# The Latest Fifth Generation LASIK: Amalgamation of Wavefront-Guiding, Femtosecond Laser Blade & Active Eye-Tracking

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## Abstract

LASIK, a widely performed surgical treatment for reshaping the cornea and correcting refractive errors of an eye, has reached its fifth generation under persistently improvements along with technological advancements since 1990s. The three most significant and innovative features of the new generation LASIK are introduced in this paper. They are wavefront-guiding technology, photodisrupting femtosecond laser blade and active eye-tracking technology respectively.

Shack-Hartmann wavefront sensor and Tscherning aberrometry of the wavefront-guiding technology measure and analyze the wave front of the distorted light rays exiting the eyeball due to the eye's built-in aberrations. An ablation pattern to recompense the built-in aberrations of the eye is constructed, and therefore provides customized LASIK treatments for patients suffering from refractive errors by correcting not only their eyes' errors but also their built-in aberrations.

By embarking laser-induced optical breakdown on corneal tissues, photodisrupting femtosecond laser blade offers a safer, high quality and precision replacement technique to traditional mechanical methods in performing necessary incision on the cornea.

Automatic active eye-tracking technology follows the patient's eye constantly and adjusts the relative positioning of delivered laser pulse to offset the motion of the eye during treatment such that each pulse is accurately placed on the cornea, producing smooth and precise reproduction of the desired ablation pattern.

The improvements that these three latest technologies in the newest generation of LASIK compared to conventional LASIK are presented and discussed.

## Introduction

Laser-assisted in situ keratomileusis, or LASIK, is the dominant surgical procedure for reducing refractive errors such as myopia, hyperopia, and astigmatism in the eye. In this procedure, a device called microkeratome is used to shear a thin, hinged 150-180 um flap in the cornea. The flap is then folded to expose the internal corneal tissue (stroma) for the shape modification by an excimer laser operating at a wavelength of 193 nm.[1] The laser permanently changes the shape of the cornea by ablating a small amount of targeted tissue from the front of the eye, just under the flap or epithelium. The sculpted pattern is relocated at the front surface of the cornea. In order to correct myopia, a smaller overall power of the eye is desired; hence the radius of curvature of the anterior cornea is ablated to be longer. In opposition, the radius of the cornea is made shorter to produce a higher overall power of the eye so as to correct hyperopia. For correction of astigmatism, a toric pattern is transferred to the surface of the cornea.[2] The flap is then replaced and acts as a natural bandage of healing the wound of the cut.

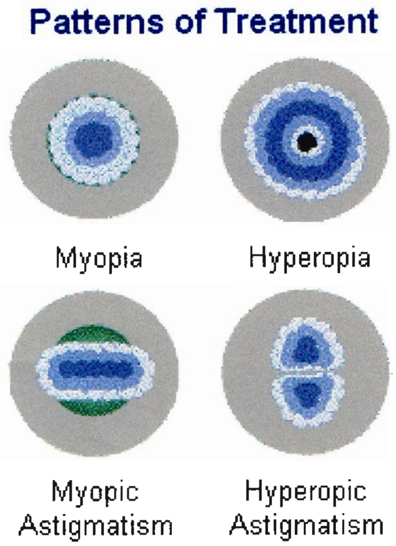

Figure 1: The sculpted patterns for correcting the four main refractive errors of the eye.

LASIK was first made available in the United States in 1996 and approximately 1.5 million LASIK procedures have been performed in 2002. The demand for LASIK and other refractive surgeries is expected to be astounding based on the fact that there are more than 140 million adults in the U.S. suffering from refractive errors.[3]

Conventional LASIK though proved to be successful, has a few down sides. Only about two-thirds of patients who undergo conventional refractive surgery achieve the desired 20/20 level of vision. Moreover, about 20% of patients suffer visual disability under darkened conditions due to halos and glare after surgery.[4] In other words, the desired vision does not hold under all lighting conditions, which is a serious threat to night driving. Furthermore, LASIK complications, occurring in as many as 5% of surgery cases, including intraoperative complications such as abrasions of the epithelium and incomplete cuts, and also postoperative complications for instance, flap slippage or dislocation and severe inflammation.[5]

In order to further increase and ensure the safety, reliability and accuracy of LASIK surgery, comprehensive researches and developments are undergoing by the optical academic community and the three leading optical surgery equipment and technology companies, which are Alcon, Baush & Lomb and VISX respectively. The three most critical technological advancements in LASIK surgery are wavefront-guided LASIK, femtosecond blade and active eye-tracking during surgery operation. This paper summarizes the improvements and optical technology involved in the three new technologies that give birth to the new generation of LASIK of enhanced precision and reliability.

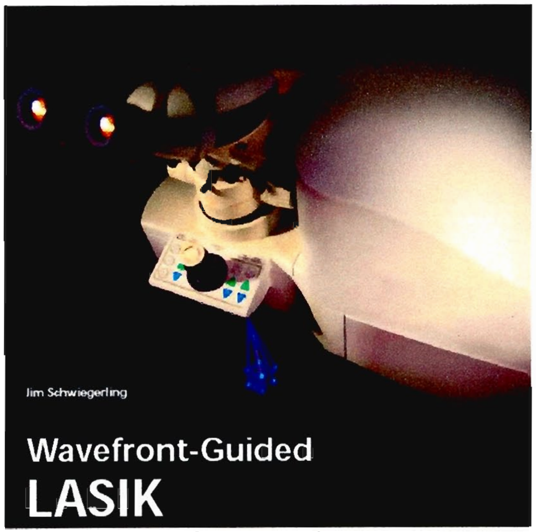

Figure 2: A wavefront-guided LASIK seven-beam laser designed to tackle conventional LASIK problems.

## Wavefront-Guided LASIK

Built-in aberrations are the limiting factors to the performance of a typical eye. Apart from replacing the Munnerlyn formula[6] that uses the preoperative corneal curvature and prescription of the patient to calculate the required ablation pattern, wavefront sensing also measures the eyeball's aberration content and is therefore capable of improving post-LASIK surgery visual performance dramatically. With the correction of built-in aberrations, resolution level of an eye could further be improved to the theoretical limit of 20/8. Low-contrast vision could also be improved as well.[7] With the application of wavefront sensing technology in LASIK surgery, the number of patients achieving uncorrected vision of 20/20 after surgery significantly increases and incidents of night vision problems are strikingly reduced. According to the Alcon FDA clinical trial conducted in 1999-2001, 90% of patients that had wavefront-guided LASIK achieved 20/20 or better vision after six months, comparing to 67% of conventional LAISK surgery.[8] Furthermore, the clinical trial of Bausch & Lomb's Zyoptix wavefront-guided system shows that 89% of patients – compared to 77% for conventional LASIK – reported that their night driving capability and post-surgery vision was the same or better under dim lighting conditions.[9]

There are mainly two wavefront sensing technologies being used in LASIK surgery – Shack-Hartmann sensor and Tscherning aberrometry.

**Shack-Hartmann wavefront sensor** was first developed by the astronomy community to measure aberrations caused by atmospheric turbulence.[10] This technique is then applied to the eye in LAISK surgery. Here is how the technique works:

First a dim laser beam is emitted and passes through the eyeball and is focused to a point on the retina. That point of light acts as a secondary light source due to scattering and radiates spherical wave fronts that pass out the eye. As these wave fronts travel through the internal optical constituents of the eye, they become distorted by the built-in aberrations of the eye. The exiting wave fronts then pass through an array of small, regularly spaced lenslets that accurately sample the wave front at various points. A perfectly planar wave front produces uniform spacing between the focal spots of the various lenslets, which lie on the same focal plane. On the other hand, an aberrated wave front produces non-uniform focal spots spacing. By utilizing the aberrations data shown by the focal spots spacing, an ablation pattern to recompense the built-in aberrations of the eye can be constructed.[11]

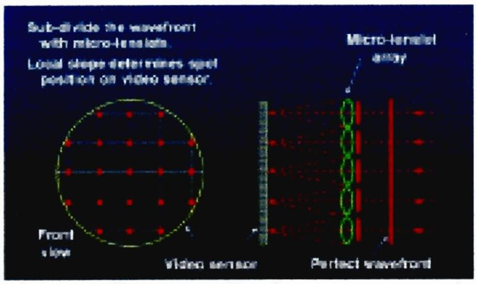

Figure 3: Hartmann-Shack sensors measuring an aberration-free wave front that is focused by the lenslets to a regular grid of spots.

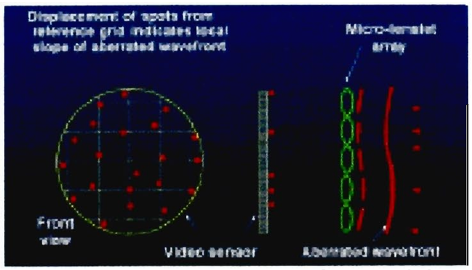

Figure 4: An aberrated wave front and the resulting distortion in the grid spacing of the spots is shown.

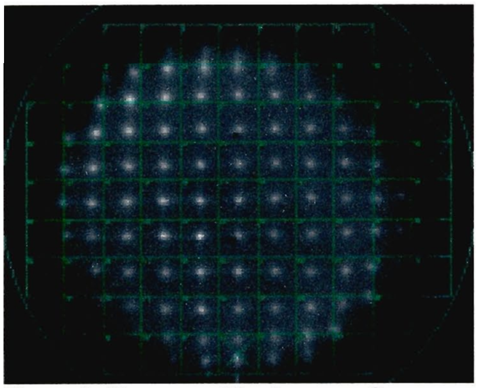

Figure 5: Hartmann-Shack output for a sample eye.

The other technique, Tscherning aberrometry, in opposition to the Shack-Hartmann technique measures the wave front converging towards the retina. First, a regular grid of pencils of light, generated by passing a collimated beam through a mask, enters the eye. The eye is made effectively myopic by placing a convex lens in front of the eye. Such setup causes the light to focus in front of the retina and further diverges to form a grid of pattern on the retina. A minified version of the grid pattern on the mask is observed for an aberration-free eye. Conversely, distorted grid pattern is found for eye with aberrations. A modified fundus camera is then used to capture the grid pattern on the retina. The transverse ray errors are calculated and a correction ablation pattern to compensate the eye's built-in aberrations is then constructed.[12]

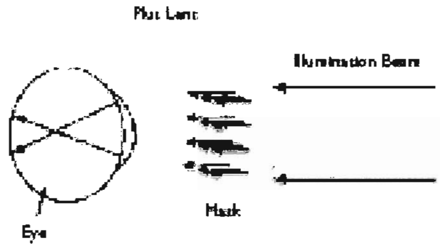

Figure 5: A mask is used to separate the illumination bean into a uniform grid of light pencils in a Tscherning aberrometer.

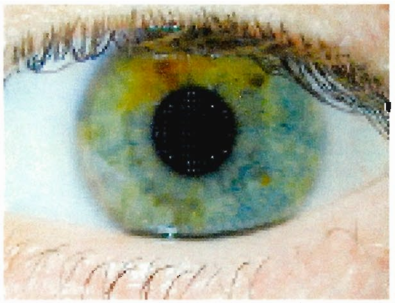

Figure 6: A minified grid of pattern is projected on the retina.

The two wavefront sensing techniques enable the provision of customized LASIK treatments for patients suffering from refractive errors by correcting not only their eyes' errors but also the built-in aberrations. The goal of achieving uncorrected vision of 20/20 is therefore greatly enhanced.

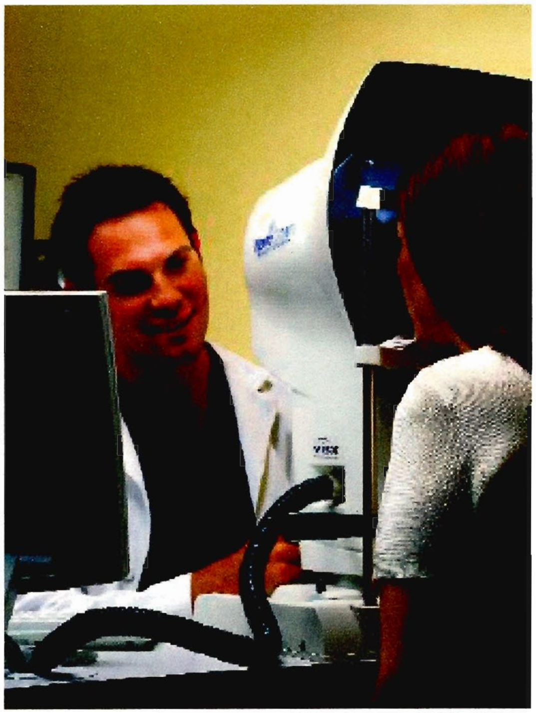

Figure 7: A patient's wave front is scanned to construct a customized ablation pattern.

## Femtosecond Blade

Tradionational LASIK uses mechanical blade, or microkeratome, to cut and create a corneal flap. Nonetheless, outcome variability and patient anxiety have always been the major concerns. Intraoperative and postoperative complications and the risk of delay in visual acuity recovery or even permanent loss of visual acuity arouse the urge to seek a safer and extra high-precision technique replacement to mechanical methods in performing the needed cut on cornea.

The photodisrupting femtosecond laser brings about a new generation of ultra-precision cutting technology by offering programmable incision geometries, micrometer feature sizes, minimal collateral tissue damage, and consistent cut quality.[13]

The photodiscruption procedure begins with laser-induced optical breakdown. A plasma state is created by strongly focused, short-duration laser pulse, which produces a high-density electric field. The hot plasma then displaces surrounding tissues and expands at supersonic velocity. As the expansion slows down, the displacement propagates through the surrounding tissues as a shock wave, which continues to lose energy and velocity, and eventually relaxed to an ordinary acoustic wave that disperses harmlessly. The rapid adiabatic expansion (less than 1 us) and small amount of deposited energy preclude significant heat transfer to surrounding tissue that might result in damages. Besides, experiments with femtosecond photodisruption have shown narrow collateral tissue damage zones in *ex vivo* tissue compared to cut by traditional mechanical blade.[14]

Figure 8: Laser-induced optical breakdown occurs at the beam focus. A high-density plasma then expands outward where Rs is the radius at which the shock wave has relaxed to an ordinary acoustic wave.

Femtosecond photodisruption also exhibits an important ability in controlling the optical breakdown process.

Optical breakdown proceeds generally by avalanche ionization, which is a highly nonlinear and probabilistic process. By operating with electric fields strong enough to produce seed carriers that initiate avalanche process through multiphoton and tunnel ionization, femtosecond pulses can achieve very deterministic and repeatable incision quality.[15]

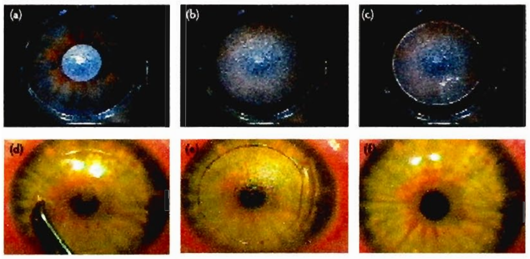

Figure 9: (a) and (b) show the scanning procedures before femtosecond laser incision; (c) successive arc cuts on the cornea; (d) and (e) show the elevation of the corneal flap; (f) postoperative appearance of the cornea after 1 week.

As a result, contiguous high-precision tissue separations are enabled by the computer-controlled femtosecond laser scanning optical delivery system, and therefore allowing the surgeon to precisely control flap parameters, for instance flap thickness, diameter and cut angle, which may affect clinical outcomes.

## Active Eye-Tracking

Patients are awake during LASIK treatment and their eyes are in constant motion during laser delivery. Therefore, the eyeball movements must be carefully and accurately tracked.

Tracking in conventional LASIK is done by a surgeon-controlled joystick that aligns the patient's eye to the laser axis. The surgeon can interrupt the pulse delivery if the eye drifts too far from the laser axis and carry on the treatment after realigning the patient.

In the new generation of LASIK, surgeon-guided eye-tracking is replaced by automatic active eye-tracker, which follows the patient's eye constantly and adjusts the relative positioning of delivered laser pulse to offset the motion of the eye during treatment. The technology of active eye-tracking is emerged from the Strategic Defense Initiative and video-based pupil detection techniques. By adjusting fast x-y mirrors to realign the laser pulse with the patient's eye and automatically terminate laser delivery when rapid eye motion is detected[16], active eye-tracker can ensure result of 8 micron accuracy within response time from 4 to 8ms[17] such that each pulse is accurately placed on the cornea, producing smooth and precise reproduction of the desired ablation pattern.

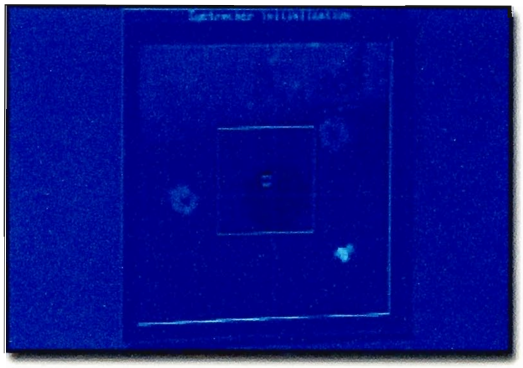

Figure 10: Active eye-tracker align laser pulse with the patient's eye automatically.

| Diopters of Correction Needed | 1 | 2 | 4 | 6 | 8 |
|---|---|---|---|---|---|
| Seconds of actual laser treatment | 4 | 7 | 14 | 21 | 27 |

*Times will vary depending on type of refractive error and the size of the treated optical zone

Figure 11: Automation and computer-controlled LASIK procedures enable the treatment to be completed in a very short period of time.

## Summary

This paper makes an overview of the three critical features, wavefront-guiding technology, photodisrupting femtosecond laser blade and active eye-tracking technology, that are incorporated in the latest fifth generation of LASIK. Clinical trials and real treatment practices results have confirmed the significant improvement in safety, surgery outcome precision, and most importantly the ability to provide customized correction tailored to the specific subtleties in refraction that characterize each individual.

In addition, inspirations of potentially further fine-tuning LASIK technology are embarked. For instance, efforts to adjoin reliable measurement and prediction of the mechanical response of the individual cornea to surgery to wavefront-guided treatment are under way. Moreover, LASEK and Epi-LASIK[18] are two emerging alternative refractive surgical techniques to combat the weakening of the cornea's surface mechanical strength and causing of bulging in peripheral cornea due to the incision during the treatment.

It is believed that hundreds of millions of people will eventually benefit from LASIK surgery technology and the persistent advancements of it. Hence, efforts and capitals have been devoted to lower the cost to an affordable level for the general public such that everyone could benefit from it.

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