Preoperative Simulation of Outcomes Using Adaptive Optics

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ABSTRACT

Measurements of the wavefront of light reflected from the retina of the human eye can be used to determine optical aberrations of the human eye for large pupils. An instrument based on the Hartmann-Shack principle was developed. The wavefront is refracted by a microlens array and detected by a CCD camera. In first clinical studies human volunteer eyes and preoperative and post-operative refractive surgical patient eyes have been examined. An adaptive optical closed loop system has been devised for preoperative simulation of refractive outcomes of aberration free refractive surgical procedures. [*J Refract Surg* 2000;16: S608-S610]

Wavefront technology was originally developed for astronomy applications. It was used to measure wavefront distortions that occurred when light traveling through the atmosphere entered an optical telescope. By applying adaptive optical closed loop controls, the speckle patterns of the star images could be improved toward diffraction-limited performance. Most of the technology was developed in association with anti-missile defense systems research in the late 1970s.

Starting in 1978, the principle of wavefront measurement and compensation was adapted at the University of Heidelberg for ophthalmic applications. The technique is based on Hartmann-Shack wavefront sensing—measuring the optical path of light rays through the eye to detect the higher order aberrations in the optical system of the human eye. Adaptive optical systems were developed that measure and compensate wave aberrations of the human eye with closed loop control.[1,2]

Recently, the application of wavefront sensing for preoperative evaluation of refractive surgical procedures has been proposed. Adaptive optical closed loop systems can be used to measure objectively higher order optical aberrations of the human eye. The patient can then be shown the resulting correction and be asked to adjust it to their preference. The final result of this process can be used as the parameters for the surgical procedure.

MEASUREMENT OF THE OPTICAL ABERRATIONS OF THE HUMAN EYE

In Figure 1, the principle of operation of a Hartmann-Shack wavefront sensor is demonstrated. On the left side, the processing of an ideal plane wave is depicted. The incident plane wave results in a square grid of spots in the focal plane of the microlens array. On the right side, the imaging of a distorted wave is shown. The distorted wavefront causes lateral displacements of the spots on the CCD array. From the spot pattern the shape of the incident wavefront can be reconstructed based on appropriate curve fitting algorithms.

In Figure 2 the results of wavefront measurements on two human eyes are shown. The dependence of the root mean square (RMS) wavefront error (RMS in µm) on the diameter of the pupil is plotted. The optical aberrations of the human eye increase considerably with larger pupil sizes.

CLINICAL RESULTS OF REFRACTIVE WAVEFRONT MEASUREMENTS

The clinical validity of wavefront measurements was tested on human volunteer and refractive surgical patient eyes. In Figure 3, the computer display of the WaveScan instrument is shown demonstrating the wavefront results of a human volunteer eye. In the lower left part of the display, the AcuityMap

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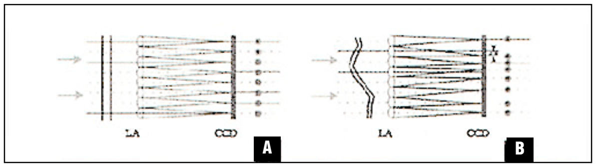

Figure 1. Principle of operation of a Hartmann-Shack wavefront sensor. **A)** Plane wave, **B)** Distorted wave.

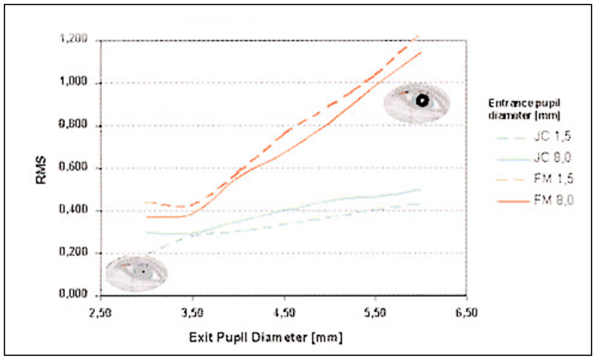

Figure 2. Root mean square (RMS) error independent of pupil diameter.

over a 5 mm pupil is depicted. In the lower center of the display the higher orders of the optical aberrations beyond sphere and astigmatism are plotted demonstrating considerable wavefront deviations in the outer segments of the pupil, even in a case of a 20/15 human eye. In Figure 4, the computer display of the WaveScan instrument is shown depicting the measurement data of a patient eye that had photorefractive keratectomy (PRK) previously. The image of the high order optical aberration in the lower part of the display indicates the presence of a small coma aberration.

PRINCIPLE OF ADAPTIVE-OPTICAL CLOSED LOOP CONTROL

In Figure 5, the principle of adaptive optical closed loop control is schematically demonstrated. The wavefront of light that is distorted due to optical aberrations of the optical system, eg, the human eye, is measured by a wavefront sensor. The reconstructed wavefront is dithered on a wavefront controller, eg an active mirror, to compensate for the associated optical aberrations. Finally, an aberration free optical image through an aberrating medium can be achieved.

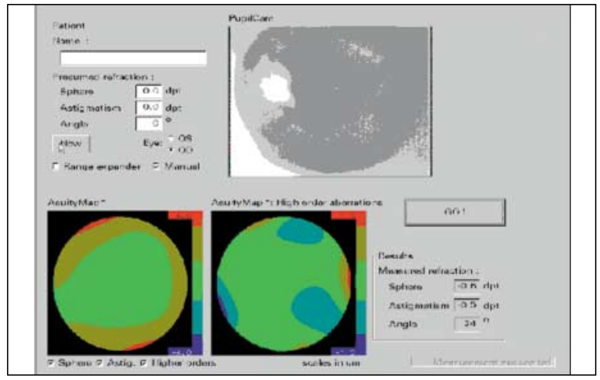

Figure 3. Computer display AcuityMap images of a normal eye.

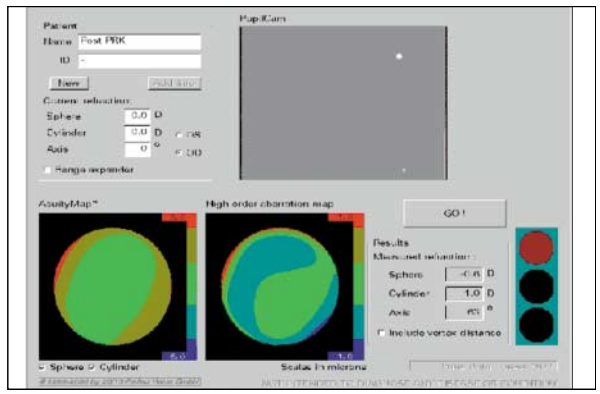

Figure 4. Computer display of AcuityMap images of an eye after photorefractive keratectomy.

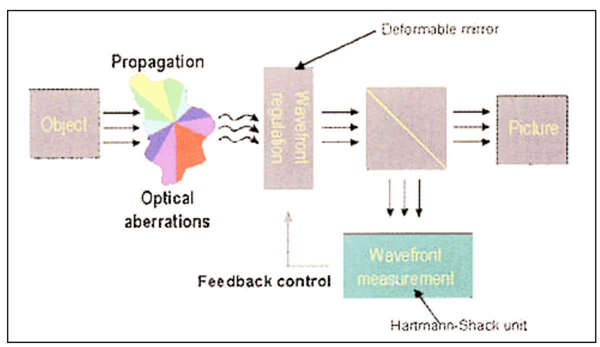

Figure 5. Schematics of a closed loop adaptive optical system.

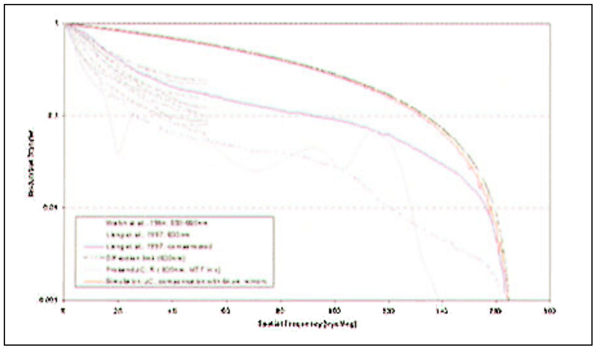

Figure 6. Preoperative simulation of refractive outcome using closed loop adaptive optical control.

PREOPERATIVE SIMULATION OF SURGICAL OUTCOMES USING ADAPTIVE OPTICS CLOSED LOOP CONTROL

In Figure 6, measurements and simulations of the preoperative evaluation of aberration-free refractive surgical procedures are summarized. The simulation results are based on the application of multi micromirror integrated active mirror matrices. In all situations the modulation transfer function (MTF) is plotted in dependence of the spatial frequency (cycles per degree). A number of modulation transfer functions for normal human eyes are plotted, as well as the modulation transfer function for an ideal 6 mm pupil human eye. Simulations of visual improvement using closed loop compensation of mirrors with 64-µm micromirror size and 116-µm micromirror size, respectively, are demonstrated. It is obvious that the application of segmented multi-micromirror active mirror systems can be applied reliably for simulating diffraction limited performances of human eyes preoperatively, enabling the surgeon to test subjectively the influence of higher order optical aberrations on the visual performance of human eyes.

REFERENCES

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2. Liang J, Grimm W, Goelz S, Bille JF. Objective measurement of the wave aberrations of the human eye using a Hartmann-Shack wavefront sensor. J Opt Soc Am A 1994;11:1949-1957.