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Method for the Detection of Blood Perfusion in Intracranial Tissues with Optical Fiber Sensor

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Summary:
The proposed method integrates an optical probe to detect blood and prevent internal bleeding during biopsy, by acquiring reflected signals to identify the presence of blood in real time. This approach is validated using a modulated peristaltic pump that simulates blood flow in an artificial vein. During testing, the phantom is illuminated while a spectrometer collects the reflected light. To enhance detection, a lock-in technique tracks heartbeat-related light variations. Results confirm reliable blood detection, using a biopsy-compatible probe and a prism that replicates the lateral aperture of a typical biopsy needle.

Keywords: Optical Fiber Sensor, Blood Perfusion Detection, Lock-In Detection, Non-Invasive Detection, Optoelectronic System.

Introduction

In brain biopsies, detecting blood flow in real time is vital to prevent serious complications [1]. Usually this type of procedure is guided by imaging tests, such as computer tomography and magnetic resonance, which often run into problems of misalignment between preoperative images and the actual brain anatomy [2]. Optical techniques offer minimally invasive, high-resolution tools to assess tissue health and vessel location [3]. Technologies like laser Doppler [4] allow detailed hemodynamic monitoring. In this work, an optical fiber sensor to detect blood perfusion using a lock-in method is proposed. The system employs a probe to illuminate a silicone vein model perfused with synthetic blood via a modulated peristaltic motor. The lock-in approach enhances the signal-to-noise ratio, enabling precise detection of blood flow and estimation of vein distance.

Methods

The proposed concept aims to associate the blood flow within a vein with the light it reflects, using a distinct modulation signal. By demodulating the acquired optical signal at the modulation frequency, the presence of blood perfusion can be accurately detected. To validate this approach, the experimental setup shown in Figure 1 was implemented. Here, synthetic blood circulates through the test vein, driven by a peristaltic pump operating at 500 rpm. A square wave generator simulates the heartbeat by toggling the pump on and off at a frequency of 1 Hz. The optical part comprises of an optical fiber probe from AVANTES designed with six fibers arranged circularly for illumination and one in the center for reception, with a total diameter of 1.5 mm. The illumination is provided by the AVANTES Avalight-HAL, in the spectrum range of 200-1100 nm. The light illuminates the vein under test, providing a reflected signal addressed to a spectrometer, via a splitter. The employed spectrometer matches the spectral range of the light source and includes dedicated software for light acquisition, allowing for adjustable integration time and data plotting in either time or frequency domain. The reflected signal was acquired from the same probe and processed in MATLAB environment. The vein under test was manufactured using a medium-hard silicone rubber, consisting of an empty internal channel parallel to the working surface, which serves both to pass the synthetic blood and to simulate a vein. Due to its consistency, the flowing synthetic blood caused the external walls to expand at its passage.

Results

Tests were performed measuring the reflected light from a lateral illumination by means of a 45° prism. The light is irradiated inside a drill performed in the phantom at 1 mm of distance from the vein for a time window of 1 and 10 seconds with 100 ms of integration time, and a frequency sampling of 10 Hz.

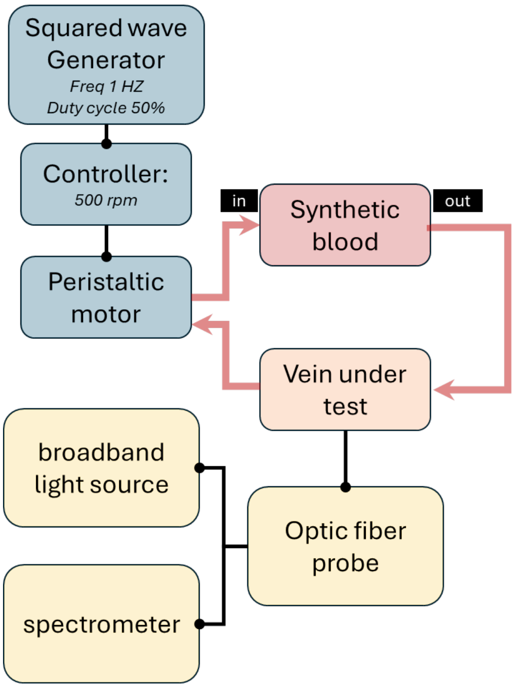

Fig. 1. Block scheme describing the experimental setup.

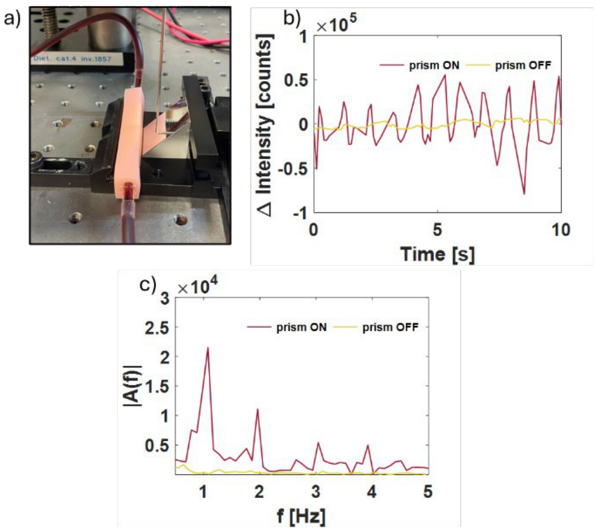

Fig. 2. Illustration of the probe and the phantom under test (a) with relative results in time domani (b) and in frequency (c)

Moreover, data were processed in time and in frequency domain, comparing the results obtained when the motor was in ON state (blood flowing) and in OFF state (blood static). In Figure 2 results are shown: the illustration of the phantom under test subjected to lateral illumination is reported in (a); the time domain variation of the acquired signals is reported in (b). It can be noted the difference between the presence of flow due to the motor, (prism ON and OFF in the plot) since a modulation can be observed. Moreover, to further validate the result, a Fast Fourier Transform (FFT) was performed (c), processing the signal with a Hammington window showing a difference in the 1 Hz harmonic magnitude (modulating frequency) between the signals acquired when the motor was in ON and OFF state. What is worth noting is that the 1 Hz modulation is significant compared to the different condition of motor on/off in time and in frequency domain. Finally, the modulation amplitude was calculated for the position previously described, following the method described in [5], comparing the results in case of blood flowing and in case of static blood. The results in Tab 1 show that the signal amplitude differs by approximately two orders of magnitude between the ON and OFF states. This confirms that when the fundamental harmonic of the reflected light aligns with the modulation signal, the lock-in technique successfully detects the presence of blood flow. Finally, it was demonstrated that the system can reliably detect blood perfusion in the artificial vein using a probe compatible with standard biopsy needles, typically designed with lateral aperture.

Tab. 1: Results on the amplitude calculated in static and dynamic blood flowing in different time intervals

Time interval	Blood flowing (motor ON)	Blood not flowing (motor OFF)
10 sec	9.44×10^3	0.15×10^3
1 sec	8.22×10^3	0.23×10^3

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