Parallel line scanning ophthalmoscope for retinal imaging

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2016

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Purpose

To visualize the retinal structures using a newly developed parallel line scanning ophthalmoscope (PSLO) [1].

Materials & Methods

IN THE OPTICAL DESIGN THE SCANNING MIRRORS ARE REPLACED BY A DIGITAL MICROMIRROR DEVICE (DMD).

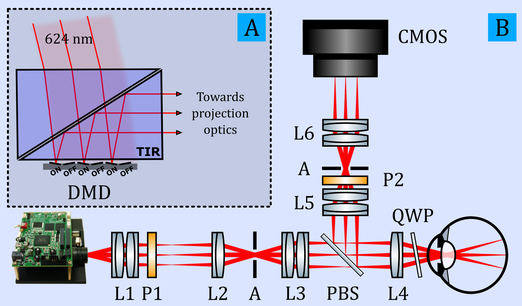
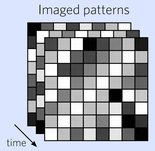


Fig. 1. Optical layout of the PLSO system. (A) The DMD is illuminated with 624 nm light and the light propagates via the on-switched micromirrors out of the TIR prism. (B) Polarizing optics are used to reduce the effects of reflections within the system. L: achromatic doublet lens, P: linear polarizer, A: aperture, PBS: polarizing beamsplitter, QWP: quarter wave-plate, TIR: total internal reflection prism, DMD: digital micromirror device, CMOS: global shutter camera.

TECHNICAL DETAILS

Imaging wavelength:	624 nm
Optical power on the cornea:	100 µW
Binary pattern projection speed:	100 Hz
Camera frame rate:	180-720 fps

THERE ARE NO PINHOLES SO THE CONFOCALITY HAS TO BE ACHIEVED WITH IMAGE PROCESSING.



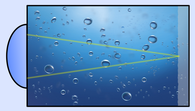
Acquired patterns are stacked together to create an image stack.

For each location maximum and minimum intensity values a subtracted from each other to create a confocal image [2].

Highest values represent the signal in focus, lowest values are regarded as background (mainly from cornea).

Values between maximum and minimum intensities represent varying degree fo the out-of-focus-signal.

A MODEL EYE WAS DESIGNED TO CHARACTERIZE THE IMAGING PERFORMANCE.



Parameter	Model eye	Human eye
r_{cornea}	7.7 mm	7.8 mm
n_{cornea}	1.52	1.38
$n_{vitreous}$	1.33	1.34
μ_{retina}	10 mm^{-1}	5 mm^{-1}

1/2´´ uncoated plano-convex lens was used to mimick the curvature and refractive index of the cornea.

A chamber was filled with water to simulate the water dispersion in the eye caused by the vitreous humour.

Titaniumdioxide (TiO_2) layer acts as an artificial retina and the scattering properties of the slab imitate those of the retina more or less.

Results

THE ACHIEVED RESOLUTION WAS 3.9 MICROMETERS.

The resolution performance was tested with a 1951 USAF resolution test target as the model retina, which was positioned in the focal plane of the model eye.

The smallest resolvable group corresponds to a lateral resolution of 3.91 µm, when pupil size is larger than 2 mm (limited by the camera pixel size). For larger pupil sizes the Rayleigh criterion is applicable (r = 0.61λ/NA).

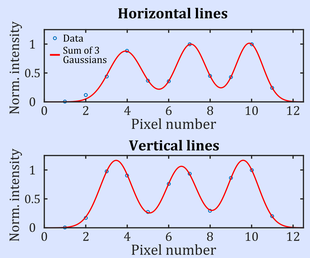


Fig. 2. Lateral resolution of the PLSO. The confocal image of the resolution target was obtained using seven parallel illumination lines. The resolution lines in group 7 element 1 are visible with the naked eye and when taking the cross-section from the horizontal and vertical line groups, three different peaks are resolved giving a resolution of 3.91 µm according the datasheet.

THE SNR INCREASES WHEN FEWER ILLUMINATION LINES ARE USED.

The signal-to-noise ratio (SNR) of the sensor can be calculated as (shot noise dominated):

$$SNR(\mu_p) = \frac{\eta\mu_p}{\sqrt{\eta\mu_p}} \qquad \eta = \text{quantum efficiency}, \ \mu_p = \text{mean number of photons}$$

This signal can be divided into a) light reflected from the retina and b) light reflected from the cornea which is severely out-of-focus and creates uniform background. The SNR of the retinal signal can then be written as

$$SNR_e = \frac{\mu_{e,signal} - \mu_{e,background}}{\sqrt{\mu_{e,signal}}} \qquad \mu_e = \eta\mu_p, \ \mu_e = \text{mean number of electrons}$$

It was found that fewer illumination lines cause less background from corneal scattering and therefore the SNR increases. However sparser line pattern will decrease the imaging speed.

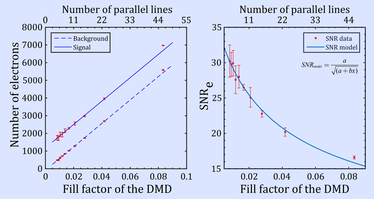


Fig. 3. Determining the SNR of the PLSO. (left) From each fill factor sequence, one frame was taken and obtained mean signal and mean background electrons plotted as a function of the DMD fill factor show linear trend. The retinal signal is present on top of the background and has a constant value regardless of the DMD fill factor. (right) SNR_e plotted as a function of the DMD fill factor shows that the SNR_e of the system decreases when the fill factor increases (denser line pattern).

IN VIVO IMAGING REVEALS THE FINE STRUCTURE OF THE FOVEA AND OPTIC NERVE HEAD.

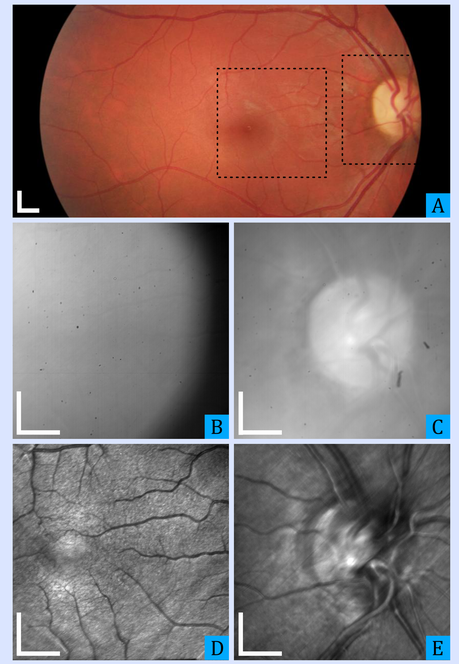


Fig. 4. In vivo images of the retina from healthy subject. (A) Fundus photo from a right eye, dashed boxes showing the areas imaged with the PLSO. (B-C) Non-confocal PLSO images and (D-E) confocal PLSO images of the fovea/macula and optic nerve head respectively. For non-confocal images the PLSO frames were simply averaged and the confocal images were processed with the previously mentioned method. In Fig. 4B the light incident on the eye was not centered on the pupil, and at the right edge of the image (the dark portion) the corneal reflections were blocked by the apertures in the system. The images were acquired through a dark-adapted pupil without any dilation. Scale bars are 2° in size.

Conclusion

The PLSO provided high contrast images of the retina showing detailed structures. The DMD makes it possible to have high acquisition speed which can be utilized in the future to avoid eye motion artifacts but also analyze eye motion [3].

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Commercial interests:
Johannes F. de Boer: P, F (VU)
Koenraad A. Vermeer: P (ROI)

Acknowledgements:
Combined Ophthalmic Research Rotterdam
ZonMW (Grant number 91212061)
Dutch Technology Foundation STW

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