Ultra highspeed in-vivo Fourier domain full-field OCT of the human retina

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ABSTRACT

In-vivo full field (FF) optical coherence tomography (OCT) images of human retina with up to 6.8 million A-lines/s are presented by using a rapidly tunable laser source in combination with an ultra-high speed CMOS camera. It is shown that Fourier domain (FD) full field OCT could provide a way to overcome limitations in imaging speed which are posed by the maximal possible exposure (MPE) of the retina. With a 100 Hz sweep rate FF-OCT was fast enough to acquire OCT images without motion artifacts, but with rather low sensitivity of 77 dB limited by an undesired incoherent background. Nevertheless, FF-OCT may become an attractive alternative for ultrafast retinal imaging boosting image speed by a lack of moving parts and the use of considerably higher irradiation power, if it is possible to to increase the sensitivity by reducing incoherent straylight.

Keywords: Optical coherence tomography, Lasers (tunable), Three-dimensional image acquisition, Ultrafast measurements

1. INTRODUCTION

Since the first demonstration of in-vivo imaging of the retina,[1] optical coherence tomography (OCT) has changed the diagnosis in ophthalmology. Eventually, the fundamental speed limit to retinal imaging may not be given by the technology but by the exposure limit of the retina. The limited photon flux, which is allowed to enter the eye, directly links imaging speed and OCT sensitivity, which is in the photon noise limit determined by the number of photons detected in one A-scan. For that reason, time domain OCT (TD-OCT) imaging was limited to below 1000 A-scans/s, because it measures only the photons from one voxel at one time. With the introduction of Fourier Domain OCT (FD-OCT), the acquisition was parallelized with respect to the depth, i. e. all photons from one A-scan were measured and evaluated in parallel. At the same sensitivity, the acquisition speed could be increased by more than two orders of magnitude.[2] Recently retinal imaging at more than 300.000 A-scans/s was demonstrated at a sensitivity of 89 dB with CMOS camera based OCT System.[3] For a focused beam which is used during retina scanning the safety regulations allow for a maximal permissible exposure (MPE) of 740 μW at 840 nm, the typical wavelength used for retina imaging. A further increase of imaging speed without sacrificing sensitivity is only possible by parallel image acquisition. An extended illumination of the retina increases the MPE up to a factor of 66.7, which in principle could be turned in a 70 times faster imaging.

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Full-field OCT (FF-OCT) uses such an extended illumination and 2D camera to acquire volumetric OCT images. Time domain FF-OCT with impressive images of ex-vivo samples has been presented.[4–7] To take benefit from the higher retina exposure, FF-OCT has to be combined with FD-OCT, as it was demonstrated for finger print analysis[8] and ex-vivo imaging of retina.[9,10]

Here we show that recently available CMOS cameras[11] are fast enough for in-vivo imaging of the retina. A principle disadvantage of FF-OCT is the sensitivity to stray light and cross-talk between neighboring image points, which is avoided in classical OCT by the confocal detection. The images presented here prove that spatially incoherent illumination is not necessary for imaging the retina with FF-OCT, which reduces the demands on the quality of the optics.

With a SS-FF-OCT setup and a high speed camera (Redlake Y4), retinal images of volunteers were taken with 1.5 mW on the sample at 100 Hz sweeping rate (1024 frames at 100,000 fps).[12] Single B-scans from the recorded volume of 640x24x512 voxels showed the layered structure of the retina without noticeable motion distortion (Fig. 2 and 3). With 70 Hz sweeping rate (70,000 fps), images started to look blurred, with 50 Hz sweeping rate (50,000 fps) it was impossible to record artifact-free images. For comparison, an A-scan rate of a few thousand Hz is needed with spectrometer based FD-OCT to prevent fringe washout which destroys the OCT signal. For SS-OCT imaging speed is not limited by fringe washout, because the actual integration time is 2-3 orders of magnitude shorter than the A-scan acquisition time. Instead movements will distort image geometry and reduce the depth resolution and signal height by introducing a chirp to the spectral interference signal.

After rescaling the spectral data to a linear wavenumber scale a depth resolution of 15 μm in air was determined. The lateral diffraction-limited resolution was 13 μm. A sensitivity of 72 dB was measured, where as 83 dB would be theoretically possible. The difference is mainly caused by the camera, which is not working quantum noise limited. To overcome this limitations as well as the restrictions due to the small number of lines of the area of interest, a different camera was used for further experiments, namely the Photron SA5.

2. EXPERIMENTAL SETUP

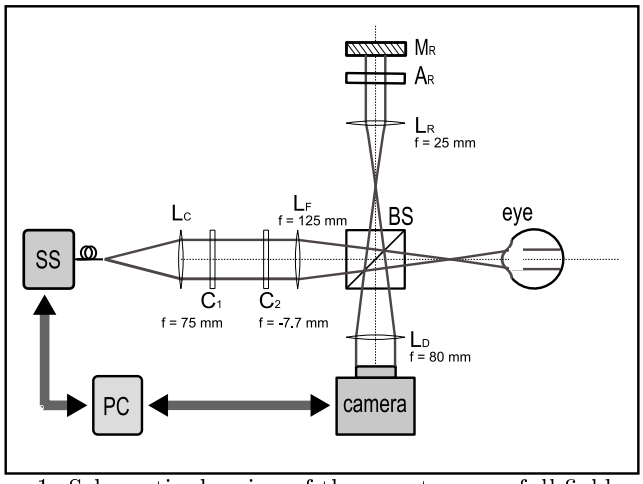


Figure 1: Schematic drawing of the swept source full field setup.

The experimental set up is based on a simple Michelson interferometer (Fig. 1. A tunable light source (Broadsweeper BS840-01, Superlum), which offers 3 mW of output power and a sweep range of 50 nm around a center wavelength of 850 nm, was used. With an additional booster module, up to 25 mW of output power are obtaineable. The output of the light source was coupled by a mono mode fiber to the input of the interferometer. The imaging depth range was 3.84 mm (6.8 dB roll off), which is consistant with the specified instantaneous line width of 0.05 nm. After collimation by the lens L_C (f=50 mm, Techspec VIS-NIR achromats, Edmund Optics) and reshaping by the two cylindrical lenses C_1 (f=75 mm, Thorlabs, Newton, USA) and C_2 (f=-7.7 mm), the telescope formed by L_f (f=125 mm; Techspec VIS-NIR achromat from Edmund Optics like also L_R and L_D) and

the refractive surfaces of the unaccommodated eye, illuminated a 2.6 mm x 0.1 mm rectangular area of retina with a collimated beam of 1.4 mW. A second telescope, which is formed by L_F, the beam 50:50 splitter B_S (BS014, Thorlabs, Newton, USA) and L_R (f=25 mm) projected the collimated rectangular beam onto the reference mirror (M_R). Both, the retina and the reference mirror were imaged with help of the achromat L_D (f=80 mm) onto an ultra-fast CMOS camera. The first camera which was tested (Y4(S3), Redlake/IDT, Tallahassee, FL,USA) was capable of delivering 5000 images per second at the maximal resolution of 1024x1024 pixels, which each had a full-well capacity of approximately 40,000 electrons. The quantum efficiency was approximatly 8%. By reducing the area of interest to 640x24 pixel, frame rates of up to 100,000 fps were achieved. The framerate thereby mainly depends on the number of lines. With 1024 frames per spectral sweep, the equivalent A-scan rate was 1,500,000 lines/s. A volume of 640x24x512 voxels could be recorded in 10 ms.

Later, a second camera with improved performance was used (SA5, Photron, Tokyo,Japan) which is capable of recording with 7000 fps at the full resolution of 1024x1024 px. It has a higher quantum efficiency of 18%, and with a reduced area of interest, 100 000 fps are possible as well, while the framerates only depends on the number of pixels that are read out, so that images with 256x232 pixel are possible. As this camera allows for equilateral areas of interest, the cylindrical telescope formed by the lenses C_1 and C_2 was removed, a collimator with 60 mm focal length(Schäfter und Kirchhoff, Hamburg, Germany) was used and the focal length of the achromat L_f was changed to 50 mm. The booster module was used as well, so that the retina was illuminated with a parallel beam of 5.4 mm diameter with a power of 12 mW. For imaging the retina on the camera, a focal length of 75m for L_D was used.

3. RESULTS

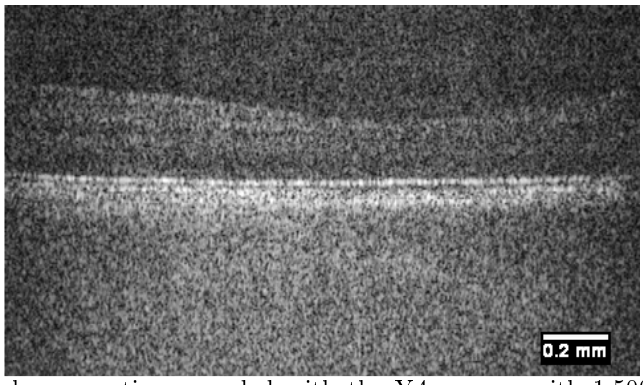


Figure 2: Single B-Scan of human retina recorded with the Y4 camera with 1,500,000 A-scans/s at 1.4 mW radiant flux.

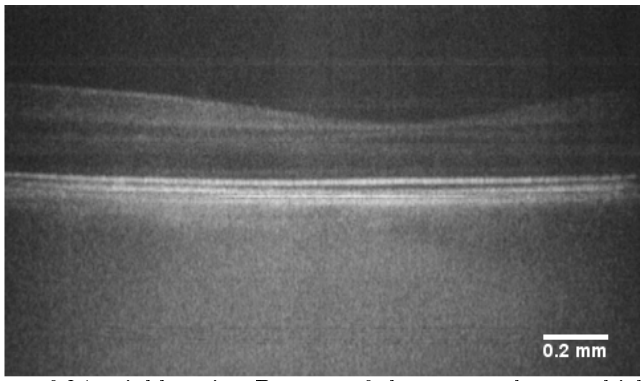
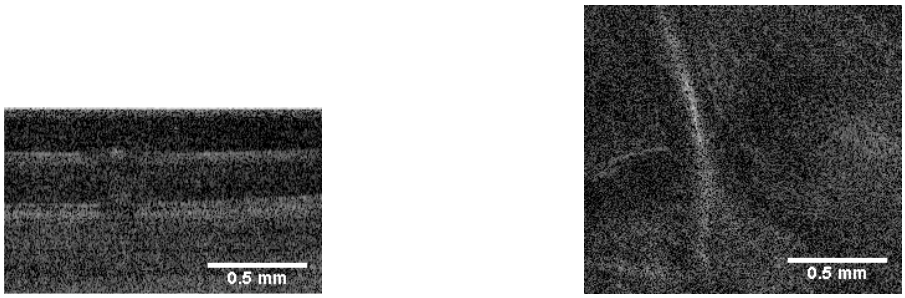


Figure 3: Averaged projection of 24 neighbouring B-scans of the same volume, which improves image quality by reducing speckle noise.

Figure 2 and 3 show images taken with the Redlake Y4, as already published. As mentioned earlier, with 72 dB the measured sensitivity was 11 dB below the shot noise limited theoretical value. Therefore, for both available cameras, the Y4 and the SA5, photon transfer functions (PTFs) were measured, showing that only the SA5 offers shot noise limited detection. As a result, for further measurements the SA5 was chosen.

Figure 4 shows a B-scan and an en-face sclice of a volume consisting of 256x232 A-scans which was recorded with the full-field set-up and the Photron SA5. The camera operated at 100,000 fps and within one sweep 1024 images were recorded, so that the volume acquisition time was 10.24 ms, leading to a equivalent rate of 5,800,00 A-scans/s.



(a) Full-field B-scan (b) En-face image

Figure 4: B-scan and En-face image of the retina taken from a volume with 256x232x512 voxels,recorded within 10.24 ms.

Figure 5 shows a B-scan taken from a volume of 768x88 A-scans which was again recorded within 10.24 ms, corresponding to 6,771,875 A-scans/s. With the total power of 12 mW applied to the eye, the number of incoming photons per A-scan was calculated to be $3 \cdot 10^9$. The measured sensitivity was 77 dB, is close to the theoretically expected value of 80 dB, which indicates a much better camera performance of the new SA5 compared to the Y4, so that one can assume that the detection is working close to the shot noise limit. As a comparison, Figure 6 shows a similar B-scan which was recorded with a conventional state of the art scanning OCT system with an imaging speed of 40,000 A-scans/s and 1mW on the sample. The sensitivity of this system is above 90 db and the number of incoming photons per A-scan was calculated to be $105 \cdot 10^9$, which explains the obviously much better image quality compared to the full-field image.

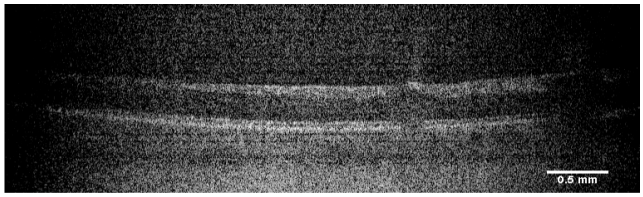


Figure 5: Full-field OCT B-scan of the retina taken from a volume with 768x88x512 voxels,recorded with 6,771,875 A-scans/s.

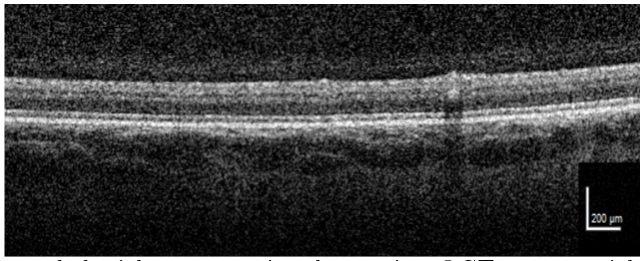
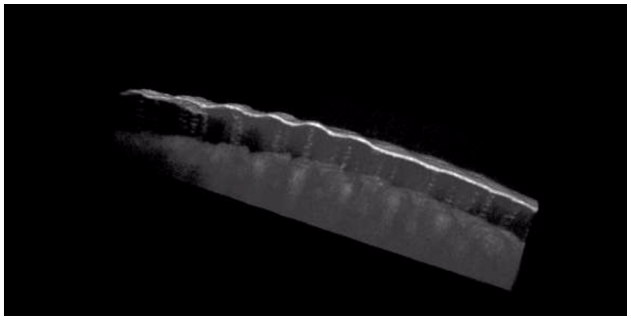


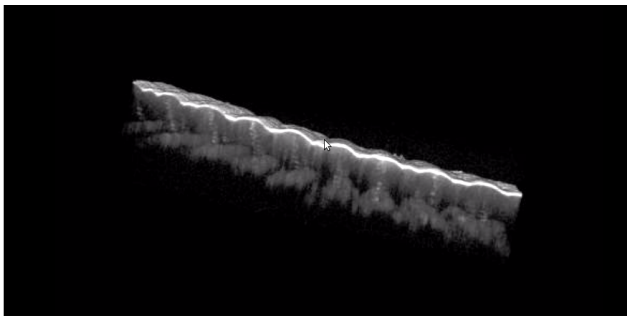
Figure 6: B-scan recorded with a conventional scanning OCT system with 40,000 A-scans/s.

With the low sensitivities achieved so far, full-field OCT can not compete with todays state of the art scanning ophtalmic OCT systems. Any attempts to increase the sensitivity by increasing the irradiance, for instance with an decreased illumination diameter, failed till now. Presumedly, stray light due to incoherent reflections from the optical surfaces of the eye and different optical surfaces within the setup, which cause noise on the detector without contributing to the interference term limit the sensitivity we can achieve.

With a simpler sample, like for instance a finger-tip, an image quality comparable to scanning OCT systems could be shown at significantly higher imaging speed for volumetric OCT images. Figure 7 shows two rendered volumes recorded with the full-field set-up and a Thorlabs Hyperion, a scanning spectrometer based OCT system. With the full-field system, the volume was recorded in 28 ms with 12 mW on the sample, whereas with the scanning system the recording time was approximately 1 s and the power on the sample was 5 mW. So with twice the power, the full field system was roughly a factor of 30 faster, showing similar image quality.



(a) Projection of a rendered volume of 512x192 A-scans recorded with 3,450,600 A-scans/s with the full-field setup.



(b) Projection of a rendered volume of 512x192 A-scans recorded with 127,000 A-scans/s with a conventional scanning OCT-system.

Figure 7: Comparison of full-field and conventional volumetric finger images.

4. CONCLUSION

With 12 mW on the eye, retinal imaging with 6.8 million A-scans/s with a sensitivity of 77 dB was achieved, which is 3 dB below the theoretical limit. Crosstalk between neighbouring image points was not critical for the low scattering retinal layers above the RPE. Volumetric measurements at the finger tip with 3.5 million A-scans/s were comparable with measurements carried out with a high speed spectrometer based scanning OCT system operating at 127,000 A-Scans/s.

Swept source full field OCT was presented as an alternative approach for retinal imaging, which would possibly be a promising technique if incoherent reflections could be reduced and the sensitivity could be increased. It combines a simple setup without any moving parts with a spatially parallel image acquisition which allows for a significantly higher retinal exposure and higher imaging speeds. At a sweep rate of 100 Hz the in-vivo OCT images of the retina which were apparently only limited in quality by the relatively low radiant flux per pixel and incoherent straylight but not by motion artifacts.

The next steps will be to reduce the incoherent background and then to increase the sensitivity, so that one can really compare the image quality to conventional state of the art scanning OCT systems.

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