UC Davis

UC Davis Previously Published Works

Title

Retinal imaging with a combined adaptive optics - Optical coherence tomography and adaptive optics - Scanning laser ophthalmoscopy system

Permalink

<https://escholarship.org/uc/item/33m311b9>

ISBN

9780819479464

Authors

Zawadzki, RJ
Jones, SM
Pilli, S
et al.

Publication Date

2010-12-01

DOI

10.1117/12.842946

Peer reviewed

Retinal Imaging with a Combined Adaptive Optics - Optical Coherence Tomography and Adaptive Optics - Scanning Laser Ophthalmoscopy System

Robert J. Zawadzki¹, Steven M. Jones², Suman Pilli¹, Dae Yu Kim¹,
Scot S. Olivier² and John S. Werner¹

¹ Vision Science and Advanced Retinal Imaging Laboratory (VSRI) and UC Davis Eye Center,
University of California Davis, 4860 Y Street, Suite 2400, Sacramento, CA 95817

² Lawrence Livermore National Laboratory, 6000 East Avenue, Livermore, CA 94550

ABSTRACT

We describe results of retinal imaging with a novel instrument that combines adaptive optics - Fourier-domain optical coherence tomography (AO-OCT) with an adaptive optics scanning laser ophthalmoscope (AO-SLO). One of the benefits of combining Fd-OCT with SLO includes automatic co-registration between the two imaging modalities and the potential for correcting lateral and transversal eye motion resulting in motion artifact-free volumetric retinal imaging. Additionally this allows for direct comparison between retinal structures that can be imaged with both modalities (e.g., photoreceptor mosaics or microvasculature maps). This dual imaging modality could provide insight into some retinal properties that could not be accessed by a single imaging system. Additionally, extension of OCT and SLO beyond structural imaging may open new avenues for diagnostics and testing in ophthalmology. In particular, non-invasive vasculature mapping with these modalities holds promise of replacing fluorescein angiography in vascular identification. Several new improvements of our system are described, including results of testing a novel 97-actuator deformable mirror and AO-SLO light intensity modulation.

Keywords: Adaptive optics; Optical coherence tomography; Scanning laser ophthalmoscopy; Ophthalmology; Imaging system; Medical optics instrumentation; Aberration compensation

1. INTRODUCTION

We previously described an adaptive optics (AO) system with combined ultrahigh resolution (UHR) optical coherence tomography (OCT) and scanning laser ophthalmoscope (SLO). Testing was carried out on a model eye. Here, we report the results of its implementation for *in-vivo* retinal imaging. Briefly, image acquisition in our system uses two separate wavelengths for OCT and SLO. The OCT light serves as the beacon for wavefront sensing in the AO sub-system. Our AO-SLO subsystem shares all but three components (resonant scanner and two spherical mirrors) with the AO-OCT system sample arm (see Figure 1.). The light source for OCT in the current configuration is a Superluminescent diode (SLD) Broadlighter operating at 836 nm with 112 nm spectral bandwidth (Superlum LTD), allowing 3.5 μm axial resolution at the retina. The light source for the SLO subsystem is also an SLD from Superlum Ltd., operating at 680 nm with 10 nm spectral bandwidth. A pupil diameter of 6.7 mm used in our imaging system allows for up to 3 μm lateral resolution for both subsystems when AO correction is optimized. A bite-bar and a forehead-rest assembly have been mounted on an X-Y-Z translation stage to reduce head motion and precise positioning of the subject's eye pupil. Eye fixation is directed to an external target to minimize head and eye motion and to allow precise imaging at different retinal locations.

Results of testing system performance are presented, including use of a novel deformable mirror (a new high stroke 97-actuator ALPAO membrane magnetic deformable mirror), AO-SLO light intensity modulation and fiber pigtailed SLO detector.

*rjzawadzki@ucdavis.edu; phone 1 916 734-5839; fax 1 916 734-4543; <http://vsri.ucdavis.edu/>

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 [1]. Some details on combined AO-OCT/AO-SLO system have also been published last year in our SPIE BiOS 2009 Manuscript [2]. Therefore we will focus on changes made to the sample arm to accommodate an AO-SLO subsystem. Some details about the new large stroke deformable mirror (DM) from ALPAO that was used instead of an AOptix DM are provided. Due to implementation of two independent light sources for imaging, and the goal of minimizing powers levels at the retina, we modulated the SLO light delivery with an AOM.

2.1. Experimental system

Figure 1 shows a schematic of our combined AO-OCT and AO-SLO system sample arm as well as a timing diagram for vertical and both horizontal scanners. Red rays represent the sample arm path of our AO-OCT system described already in our previous papers. Blue rays denote the AO-SLO subsystem. Three dichroic mirrors (CVI Melles Griot: LWP-45-RU670-TU800-PW-1025-C) are used to separate OCT and SLO beam paths. The first is placed in front of the OCT collimator allowing the introduction of the SLO beam into the system. Two others placed between spherical mirrors S5 and S6 and between S7 and S8 direct the reflected SLO beam (blue ray) to horizontal resonant SLO scanner (H_{SLO}). Using the same magnification for both OCT and SLO channels limits non-common path aberrations between them. This is critical because the OCT beam is used to sample the wavefront for the AO system (A high-pass filter is placed in front of the WFS, Semrock: FF735-Di01-25x36). Therefore any noncommon aberrations between SLO and OCT paths (besides defocus) are not corrected. The detection channel of the SLO system consists of a fiber collimator focusing the SLO beam to the 50 μm 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 is similar in size to our previously reported AO-OCT system, occupying a 5 ft x 6 ft laboratory optical table.

Fig. 1. Left: Schematic of AO-OCT / AO-SLO instrument sample arm. Red rays – AO-OCT path; blue rays – AO-SLO path. H – horizontal scanner (OCT or SLO); V – Vertical Scanner; DM 2 – position where 97-actuator ALPAO membrane magnetic deformable mirror was inserted into our system (replacing AOptix DM). Right: Timing diagrams of vertical scanner (VS) and horizontal OCT/SLO scanners H_{OCT} H_{SLO} for volumetric data acquisition.

Note that both systems share the vertical scanner operating at 27 Hz, which sets the AO-(UHR-OCT/SLO) frame rate. Thus, the horizontal positions of the OCT B-scan (acquired in our system vertically) with respect to the SLO frame is determined by offset of the OCT horizontal scanner.

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 and data acquisition. Two data sets are acquired independently on two computers so we synchronized these two PC's and are using AO-OCT software start, stop and save as pointers for AO-SLO software. Start of OCT acquisition also starts SLO data streaming to the circular buffer. Stop of OCT data collection also stops SLO data streaming. Therefore both OCT frames and the last SLO frames sent to the buffer have been acquired simultaneously. Saving OCT data also saves

SLO data sets with corresponding time stamps. A figure showing a schematic of the electronic connections between the SLO and OCT computers allowing synchronization of OCT and SLO scanners and data acquisition can be found in our previous manuscript [2].

As already noted 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} . To illustrate the timing within a single frame, Figure 2 shows three time points during single frame acquisition with the scanning path of SLO and OCT beams on the retinal plane with corresponding retina data sets as acquired up to the each point in time within this frame.

Fig. 2. Simultaneously acquired AO-OCT and AO-SLO data sets with schematic scanning path during single frame acquisition at 30% (a) 60% (b) and 100% (c) of the finished frame acquisition (only path already scanned are showed on the image) Blue rectangle represent AO-SLO acquisition area, red arrow represents horizontal position of AO-OCT acquisition line. Note that OCT B-scan is acquired perpendicular to the AO-SLO frame.

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 the SLO channel. As a result each saved data set consists of 100 AO-OCT B-scans and simultaneously acquired 100 AO-SLO Frames.

2.3. Laser Safety Consideration

To ensure that the light levels used for imaging the human retina *in vivo* are safe, one have to follow laser safety standards (ANSI) [3]. Recently Delori *et al.* [4] published an article with practical examples of the ANSI standards applied to ophthalmic imaging systems. In our previous manuscript [2] we presented calculations for maximum permissible powers (MPP) for our combined AO-OCT / AO-SLO instrument using different scanning scenarios. Because our instrument uses both SLO and OCT beams simultaneously, the light powers must conform to the following equation for multiple light sources [4]:

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

In our initial 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 (1 deg scanning field for AO-SLO and line scan for OCT) yields: $0.47 + 0.27 = 0.74 < 1$; resulting in power levels below the ANSI limits. To further reduce light exposure we decided to modulate the SLO beam power. Since our SLO data acquisition has a duty cycle of about 40% (we acquire SLO data only during one-way sweep of resonant scanner) we implemented a fiber-pigtailed acousto-optic modulator (AOM) from AA Optoelectronic MT200-R9-FIO and placed it between the SLO light source and input to the AO-OCT system. This results in a 60% reduction of average power and reduction of MPP ratio for SLO channel from 0.27 to 0.11. There is an additional 3-4 dB insertion loss in the AOM so a more powerful light source should be used for the SLO channel to match system sensitivity in its previous configuration. However one could increase input light power more than two times above initial average powers without increasing average light levels at the retina. This improvement in SLO system sensitivity should be helpful when imaging older subjects who have more scattering ocular media.

2.4. ALPAO 97-actuator membrane magnetic deformable mirror

Our two-deformable mirror AO subsystem has been described in detail in previous publications. Briefly, a separate PC controls the wavefront sensor and drives both deformable mirrors (one at a time) in a closed loop. In our original AO sub-system we used: a 37-actuator Bimorph deformable mirror from AOptix and a 140-actuator MEMS deformable mirror manufactured by Boston Micromachines. The AO system uses the bimorph DM mainly for low-order aberration correction (defocus and astigmatism) eliminating the need for trial lenses to correct individual subject’s refractive errors up to ± 3 diopters of defocus. The same mirror is also used to shift the focus of the AO-OCT beam axially onto retinal structures of interest.

To evaluate the new high stroke 97-actuator ALPAO membrane magnetic deformable mirror that was used in single-DM AO configuration, both the AOptix and MEMS DM’s were removed from the system. The ALPAO DM was placed at the AOptix position and a flat mirror at the MEMS DM position. Figure 3 shows actuator geometry and an image of ALPAO DM and AOptix DM for comparison.

Fig. 3. Actuator geometry and an image of the 35 +2 element Bimorph DM (left) and 97 element ALPAO DM (right). The gray area represents mirror surface of the DM. The image of the subject’s eye pupil (diameter 6.75 mm) matches the AOptix DM diameter of ~ 10 mm and is marked by the red dashed circle on the ALPAO DM.

The objective of ALPAO mirror testing was to evaluate it as a possible replacement for AOptix DM. Table 1 shows specifications for these two mirrors clearly revealing the potential of the new mirror.

Table 1. Specification of AOptix DM and ALPAO DM.

	AOptix	ALPAO
Active area:	10 mm, round	13.5 mm, round (10mm)
No of actuators:	35 (19 +16) + 2	97 (69)
Mirror surface:	Continuous surface	Continuous surface
Stroke (wavefront):	Defocus: +/- 32 mm Maximum deflection: +/- 16 μ m	Tip/tilt: +/- 60 μ m Inter actuator: > 3 μ m 3x3: > 30 μ m
Speed:	Response speed: ~ 4 kHz	Bandwidth: 750 Hz

3. RESULTS

In this section we present initial results of testing the ALPAO deformable mirror. Additionally, images acquired with AO-(UHR-OCT/SLO) system will be presented along with examples of multi-system image visualization.

3.1. Testing dynamic range of ALPAO DM

To test the dynamic range of the deformable mirror we use a model eye as the sample and placed trial lenses in front of it to check the DM’s ability to correct different refractive error values. Tests were performed by starting with no trial lens, then closing the AO loop, and then holding it while increasing defocus or astigmatism by 0.5 Dpt increments. This permitted tests of high optical powers that usually will not be properly detected by our wavefront sensor. Figure 4

compares defocus and astigmatism correction for the ALPAO DM and defocus correction for our original two DMs (AOptix and MEMS DMs).

Fig. 4: Left: AO correction of defocus for AOptix and MEMS 2DM system. Right: AO correction of defocus and astigmatism for ALPAO DM only.

Note that in our original AO system the defocus correction range was limited by the AOptix DM stroke to ± 3 Dpt. In contrast, for ALPAO correction we are now limited by the optical system itself. That is, aberrations larger than ± 3.5 Dpt cannot be imaged in our system (imaging beam is clipped by optical elements). Thus, changes in optical design of the sample arm are necessary to fully utilize the potential of the ALPAO DM. Additionally no difference between defocus and astigmatism correction range for the ALPAO mirror could be seen. This is important because the dynamic range of astigmatism correction for AOptix was limited to only ± 1 Dpt range.

3.2. *In vivo* retinal imaging and visualization.

Here we show images acquired with the AO-(UHR-OCT/SLO) system along with our custom multi-modality image visualization. One of the benefits of combining Fd-OCT with SLO includes automatic co-registration between the two imaging modalities. Additionally this allows for direct comparison between retinal structures that can be imaged with both modalities (e.g., photoreceptor mosaics or microvasculature maps).

Figure 5 shows simultaneously acquired AO-OCT and AO-SLO frames with custom multi-modality image visualization.

Fig. 5. Visualization of AO-(UHR-OCT/SLO) frame (acquired for one period of vertical scan marked as blue rectangle on Figure 2. Left: AO-UHR-OCT frame; Center: AO-SLO frame; Right: visualization of co-registered AO-UHR-OCT and AO-SLO frames.

4. CONCLUSIONS

We presented an AO-OCT / AO-SLO system and used it to simultaneously acquire *in vivo* images of the human retina. Several features of the instrument design and some improvements are described along with tests of the new ALPAO DM dynamic range and AOM SLO light input modulation. As an example of system performance, OCT and SLO data simultaneously acquired on a 30-year-old volunteer are presented. Future work will include application of this instrument for clinical retinal imaging. This dual imaging modality could provide insight into some retinal properties that could not be accessed by a single imaging system. We also plan to work on correcting lateral and transversal eye motion using AO-SLO images to create motion artifact-free volumetric AO-OCT retinal images. Additionally, extension of OCT and SLO beyond structural imaging may open new avenues for diagnostics and testing in ophthalmology. In particular, non-invasive vasculature mapping with these modalities holds promise of replacing fluorescein angiography in vascular identification.

ACKNOWLEDGEMENTS

We gratefully acknowledge the contributions of Donald Miller and Barry Cense from Indiana University and Joseph A. Izatt, from the Dept of Biomedical Engineering, Duke University Durham, NC. The help of Bioptigen Inc. for providing OCT data acquisition software is appreciated. We also thank Julien Charton and Frédéric Rooms from ALPAO Saint Martin d'Hères, France for providing magnetic forces deformable mirror and wavefront sensor for testing and help with WFS data processing. This research was supported by the National Eye Institute (EY 014743).

REFERENCES

1. R. J. Zawadzki, B. Cense, Y. Zhang, S. S. Choi, D. T. Miller, and J. S. Werner, "Ultrahigh-resolution optical coherence tomography with monochromatic and chromatic aberration correction," *Opt. Express* **16**, 8126-8143 (2008)
2. R. J. Zawadzki, S. S. Choi, J. W. Evans, and J. S. Werner "Combined Adaptive Optics - Optical Coherence Tomography and Adaptive Optics - Scanning Laser Ophthalmoscopy system for retinal imaging" *Proc. SPIE Vol. 7163*, 71630F (2009)
3. ANSI, American National Standard for the Safe use of Lasers, ANSI Z136.1 (Laser Institute of America, Orlando, FL, 2000)
4. F. C. Delori, R. H. Webb, and D. H. Sliney, "Maximum permissible exposures for ocular safety (ANSI 2000), with emphasis on ophthalmic devices," *J. Opt. Soc. Am. A* **24**, 1250-1265 (2007)