegretto, Wavelight, Erlangen, Germany) with a spot diameter of 1.0 mm, a laser repetition rate of 200 Hz, and a Gaussian shaped beam cross section. The eye-tracking device followed eye movements with a response time of <8 msec. The ablation pattern was derived from the reconstructed wavefront aberration map. In addition, the ablation profile includes correction factors that consider changes in the ablation rate due to the lasertissue interaction, corneal curvature, and the wound healing (Mrochen and colleagues, unpublished results, 1999).9 Later on, the data were transferred to a computer program that calculates the accurate position of each single laser spot to achieve a theoretical shape accuracy of the ablation pattern of less than 1  $\mu$ m. The calculated refractive error had to be within ±0.50 D of manifest refraction. The laser procedure was centered onto the center of the entrance pupil (line of sight) according to the wavefront measurements.

## RESULTS

LASIK surgery including early postoperative healing was uneventful in all 15 eyes. The manifest spherical equivalent refraction changed from  $-3.90 \pm 2.80$  D preoperatively to  $+0.10 \pm 0.60$  D at 1 month after surgery. Cylinder was reduced from  $1.00 \pm 0.70$  to  $0.20 \pm 0.40$  D.

At 1 month, change of the monochromatic aberrations ranged from -40% to +130% compared to the preoperative root mean square wavefront error with an average of +40%. Figure 1 shows preoperative and 1 month postoperative wavefront deviation of one of the eyes treated. All patients with postoperatively supernormal vision had a reduction in root mean square wavefront error.

Best spectacle-corrected visual acuity increased on average from 1.3 (equivalent to 20/15 Snellen scale) to 1.54 (equivalent to 20/12 Snellen scale). Supernormal visual acuity, defined as 2.0 and better (20/10 and better) was achieved by 4 eyes (27%). Nine eyes gained 1 line or more and 2 eyes lost 1 line, whereas 4 eyes gained 2 lines or more, and no eye lost 2 lines or more. The increase in visual acuity was statistically significantly correlated with the reduction in root mean square wavefront error ( $\mathbb{R}^2 = 0.86$ ; P = .002) as shown in Figure 2.

#### DISCUSSION

The key finding of this study is that visual acuity can be increased by operative improvement of the optical quality of the retinal image. At this point, however, it is not clear whether supernormal visual acuity of approximately 2.0 (20/10) represents the real upper limit of visual acuity or whether we did not obtain better acuities because the correction of the wavefront errors was incomplete. Even in eyes with an increase in visual acuity, we achieved only a reduction of the wavefront errors of maximally -40%. It must be mentioned that the presented increase factor of BCVA is not corrected for magnification factor and this, however, might decrease the correlation coefficient between the increase factor of BCVA and the increase factor of the rms in Figure 2 to a certain degree. On the other hand, this reduc-



Figure 2. Increase of best corrected visual acuity as a function of the increase factor of the higher order optical aberrations. A decrease in the higher order optical aberrations leads to an increase in best corrected visual acuity.

tion of aberrations was significantly correlated with the increase in visual acuity, indicating that in many eyes visual acuity is limited by optical errors of higher order of the optical apparatus of the human eye (consisting of cornea and lens). By compensating for aberrations by means of adaptive optics, Liang and coworkers resolved fine gratings (55 c/deg) that were invisible under normal viewing conditions.<sup>5</sup> The mean increase in wavefront error by 40% is a disappointing result on first glance, however, is promising when compared with the more then 10-fold increase after standard excimer laser surgery.<sup>4,5</sup>

Corneal healing after surgery may stabilize the operatively changed shape of the outer cornea but may also level out the newly formed structure. Although stromal remodeling is considered minimal after LASIK, hyperplasia of the corneal epithelium may occur which is also responsible for some regression of the refractive effect during the first 3 to 6 months after LASIK. Longer follow-up is necessary to estimate the influence of regression on visual acuity. We expect that different wavefront errors will be affected specifically by regression, for example spherical aberration may be more strongly influenced than coma-like aberrations. Such effects can be overcome by the strategy of tuning factors in the ablation algorithm that are different for different aberrations. However, such tuning factors should be determined only after 6 months when regression is most probably complete.

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Currently, the technique of wavefront-guided LASIK is proposed as an additional feature during refractive laser surgery for correction of ametropia. Although the procedure may be considered safe in this series because no visual loss occurred, this must be substantiated in prospective trials that include a larger number of patients. Once it has proven to be a safe and more effective procedure, wavefrontguided LASIK may also be applied to emmetropic eyes aiming toward improved visual acuity only.

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