

MEMS-based adaptive optics scanning laser ophthalmoscopy

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We have developed a compact, robust adaptive optics (AO) scanning laser ophthalmoscope using a micro-electromechanical (MEMS) deformable mirror (DM). Facilitated with a Shack–Hartmann wavefront sensor, the MEMS-DM-based AO operates a closed-loop modal wave aberration correction for the human eye and reduces wave aberrations in most eyes to below $0.1 \mu\text{m}$ rms. Lateral resolution is enhanced, and images reveal a clear cone mosaic near the foveal center. The significant increase in throughput allows for a confocal pinhole whose diameter is less than the Airy disc of the collection lens, thereby fully exploiting the axial resolution capabilities of the system. © 2006 Optical Society of America

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The invention of the confocal scanning laser ophthalmoscope (SLO) by Webb *et al.*^{1,2} represented a major advance in ophthalmoscopy. The confocal SLO possesses many of the merits of the confocal scanning mechanism, such as enhanced resolution and optical sectioning ability, a series of facts that were very well treated in the literature.^{3,4} But SLO imaging quality is unfortunately degraded by the ocular aberrations of the human eye, which is the objective lens that a SLO system has to employ. The recent report of the adaptive optics (AO) SLO (AOSLO) by Roorda *et al.*⁵ demonstrated a system that used AO to overcome the limits imposed by ocular aberrations and produced real-time, microscopic views of the living human retina with unprecedented optical quality and axial resolution.⁶

AO has proved to be indispensable for high-quality ophthalmic optical imaging, and the deformable mirror (DM) plays a key role in the realization of an AO system. Dreher *et al.*⁷ used a 13-segment DM to compensate for the astigmatism of the eye. Liang *et al.*⁸ successfully employed a 46 mm aperture, 37 channel mechanical DM (Xinetics, Andover, Massachusetts) to correct high-order ocular aberration. Based on that system, Hofer *et al.*⁹ realized a dynamic closed-loop AO retinal imaging system and further improved the image quality. Improvements of the same system were achieved with a 97 channel Xinetics DM by Palikaris *et al.*¹⁰ Fernandez *et al.*¹¹ and Hermann *et al.*¹² applied a 37 channel micromachined membrane DM (OKO Technologies, The Netherlands). Vargas-Martin *et al.*¹³ exploited a transmissive liquid-crystal spatial light modulator. More recently, Doble *et al.*¹⁴ explored a prototype microelectromechanical (MEMS) DM [Boston Micromachines Corporation (BMC), Watertown, Massachusetts] for AO in the human eye. Evidently, the evolution of AO systems used for vision applications, to a very large extent, has been marked by the manufacturing technology progress of the DM. Judged by the actuator density, maximum stroke, response speed, compactness, and potentially low cost, the MEMS DM demonstrates a significant advantage in building a robust AO system and represents the most promising technology. BMC has developed the MEMS DM from a prototype to a

real product that,¹⁵ to a reasonable degree, meets the requirements of AO systems for visual optics.¹⁶

Shown in Fig. 1 is the MEMS-DM-based AOSLO. The light from the single-mode fiber is collimated and relayed by the telescope and beam splitter BS to the DM, the horizontal scanner HS, the vertical scanner VS, and finally the eye, forming a raster scan on the retina. The diffusely reflected light from the retina transmits inversely along the ingoing path to the beam splitter, where most of the light passes through and is relayed by a telescope to the collection lens. A confocal pinhole is placed at the focal point of the collection lens, and the signal is received by the photodetector, further processed, and acquired by the computer for storage and display. The DM, the lenslet array of the Shack–Hartmann wavefront sensor, HS, VS and the collection lens CL are aligned so that they are all conjugate to the entrance pupil of the eye. The wavefront is corrected for both the ingoing path (for a sharp focus on the retina) and the outgoing path (for

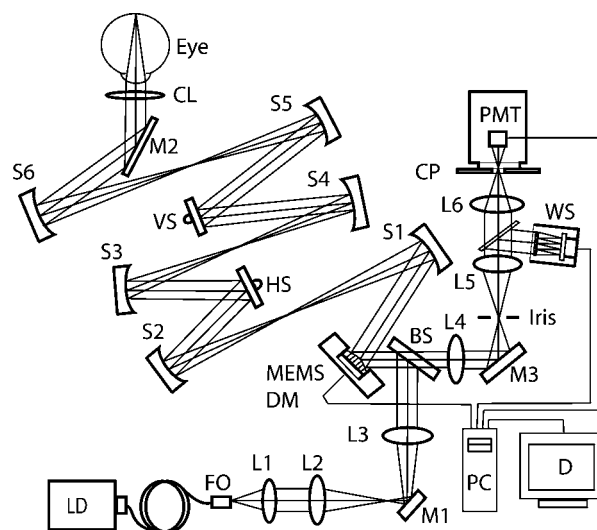


Fig. 1. LD, laser diode; FO, fiber output; PC, computer; D, display; BS, beam splitter; HS, horizontal scanner (16 KHz), VS, vertical scanner (30, 60 Hz); CL, cylindrical lens; WS, wavefront sensor; CP, confocal pinhole; PMT, photomultiplier tube; L1–L6, achromatic lenses; M1–M3, flat mirrors; S1–S6, spherical mirrors.

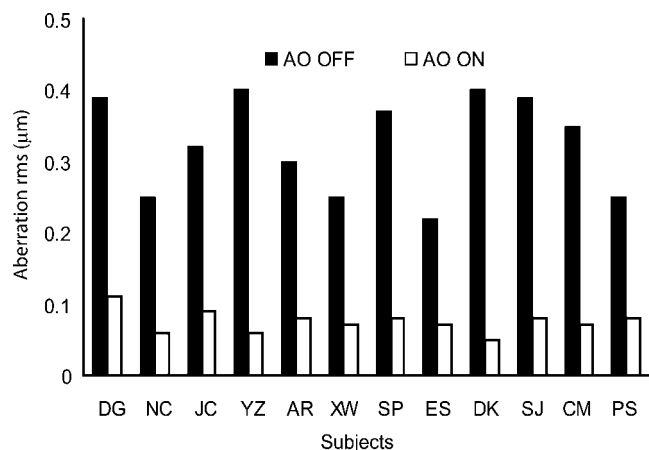


Fig. 2. MEMS-DM-based AO performance.

a sharp image of the focused spot on the confocal pinhole).

The MEMS DM has an active area of 4.4 mm \times 4.4 mm and 12 \times 12 actuators with a maximum stroke of 3.5 μ m. With the miniaturized optical aperture, we were able to design a compact and robust optical system occupying about 50 cm \times 50 cm on a mobile optical table while keeping the system aberrations diffraction limited over an imaging field of up to 3° \times 3°. A Shack–Hartmann wavefront sensor with a lenslet array of 0.328 mm \times 0.328 mm pitch and 24 mm focal length was employed to measure the eye's wavefront. A modal approach was adopted to run the AO closed loop. A tenth-order Zernike polynomial was fitted to the wavefront slopes. The actuator deflections were then calculated directly from the best-fit wavefront. We adopted a proportional control strategy and achieved a closed-loop update frequency of 10 Hz.

Two light sources are employed in the AOSLO for different scientific purposes. One is a diode laser whose wavelength is 655 nm, and the other is an 840 nm low-coherence superluminescent laser diode (SLD) (Broadlighter S840-HP, Superlum, Russia), which is used to reduce interference artifacts in the images.¹⁷

Human eyes were dilated (one topically applied drop each of 0.5% tropicamide and 2.5% phenylephrine). Before running the AO, we used trial lenses to minimize the defocus and astigmatism so that we would not saturate the DM actuators. The illumination powers for the 655 nm diode laser and the 840 nm SLD were set at 60 and 300 μ w, respectively, which are well below the ANSI safe exposure level.

Figure 2 shows the rms wave aberrations before and after AO correction. All but one subject were corrected to better than 0.1 μ m rms on average. The AO correction, consequently, demonstrates a threefold benefit for imaging, which includes increased brightness, improved contrast, and enhanced lateral resolution of the images, as shown in Fig. 3.

The robustness of the MEMS-DM-based AO is also demonstrated by its formation of a very compact focused spot at the confocal pinhole via the collection lens. This enables us to use smaller pinholes while maintaining a decent signal-to-noise ratio for imag-

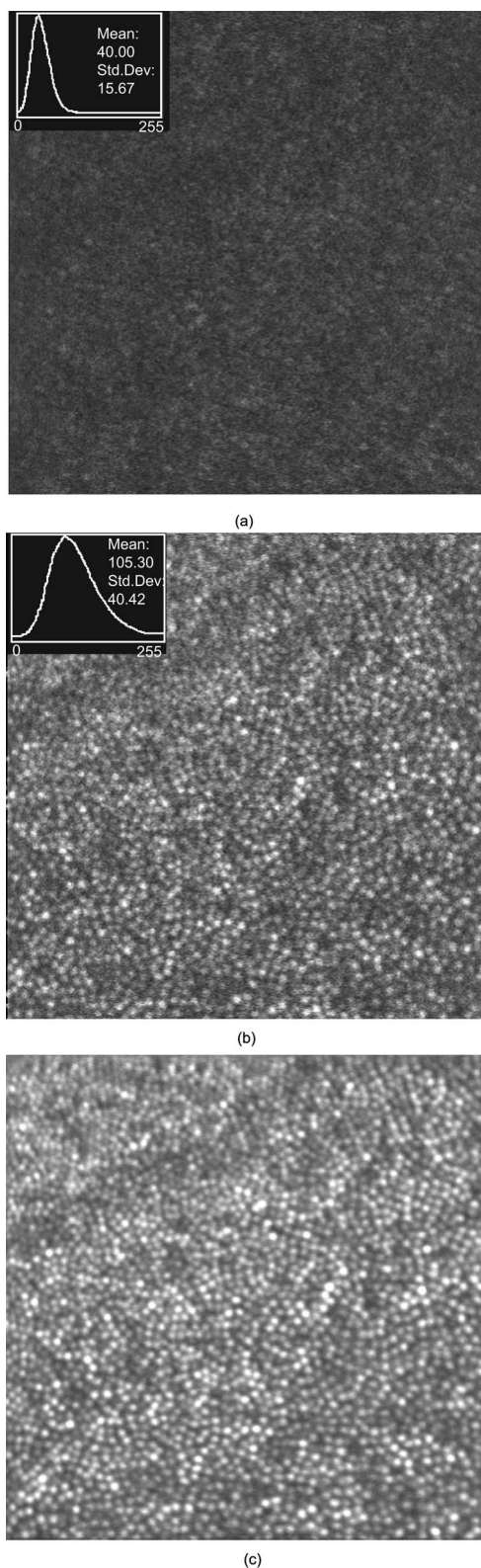
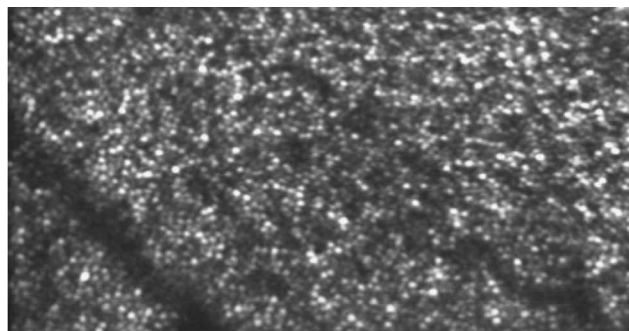
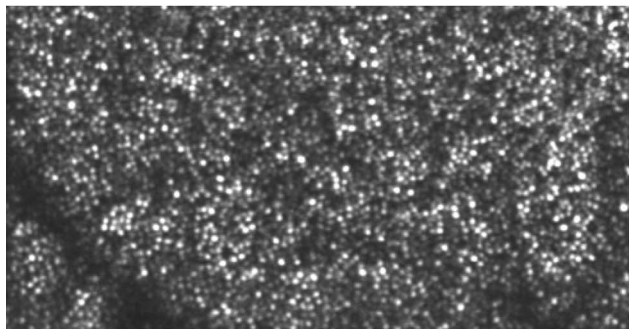


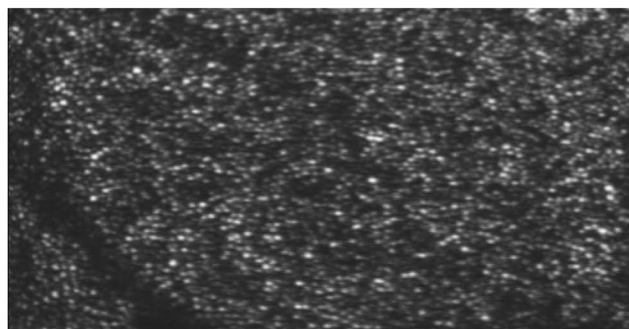
Fig. 3. (a) Single frame taken before AO correction but after the best correction of defocus and astigmatism with trial lenses; (b) single frame taken after AO correction. (c) Registered set of 10 AO-corrected images. All images have been corrected for distortions due to eye movements.¹⁸ These images were taken from a retinal location about 1° from the fovea center. The field of view subtends 0.9°, or approximately 270 μ m on a side. The image was taken with the 840 nm SLD.



(a)



(b)



(c)

Fig. 4. (a)–(c) Images taken with the 655 nm diode laser by using a (a) 75 μm , (b) 50 μm , and (c) 25 μm pinhole. The location is about 1° from the foveal center, and the field of view is $1.5^\circ \times 0.75^\circ$.

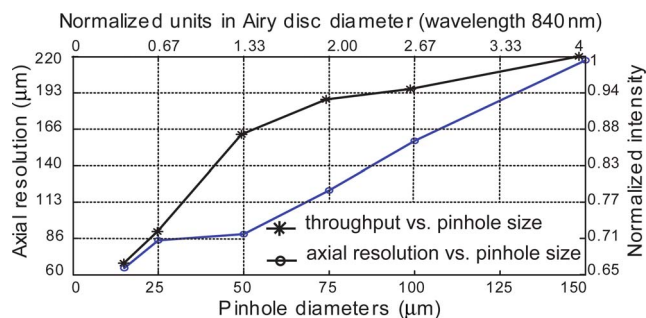


Fig. 5. (Color online) (Color online) With smaller pinholes, the expected axial resolution, shown on the left ordinate, is improved, whereas the throughput, which is normalized by the intensity obtained by the 150 μm pinhole and marked on the right ordinate, decreases.

ing. Figure 4 shows the images that were obtained from the same retinal area of a subject by using 75, 50, and 25 μm pinholes. We need to note that the 25 μm pinhole is only 0.833 times the Airy disc diameter of the collection optics (5.4 mm diameter beam, 100 mm focal length, 655 nm light). Figure 5 plots the expected improvement in axial discrimination capability as a function of pinhole size, as measured from a model eye with a diffusely reflecting retinal surface. The improved resolution comes at the cost of reduced throughput. A 50 μm pinhole represents a good compromise between axial resolution and light throughput, and thus a good imaging signal-to-noise ratio.

In conclusion, we have developed a compact and robust MEMS-DM-based AOSLO. The improved performance allows us to use confocal pinhole sizes that are small enough to fully exploit the axial resolution capabilities of a confocal SLO.

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