

Adaptive Optics Technology: Clinical Use of Visual Simulators

Visual simulators may alter refractive surgery planning and management.

BY KAROLINNE MAIA ROCHA, MD, PhD

Visual performance may be degraded by several kinds of optical phenomena, including wavefront aberrations, light scatter, and diffraction. Ocular wavefront sensing has been used to assess lower- and higher-order aberrations (HOAs) and to better understand the limits of visual function. Adaptive optics simulators, which build on this concept, allow eye care professionals to mathematically image the effect of aberrations and to measure, correct, and even produce simulations with induced aberrations.

Compact versions of adaptive optics visual simulators make it possible to reliably correct and simulate individual HOAs in the clinical setting.¹⁻⁸ This technology could prove valuable for anticipating outcomes in highly aberrated eyes such as symptomatic post-LASIK patients as well as to explore presbyopic corrections and neuroadaptation in a clinical environment.

COMPONENTS OF THE ADAPTIVE OPTICS VISUAL SIMULATOR

Adaptive optics technology has two components: a repeating wavefront sensor and a deformable mirror, which compensates for the wavefront error in real time. The shape of a deformable mirror is generally controlled by an array of actuators. Fernández and coauthors^{5,6} have demonstrated that the deformation range of an electromagnetic deformable mirror is more than 50 μm , making it suitable for the correction of wavefront aberrations in a wide variety of human eyes.

My colleagues and I performed a series of experiments with the crx1 Adaptive Optics Visual Simulator (Imagine Eyes) to understand the capacity to measure, correct, and modify patients' ocular aberrations. Three operating procedures are available:

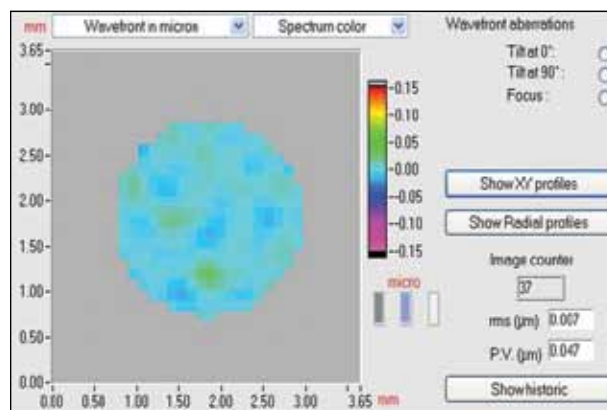


Figure 1. Wavefront measurement: ocular wavefront aberrations are recorded while the deformable mirror is set to an aberration-free shape.

- 1. Wavefront measurement.** Ocular wavefront aberrations are recorded while the deformable mirror is set to an aberration-free shape (Figure 1).
- 2. Static wavefront correction/generation.** User-defined aberrations are applied and maintained during the experiments (Figure 2).
- 3. Dynamic wavefront correction/generation.** User-defined aberrations are applied using a closed-loop system that comprises a double-pass of light through the eye so that the total aberration encountered along the line of sight remains constant.

The pupillary size can be artificially adjusted according to each experiment by selecting the diameter of an internal aperture. An eye-tracking system monitors the relative positions of the instrument's optical axis and the subject's pupil throughout the visual simulation.

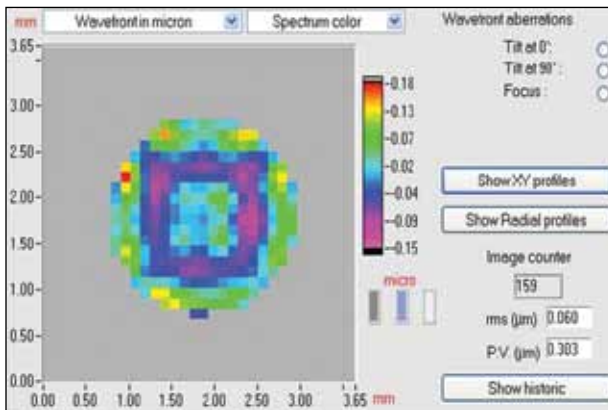


Figure 2. Static wavefront correction and generation: In this example, $0.6 \mu\text{m}$ of spherical aberration for a 6-mm pupillary diameter is applied and kept constant.

The simulator software continuously displays a residual wavefront value to monitor the fidelity of the wavefront generated by the deformable mirror.

USING ADAPTIVE OPTICS TECHNOLOGY TO ENHANCE VISION

In an experiment, my colleagues and I evaluated changes in visual acuity induced by individual Zernike ocular aberrations that were generated by the electromagnetic adaptive optics visual simulator.¹ After ocular aberrations were measured, the device was programmed to compensate for the eye's wavefront error, and different individual Zernike aberrations, using a 5-mm pupil, were successively applied. The generated aberrations included defocus, astigmatism, coma, trefoil, and spherical aberration, at a level of 0.1, 0.3, and $0.9 \mu\text{m}$. We assessed the visual acuity through the adaptive optics system using computer-generated Landolt-C optotypes (Freiburg Acuity Test – FrACT).⁹

The simulated correction of the aberrations present in the subjects' eyes (HOA correction) improved their visual acuity by a mean of 1 line (-0.1 LogMAR) when compared with their best spherocylindrical correction. The induced HOA in an amount of $0.1 \mu\text{m}$ root mean square (RMS) of Zernike aberrations resulted in a limited decrease in visual acuity (mean, $+0.05 \text{ LogMAR}$), and $0.3 \mu\text{m}$ RMS of Zernike aberrations induced visually significant acuity losses with a mean reduction of 1.5 lines ($+0.15 \text{ LogMAR}$). Larger aberrations with a magnitude of $0.9 \mu\text{m}$ RMS of Zernike aberrations resulted in a greater impairment of visual acuity that was more pronounced with spherical aberration ($+0.64 \text{ LogMAR}$) and defocus ($+0.62 \text{ LogMAR}$), and trefoil ($+0.22 \text{ LogMAR}$) was found to be better tolerated.

In this experiment, the simulated correction of HOAs

improved the visual acuity to a greater degree when compared with best spectacle correction. The introduction of both positive and negative spherical aberration using adaptive optics technology significantly shifted and expanded the subjects' overall depth of focus.

ENHANCED VISUAL ACUITY AND IMAGE PERCEPTION IN HIGHLY ABERRATED EYES

The crx1 Adaptive Optics Visual Simulator was used to correct the wavefront aberrations of 12 eyes of eight patients with keratoconus and eight eyes of five patients who were symptomatic after refractive surgery. We first measured the patients' ocular aberrations and then programmed the device to compensate for the eyes' wavefront error up to the second and then alternatively up to the fifth order for a 6-mm pupillary diameter. Visual acuity and visual perception were assessed through the adaptive optics system using computer-generated ETDRS optotypes and the Freiburg Acuity Test⁹ displayed on the internal miniature monitor.

The mean HOA errors in the keratoconic and symptomatic postrefractive surgery eyes were $1.88 \pm 0.99 \mu\text{m}$ and $1.62 \pm 0.79 \mu\text{m}$ (6-mm pupil), respectively. The visual simulator correction of the HOAs present in the keratoconic eyes improved visual acuity by a mean of 2 lines when compared with best spherocylindrical correction (mean decimal visual acuity with spherocylindrical correction was 0.31 ± 0.18 and improved to 0.44 ± 0.23 with HOA correction). In the symptomatic postrefractive surgery eyes, the mean decimal visual acuity with spherocylindrical correction improved from 0.54 ± 0.16 to 0.71 ± 0.13 with HOA correction (mean, 1.5 lines). The visual perception of ETDRS letters was strongly improved when correcting HOAs. The adaptive optics visual simulator was able to effectively measure and compensate for the HOAs (second to fifth order), which are commonly associated with diminished visual acuity and perception in highly aberrated eyes.³

APPLICATION IN PRESBYOPIC CORRECTION

In the case of eyes with presbyopia, inducing specific HOAs may expand the depth of focus (DoF) without significantly compromising the quality of vision. Nio et al found that spherical and irregular aberrations increase the DoF yet decrease the modulation transfer at high spatial frequencies.¹⁰ Cheng et al reported that spherical aberration, coma, and secondary astigmatism increase DoF.¹¹ The fundamental principle behind several presbyopic laser ablation procedures is to create a hyperprolate cornea that basically induces negative spherical aberration to the optical system.

We performed another experiment using the adaptive optics visual simulator to optically introduce individual aberrations in patients under cycloplegia: coma and trefoil at magnitudes of $\pm 0.3 \mu\text{m}$ and spherical aberration at ± 0.3 , ± 0.6 , and $\pm 0.9 \mu\text{m}$ for a 6-mm pupillary diameter. A through-focus response curve was assessed by recording the percentage of Sloan letters at a fixed size identified at various target distances. The subject's ocular DoF and center of focus were computed as the half-maximum width and the midpoint of the through-focus response curve.

The simulation of either positive or negative spherical aberration had the effect of enhancing the DoF and resulted in linear shifting of the center of focus by $2.6 \text{ D}/\mu\text{m}$ of error. This increase in DoF reached a maximum of approximately 2.00 D with $0.6 \mu\text{m}$ of spherical aberration and became smaller when the aberration was increased up to $0.9 \mu\text{m}$.² The introduction of both positive and negative spherical aberration using adaptive optics technology significantly shifted and expanded the subjects' overall DoF.

SUMMARY

Adaptive optics visual simulators represent a new paradigm in refractive surgery planning and management. This technology may be of clinical benefit when counseling highly aberrated patients regarding their maximum subjective potential for custom vision corrections. The crx1 can be successfully used in both normal and highly aberrated eyes. The possibility of assessing the limits of human vision by manipulating and correcting ocular aberrations provides a unique tool for predicting the potential benefits of custom treatments and neuroadaptation. Spherical aberration and pupillary diameter manipulation have a great impact on DoF and presbyopic correction. I anticipate that adaptive optics technology will help determine the most functional aberration values for the typical presbyopic patient, which will contribute significantly to the design of presbyopic corneal and lens-based treatments. ■

This article was reprinted with permission from Advanced Ocular Care. The article originally appeared in the July/August 2012 issue of AOC.

Karolinne Maia Rocha, MD, PhD, is from the Cole Eye Institute, Cleveland Clinic Foundation. She acknowledged no financial interest in the products or companies mentioned herein. Dr. Rocha may be reached at (216) 445-2020; karolinnemaia@gmail.com.



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