High resolution mosaic image of capillaries in human retina by adaptive optics

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Received November 4, 2004

Adaptive optics (AO) has been proved as a powerful means for high resolution imaging of human retina. Because of the pixel number of charge-coupled device (CCD) camera, the field of view is limited to 1°. In order to have image of capillaries around *vivo* human fovea, we use mosaic method to obtain high resolution image in area of $6^\circ \times 6^\circ$. Detailed structures of capillaries around fovea with resolution of 2.3 μm are clearly shown. Comparison shows that this method has a much higher resolution than current clinic retina imaging methods.

OCIS codes: 010.1080, 120.3890, 170.3880, 330.4460.

The diffraction limited high resolution image is pursued by both scientific research and applications. Retina of human eye is the only organ the inner structure of which can be observed without injury. High resolution *vivo* human retina imaging has strong potential application in very early clinic ophthalmologic diagnosis. However, resolution of retinal imaging is limited by the aberration of eye, especially high order aberration. Adaptive optics (AO) has been proved to be a powerful means of obtaining retinal image with resolution approaching to the diffraction limit by compensation for the higher order aberrations of eye[1,2]. It has been shown that the photoreceptors and the smallest capillaries of retina can be clearly imaged by AO. However, the field of view of AO ophthalmoscope is limited to about 1° by the pixel number of charge-coupled device (CCD) camera. High resolution images of larger area are important for establishing the atlas of retina. In the laboratory of Center of Vision Science, University of Rochester, we have seen a mosaic image of photoreceptors. The morphology of capillaries is more important for very early diagnosis of disease. To our knowledge, no high resolution image of capillaries in a larger area has been ever published.

We have established an AO system for retina imaging[2]. By using this system, a picture of capillaries of $6^\circ \times 6^\circ$ around *vivo* human fovea has been obtained by mosaic method. In this letter, after brief description of the AO system, the high resolution image and the comparison with current ophthalmoscopes are presented.

The optical schematic is shown in Fig. 1. A commercial laser diode (LD) with output wavelength of 780 nm and output power of 10 mW is used as the beacon. The output beam of beacon is collimated as a parallel light beam after passing through a spatial filter and the beam expander, reflected by the mirror and the beam splitter, and projected into human eye pupil.

The backward scattering light from the human eye retina exits through the eye pupil, passes through dichroic mirror, beam expander telescope, deformable mirror (DM), beam condenser, mirror and beam splitter, and projects into the Hartmann wave-front sensor (WFS). The wave-front slope data measured by the WFS is acquired by a computer. By using the directed slope algorithm and control algorithm[3], the slope data are transferred directly to control signals. The control signals are amplified by the high-voltage amplifier and used to drive the DM to realize close-loop control. After

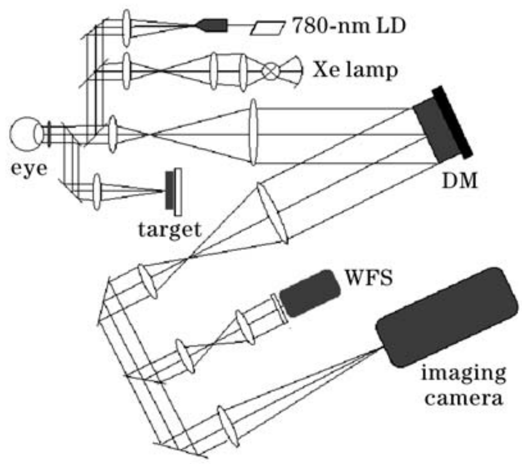

Fig. 1. Schematic of the AO for human eye retina imaging.

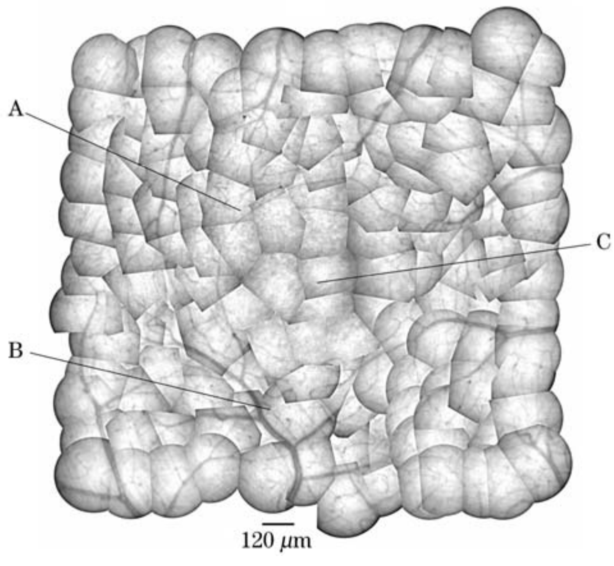

Fig. 2. Mosaic of capillary images around the fovea ($\pm 3^\circ \times \pm 3^\circ$).

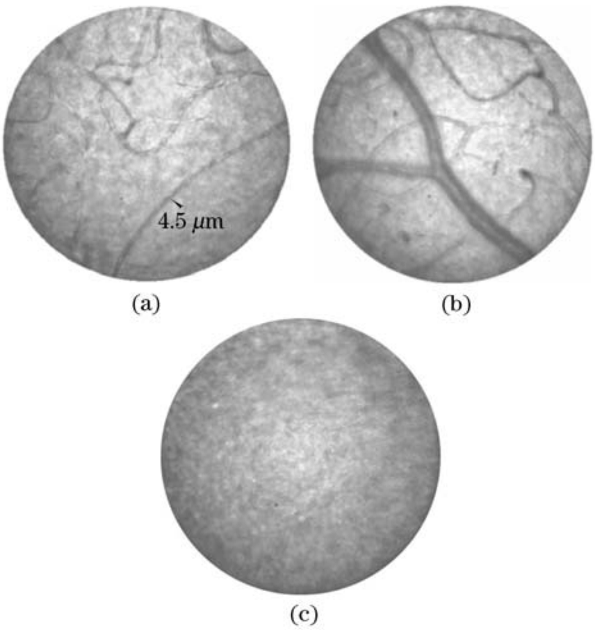

Fig. 3. Three enlarged segments marked A, B, C in Fig. 2. In the center of fovea (c), there is no capillaries.

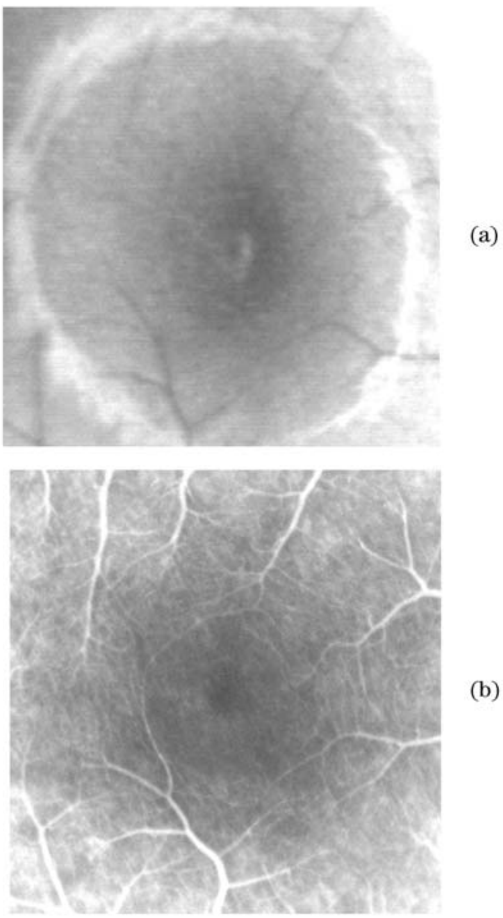

Fig. 4. Photographs of the same area as in Fig. 2 taken by fundus camera (a) and FFA camera (b).

close-loop operations, the residual wave-front error approaches to the minimum and the system is stable, meanwhile the computer triggers a flash lamp to illuminate the human eye retina. The illuminating light reflected from the retina propagates along the same optical path as the above mentioned backward scattering light, passes through the dichroic mirror, and arrives at the imaging CCD camera.

A target plate with an array of independently controlled light spots is used. When the inspected eye stares at a lighted spot, the eye rotates at a definite off-axis angle and the respective part of retina can be observed. The field of the target is $\pm 6°$ by $\pm 6°$. The imaging camera is mounted on a focusing mechanism. By adjusting the position of the camera, the structures at different layers of retina can be imaged at the imaging CCD. The first 20 order Zernike modes can be corrected effectively. Two layers of human retina, photoreceptors and capillaries, can be clearly imaged. The distance between these two layers in retina is 81—91 μm. The average full-width at half-maximum (FWHM) of the point spread function after correction is 2.37 μm, equal to 1.10 diffraction limit.

Detailed capillary distribution images cover $\pm 3°$ by $\pm 3°$ field around the fovea was obtained in our experiment, as shown in Fig. 2. Figure 2 is a mosaic image, every segment of which can be enlarged as a high resolution capillary photograph of corresponding part of retina. Figure 3 shows three enlarged segments of Fig. 2. The tube structure of the capillary and blood cells in the capillary can be clearly resolved. The diameter of capillary in the right-bottom of Fig. 3(a) is 4.5 μm. Figure 3(c) shows that there are no capillary at the center of fovea. This result is coincident with the result of anatomy. To our knowledge, this picture is the first reported high resolution capillary image of retina around the fovea.

For comparison, the retina images of the same part of Fig. 2 were taken by a fundus camera (VISUPAC /System 450 from Carl Zeiss Jena GmbH) and a fundus fluorescein angiography (FFA) camera (Visual Evoked Response Imaging System VERISTM Clinic 4.9 from Electro Diagnostic Imaging), as shown in Fig. 4. Comparing Fig. 2 with Fig. 4, it is clearly shown that the resolution of images taken by adaptive optical system is much higher than by the current clinic instruments.

In this paper, it is shown that high resolution images of capillaries in human retina can be obtained by adaptive optical system for retina imaging. The higher resolution of this system than current clinic ophthalmoscopes provides its potential applications for very early diagnosis of diseases related to retina.

This work was supported by the National Natural Science Foundation of China (No. 604380330), the National "863" Program of China (No. 2003AA136012), and the Intelligence Innovation Engineering of Chinese Academy of Sciences (No. 1999(108)). N. Ling's e-mail address is adopse@ioe.ac.cn.

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