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Combined Adaptive Optics - Optical Coherence Tomography and Adaptive Optics - Scanning Laser Ophthalmoscopy system for retinal imaging

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ABSTRACT

We describe a novel instrument that combines adaptive optics - Fourier-domain optical coherence tomography (AO-OCT) with an adaptive optics scanning laser ophthalmoscope (AO-SLO). Both systems share a common AO sub-system and vertical scanner to permit simultaneous acquisition of retinal images from both OCT and SLO. One of the benefits of combining OCT with SLO includes automatic co-registration between the two imaging modalities and potential for correcting lateral and transversal eye motion resulting in motion artifact-free volumetric retinal imaging. Results of using this system for eye model imaging are presented. Feasibility for clinical application is briefly discussed as well as potential further improvements of the current system.

Keywords: (110.4500) Optical coherence tomography; (010.1080) Adaptive optics; (170.0110) imaging system; (120.3890) Medical optics instrumentation; (170.4470) ophthalmology; (220.1000) Aberration compensation

1. INTRODUCTION

In recent years adaptive optics - optical coherence tomography (AO-OCT) [1-3] has realized an improvement allowing its successful implementation for cellular resolution imaging of the living retina. However, one of the main factors currently limiting performance of these systems is their inability to track and correct eye motion distortions. As reported recently [4], application of faster data acquisition schemes in Fd-OCT help limit this effect, however, there is a penalty in the form of system sensitivity (ability to see less reflecting retinal structures) as a result. Alternatively, several groups have shown successful implementation of retinal tracking systems to correct for motion artifact distortions. Two main approaches include an independent retina tracker [5] or retinal image- based tracking with adaptive optics scanning laser ophthalmoscope (AO-SLO) [6]. The second is especially attractive since AO-SLO by itself allows not only standard detection of back- scattered signals (primarily from the cone photoreceptor mosaic) but also measurements of autofluorescence and fluorescence, which is not possible with OCT. Therefore, the combination of OCT with SLO-based retinal tracking also offers an imaging channel in addition to the correction of eye motion in AO-OCT data sets. There have been two reports of combined AO-SLO and AO-UHR-OCT, in both cases based on a transverse scanning OCT scheme [7-8] which also included implementation of an SLO channel for retina tracking [8]. In this paper we present a combined AO-Fd-OCT / AO-SLO instrument allowing simultaneous acquisition of OCT and SLO channels, which could be used in the future for retinal motion tracking. It is based on our previously described AO-OCT system [2] which includes Fourier-domain OCT (Fd-OCT) with correction for longitudinal chromatic aberration (using a custom achromatizing lens) combined with AO allowing monochromatic aberration correction using two deformable mirrors (DM's) and an AO-SLO system [8] using the same AO configuration. In the system presented here the introduction of an SLO channel is realized by using a separate wavelength and does not affect AO-OCT system performance. In this paper we report first results on using this instrument for imaging a model eye. Additionally, feasibility for clinical application with the focus on safe light levels that can be used for imaging as well as potential further improvements of the current system design and image processing will be discussed briefly.

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2. MATERIALS AND METHODS

The UHR-AO-OCT subsystem used as a base for our combined AO-OCT and AO-SLO design has already been described in detail elsewhere [2]. Therefore we will focus on changes made to the sample arm to accommodate an AO-SLO subsystem. Some details about electrical connections as well as timing diagrams for data acquisition for both systems will be discussed. Due to implementation of two independent light sources for imaging, maximum permissible powers levels for different scanning scenarios will be provided as well.

2.1. Experimental system

Figure 1 shows a schematic of our combined AO-OCT and AO-SLO system sample arm.

Fig. 1: Schematic of AO-OCT / AO-SLO sample arm. Red rays – AO-OCT path; blue rays – AO-SLO path. Note that the focal length of spherical mirrors S6' and S7' are identical to S6 and S7. AO sub-system uses OCT light for wavefront sensing. S – spherical mirrors; WSF – Wavefront Sensor; SLD – Superluminescent diode; PMT – Photomultiplier tube; H – horizontal scanner (OCT or SLO); V – Vertical Scanner

Red rays in Fig. 1 represent the sample arm path of our AO-OCT system described already in our previous papers. Blue rays denote the AO-SLO subsystem. As a light source a Superluminescent Diode SLD: S-680 G 1-5 SM (8nm@683nm; $P_{out} = 5$ mW) from Superlum. Russia is used. A 50/50 beam splitter (Thorlabs: BSW08) directs its collimated light toward a dichroic mirror (CVI Melles Griot: LWP-45-RU670-TU800-PW-1025-C) placed in front of the OCT collimator allowing the introduction of the SLO beam into the system. To allow for different scanning speeds of SLO and OCT beams we separated the two beams with an additional dichroic mirror from CVI placed between spherical mirrors S5 and S6. The reflected SLO beam (blue ray) is directed to horizontal SLO scanner (H_{SLO}) via spherical mirror S6', after being reflected from the horizontal scanner beam toward S7' and then introduced back to the "main" AO-OCT path by one more dichroic mirror. Using the same magnification for both OCT and SLO channels should limit noncommon path aberrations between them. This is critical because only the OCT beam is used in the AO system for wavefront aberration correction (A high-pass filter is placed in front of the WFS, Semrock: FF735-Di01-25x36). Therefore any noncommon aberrations between SLO and OCT (besides defocus) would not be corrected and could limit the performance of the SLO channel. The detection channel of the SLO system consists of a fiber collimator focusing the SLO beam to the 50 μ m diameter Multimode Fiber (Thorlabs: AFS50/125 Y) that is connected to the photomultiplier tube (PMT) module (Hamamatsu H7422-20). The actual AO-OCT / AO-SLO system developed in our laboratory occupies a 5 ft x 6 ft laboratory optical table. Figure 2 shows its photo with OCT and SLO paths marked in red and blue respectively.

Fig. 2. Photograph of the AO-OCT / AO-SLO system, red rays - OCT path; blue rays - SLO path. Subject's eye is placed in the lower right corner of the image.

In our current instrument, a separate PC controls the SLO subsystem (independent from the AO-OCT system). The figure below is a schematic of the electronic connections between the SLO and OCT computers allowing synchronization of OCT and SLO scanners and data acquisition.

Fig. 3. Electronic schematic of combined OCT-SLO system (allowing synchronized scanning and acquisition).

2.2. Simultaneous Acquisition of OCT and SLO Data Sets

One of the keys for successful operation of a combined AO-OCT/ AO-SLO is proper timing of the scanning mirrors. In our current design both systems share a vertical scanner operating at 30 Hz, which sets the frame rate for both instruments.

2.2.1. Scanning Patterns.

For each AO-SLO *en-face* frame, an AO-OCT vertical B-scan is acquired at the horizontal position set by the horizontal OCT scanner H_{OCT} . As an example, Figure 4 (left) shows a timing diagram of the vertical and both horizontal scanners for AO-OCT volumetric acquisition together with the simulated beam path scanned on the retina during single- frame acquisition.

Fig. 4: Left: Timing diagrams of vertical scanner (VS) and horizontal OCT/SLO scanners (HS_{OCT} HS_{SLO}) for volumetric data acquisition. Right: Visualization of the scanner motion on the retina for one frame (acquired for one period of vertical scan marked as gray rectangle on left figure); red rays - OCT path; blue rays - SLO path.

Thus, during simultaneous OCT/SLO acquisition, OCT scanning patterns are limited to vertical line acquisition and 3D acquisition only. Using different OCT scanning patterns (circular, horizontal) would result in corrupting SLO channel.

2.2.2. Data display.

Proper interpretation of data sets acquired simultaneously with OCT and SLO channels will require novel ways of visualization. As an example, Figure 5 below shows a simulated visualization of AO-OCT and AO-SLO frames. These data have been acquired *in vivo* using our AO-OCT and AO-SLO channels operating separately (with the other channel not active).

Fig. 5: Simulated visualization of AO-OCT and AO-SLO frames (acquired for one period of vertical scan denoted by the gray rectangle in Fig. 4).

2.3. Laser Safety Consideration

When imaging human retina *in vivo* one should carefully follow laser safety standards (ANSI) [9] to ensure that the light levels used for imaging are safe. Recently Delori *et al.* [10] published an article with practical examples of the ANSI standards applied to ophthalmic imaging systems. Following these recommendations we calculated maximum permissible powers (MPP) for our combined AO-OCT / AO-SLO instrument using different scanning scenarios. As an example, Table 1 shows MPP values calculated for both OCT and SLO with an imaging field of 5 mm (15 deg) commonly used in OCT. Additionally, MPP for an imaging field of 0.3 mm (1 deg), the smallest field imaged in our AO-OCT system, is presented. Two OCT scanning scenarios (line scan and volumetric scan) are also presented.

Table 1. MPP values for different imaging scenarios. Blue color denotes the most restrictive values for both OCT and SLO sub-systems

Maximum Permissible Power (MPP) for 1 minute imaging	
<u>5mm (~15 deg)</u>	<u>0.3 mm (~1 deg)</u>
MPP _{OCT line} [830nm] = 2.7 mW	MPP _{OCT line} [830nm] = 1.4 mW
MPP _{OCT 3D} [830nm] = 10 mW	MPP _{OCT 3D} [830nm] = 2.6 mW
MPP _{SLO} [680nm] = 1.6 mW	MPP _{SLO} [680nm] = 820 μ W
Maximum Permissible Power (MPP) for 5 minutes imaging	
<u>5mm (~15 deg)</u>	<u>0.3 mm (~1 deg)</u>
MPP _{OCT line} [830nm] = 1.8 mW	MPP _{OCT line} [830nm] = 950 μ W
MPP _{OCT 3D} [830nm] = 6.8 mW	MPP _{OCT 3D} [830nm] = 1.8 mW
MPP _{SLO} [680nm] = 1 mW	MPP _{SLO} [680nm] = 550 μ W

Because our instrument will use both SLO and OCT beams simultaneously, the light powers must conform to the following equation for multiple light sources [10]:

$$\frac{P_{\lambda_1}}{MPP[\lambda_1]} + \frac{P_{\lambda_2}}{MPP[\lambda_2]} + \dots < 1 \quad (1)$$

In our current system configuration, the power of our AO-OCT beam at the eye pupil is about 450 μ W. The power of the AO-SLO beam is about 150 μ W. Entering these values into Eq. 1 and assuming the most restrictive scanning scenarios from Table. 1 (1 deg scanning field and line scan for OCT) yields:

$$\frac{P_{830}}{MPP[830]} + \frac{P_{680}}{MPP[680]} = \frac{450 \mu W}{950 \mu W} + \frac{150 \mu W}{550 \mu W} = 0.47 + 0.27 = 0.74 \quad (2)$$

Thus, our power levels used for imaging are below the ANSI limits. Note that our imaging sessions seldom exceed 1 minute per retinal location. One also has to consider that current ANSI standards do not take into account if AO correction has any effect on MPP values. Therefore using power levels at the MPP is questionable.

3. RESULTS

To test simultaneous acquisition of the AO-OCT/AO-SLO subsystems we have imaged a model eye consisting of the focusing achromatic lens and paper with a printed pattern placed in its focal plane. Figure 6 shows a schematic of our eye model and a picture of the paper used as retina (placed in its focal plane).

Fig. 6: Left: schematic of the model eye; right: picture of the paper placed in its focal plane.

Figure 7 shows results of OCT volumetric acquisition. Nine representative OCT B-scans (from 100) are presented with the corresponding locations shown on the SLO scan. Note that for each OCT B-scan, one SLO frame is acquired. Only one example SLO frame is shown on that figure.

Fig. 7: Visualization of simulated AO-OCT / AO-SLO acquisition. For each SLO Frame an OCT frame (A-I) was acquired. Red lines correspond to locations on the SLO image of presented OCT frames.

After acquiring an OCT volume, the data can be processed and viewed in our Volume Visualization software. Figure 8 shows an example frame of the volume representation of the OCT data from Fig. 7. Additionally to an OCT “fundus view” an SLO-like representation of OCT data is presented as well.

Fig. 8: Left: Volumetric visualization of OCT data acquired with model eye; right: OCT fundus view reconstructed from OCT Volume. SLO acquisition area is marked on the OCT fundus view. (Note that offset between OCT and SLO channel is due to independent settings of scanning angle and zero position of SLO and OCT horizontal scanners.

By comparing SLO data from Fig. 7 with OCT fundus-view data from Fig. 8 one can see a horizontal offset between the OCT and SLO channels. This is due to independent settings of scanning angle and zero position of SLO and OCT horizontal scanners and could be removed.

CONCLUSIONS

We presented an AO-OCT / AO-SLO system designed for *in vivo* imaging of the retina. Several features of the instrument design and operation have been described. As an example of system performance, OCT and SLO data simultaneously acquired for a model eye are presented. Additionally, we presented laser safety considerations when imaging the retina with two independent light sources. We also showed that light levels used in our experiment would be safe according to ANSI standards. Future work will include application of this instrument for retinal imaging. To further limit retinal light exposure we will consider adding light modulators to turn off the light when signals are not being acquired. This will be important for the SLO channel since its current duty cycle is below 50%.

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