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In-vivo Measurement of Pulsatile Motion of Ocular Structures with Long-range Swept-Source OCT

Vasantha Kumar Kathirvelu*[a], Evangeline Priyadharshini Devaraj[a], Lucas May[b], Daniel Ruminski[a],

Bernhard Baumann[c], Ireneusz Grulkowski[#a]

[a]Institute of Physics, Faculty of Physics, Astronomy and Informatics, Nicolaus Copernicus University in Torun, ul. Grudziadzka 5, 87-100 Torun, Poland
[b]Center for Medical Physics and Biomedical Engineering, Medical University of Vienna, Währinger Gürtel 18-2, 1090 Vienna, Austria
[c]Institute of Biomedical Physics, Medical University of Innsbruck, Müllerstraße 44, 6020 Innsbruck, Austria
[#]corresponding author email: igrulkowski@fizyka.umk.pl
**Presenting author*

1. Introduction

Ocular tissues exhibit subtle, rhythmic micro-displacements driven by fluctuations in intraocular pressure (IOP), which are synchronized with the cardiac cycle. These pulsatile deformations originating from heartbeat-induced changes in ocular blood flow can offer valuable insights into the biomechanical and vascular health of the eye. However, conventional optical coherence tomography (OCT) systems are limited by their restricted imaging range of typically ~2-3 mm, making it challenging to simultaneously visualize dynamic motion across multiple intraocular structures.

This study aims to investigate and characterize heartbeat-driven ocular pulsations across the cornea, crystalline lens, and retina using long-range swept-source OCT (SS-OCT). Unlike standard OCT systems, long-range SS-OCT enables high-speed, high-precision imaging across the full axial length of the eye, thereby capturing continuous motion profiles from anterior to posterior segments. By leveraging this extended imaging depth, we present a unified, full-depth approach for measuring intraocular tissue motion with potential clinical relevance in vascular diagnostics, ocular biomechanics, and early disease detection.

2. Methods

In this study, a prototype SS-OCT system was employed to perform high-resolution, in vivo imaging of ocular pulsations. The system operates at a central wavelength of 1060 nm with a sweep rate of 60 kHz, offering deep tissue penetration and fast acquisition suitable for capturing dynamic physiological motion. The complete experimental setup is illustrated in Figure 1. It delivers an axial resolution of 11 µm in tissue and achieves a sensitivity of 98 dB, enabling the detection of subtle, heartbeat-induced micro-movements across ocular structures. The SS-OCT system was configured to acquire long-range scans spanning the entire axial length of the eye, including the anterior segment (cornea and crystalline lens) and the posterior segment (retina and choroid) in a single imaging session. This full-depth capability allowed for continuous, high-contrast visualization of structural displacement synchronized with the cardiac cycle.

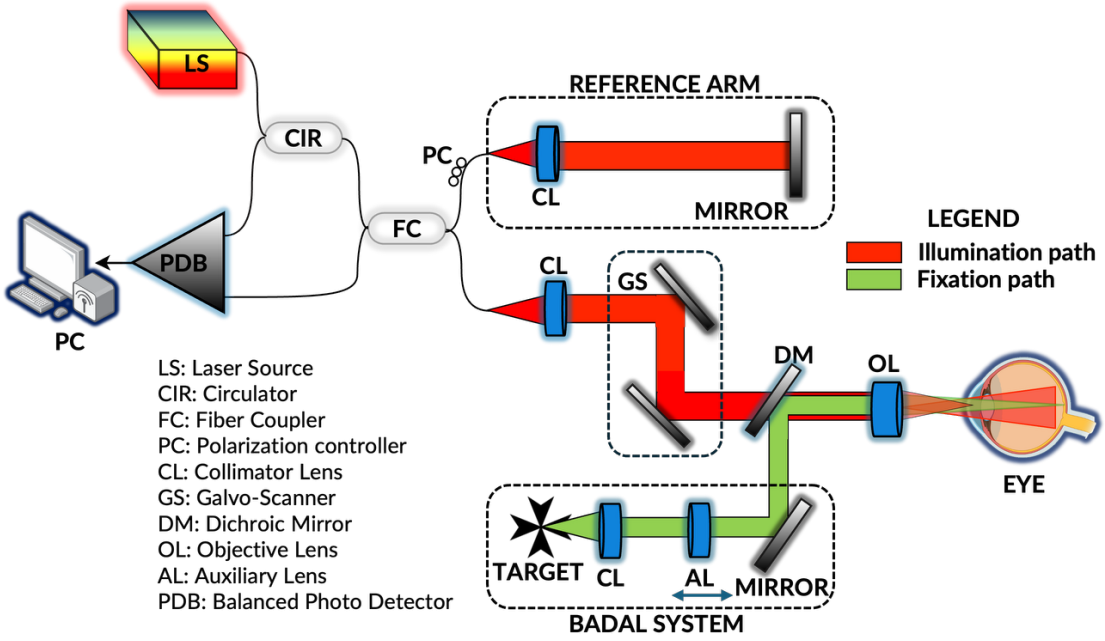

Fig. 1. Experimental setup

Multiple B-scans were captured over time to track tissue motion with high temporal fidelity, allowing the extraction and analysis of pulsation waveforms across different ocular layers. The in vivo imaging protocol was optimized for motion sensitivity while minimizing artifacts due to eye movement or signal drop-off at depth.

3. Results

While prior research has demonstrated the feasibility of using four-dimensional OCT (4D-OCT) to investigate pulsatile tissue dynamics in the murine retina and choroid shedding light on ocular biomechanics and vascular coupling mechanisms [1] - our study advances this approach by applying a long-range, intensity-based SS-OCT method for full-depth motion tracking in the human eye. Using repeated B-scan acquisitions over time, we performed an intensity-based analysis to extract axial displacements corresponding to heartbeat-synchronized tissue motion. The results revealed synchronous axial pulsations across the cornea, crystalline lens, and retina, confirming that the entire eye exhibits a coordinated biomechanical response to cardiac-induced intraocular pressure fluctuations. This global motion pattern suggests a systemic mechanical propagation of the ocular pulse across tissue layers.

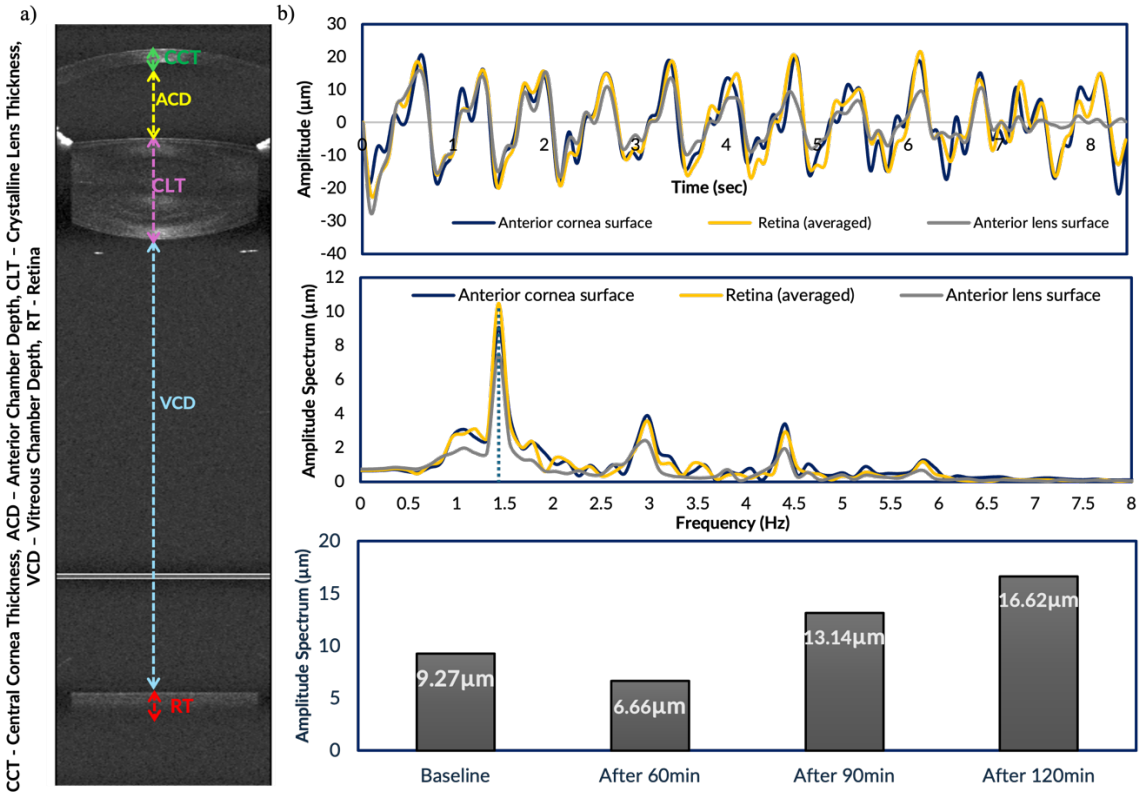

Fig. 2. Ocular Pulsation Analysis. a) Full-depth B-scan image showing structural visualization of the anterior cornea, anterior lens surface, and retina. b) Top: Axial displacement waveform (amplitude in µm vs. time in sec); Middle: Frequency spectrum with a dominant peak around ~1.4 Hz, corresponding to the cardiac cycle; Bottom: Water Drinking Test (WDT) results showing pulsation amplitude changes at baseline, and at 60, 90, and 120 minutes post-water intake.

Figure 2a shows a representative full-depth B-scan image of the human eye, clearly visualizing both anterior and posterior structures. Figure 2b consists of three plots: the top plot displays the extracted axial displacement waveform over time, capturing the cyclic motion pattern; the middle plot shows the amplitude spectrum for the cornea, lens, and retina, each exhibiting a dominant peak at ~1.4 Hz corresponding to the cardiac frequency which confirms that these anatomically distinct structures undergo synchronous pulsatile motion. The bottom plot presents the results of the Water Drinking Test (WDT). Baseline pulsation amplitude was measured prior to ingestion of 1 liter of water. At 60 minutes post-intake, a significant reduction in amplitude was observed (from ~9.3µm to ~6.7 µm), consistent with transient elevation in intraocular pressure (IOP). Measurements taken at 90 and 120 minutes showed a gradual return toward baseline values (~13.1 µm and ~16.2µm, respectively). These temporal changes reflect the eye's biomechanical adaptability and demonstrate that ocular pulsations, as measured by long-range SS-OCT, are responsive to physiological perturbations such as IOP modulation. Collectively, these findings highlight the utility of long-range SS-OCT as a noninvasive tool for monitoring dynamic ocular biomechanics in vivo and suggest that pulsation amplitude may serve as a sensitive physiological biomarker.

4. Conclusion

This study demonstrates that long-range SS-OCT can non-invasively capture and quantify full-depth ocular pulsations driven by cardiac activity. The technique reveals a global biomechanical response of ocular tissues to physiological changes, highlighting its potential as a sensitive imaging biomarker for both ocular pathophysiology and systemic vascular conditions.

5. Funding

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6. References

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