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A Pulsatile Optical Tissue Phantom for the Investigation of Light-Tissue Interaction in Reflectance Photoplethysmography

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Abstract— The aim of this study was to investigate the effect of emitter-detector separation distance and arterial depth in reflectance photoplethysmography (PPG), utilizing a homogenous pulsatile phantom that exhibits the broad optical absorbance and scattering properties of human tissue. The developed phantom comprised of embedded silicone arteries (outer diameter = 4 mm) that were arranged parallel to one another at nine increasing depths (3.2 mm to 24.4 mm). A pulsatile pump (Harvard Apparatus, MA, USA) circulated a blood imitating fluid through the vessels at the desired heart rate (60 bpm) and stroke volume (5 Lmin^{-1}). The PPG sensor's emitter and detector were isolated on a translation bridge to provide a computer-controlled separation distance between them. Recordings were taken at each vessel depth for emitter-detector separation distances from 2 mm to 8 mm in 0.1 mm steps. The optimum separation distance between the emitter and detector for vessels between depths of 3.2 mm and 10.5 mm was between 3.7 and 4.3 mm, suggesting that the maximum penetration of IR (930 nm) light in a homogenous pulsatile phantom is no greater than 10.5 mm.

I. INTRODUCTION

Photoplethysmography (PPG) is an optical technique used to measure various subcutaneous haemodynamics properties with well-established clinical monitoring applications [1]. It has achieved its dominance as a result of two distinct features; the accessibility of sensor components leading to their inexpensive price, and the robustness of its' unobtrusive operation with minimal user error. These advantages have enabled the recent expansion in the field with innovative non-invasive techniques in physiological monitoring and vascular assessment [2][3]. The recent interests in wearable technology has seen a massive growth in consumer electronics taking advantage of the PPG signals [4] [5].

Despite its clinical and now commercial importance, the precise origin of the PPG continues to be investigated. The PPG was initially associated with the fluctuations of the local blood volume [6]. This has been disproved through the experiment carried out by Challoner in 1971, where a pulsatile pump was used to circulate whole blood through rigid glass tubes [7]. A transmission probe was able to obtain a normal PPG signal. As the glass tubes prevented any volumetric changes the origin of the signal could no longer be explained by the volumetric model alone. This left an open question on what it actually measures. Attempts to further quantify the pulse amplitude have been unsuccessful in defining the entire origin of the PPG. Kim *et al.* hypothesized

that the source of the signal is from "open arterio-venous anastomoses in the cutaneous circulation" [8]. The orientation effect of erythrocytes has been also rigorously investigated and it has been demonstrated that although this mechanism does contribute to the generation of the PPG waveform, it is not yet fully understood [9] [10].

Skin and vessel phantoms have been widely used as test models for a variety of peripheral tissue imaging techniques. These are often comprised of a skin-imitating material surrounding a vessel through which blood-mimicking fluid is pumped or perfused. The literature on tissue-mimicking phantom materials is extensive and over the years several custom multi-modal phantoms have been described [11]. B.W. Pogue produced an in-depth review on phantoms and concluded that the most limiting attribute of phantom technology is the discrepancies in the measurement of its optical properties. Measurements by different groups was at best 10-15% in agreement [12]. Multi-modal phantoms incorporate several substances to produce the correct optical and mechanical properties, and with every added substance the error in properties' values increase. Due to the above inaccuracies and inconsistencies of existing phantom technologies, this work introduces a new custom-made homogenous phantom with base absorbance and scattering properties. This phantom is used to investigate light tissue interactions pertinent to photoplethysmography in an effort to reveal new knowledge contributing to the origin of the PPG.

To aid this principle research, the exploratory nature of *in vitro* experiments must be exploited, where control over every key parameter is critical. The novelty of this investigation is in the collective approach of examining the effect that changing two parameters; arterial depth and emitter-detector distance, has on the PPG. Studies have been conducted where each of the parameters have been investigated individually [13] [14].

II. METHODS

A. Design and Fabrication of a Homogenous Phantom

The phantom was modelled after the upper arm, where typically blood pressure cuffs are placed. The brachial artery sits within the hypodermis surrounded by subcutaneous fat. The phantom was thus designed with those characteristics in mind. Several research groups have measured the optical properties of various human tissues and corresponding concentrations of additives, but due to varied equipment and methods, the results differ slightly [15], [16].

Our Phantom is composed of a 4 mm outer diameter silicone vessel (Hilltop-Products, UK) with the elastic

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properties indicative of a healthy human artery. To eliminate batch inconsistencies, a single large phantom with multiple vessels was fabricated. The vessels were placed at equal distances apart at varying depths from 3.2 mm to 24.6 mm. The homogenous hypodermis-mimicking layer was produced from a mixture of 18% bovine gelatin, 1% soya milk and 0.06 % India ink solution. The fabricated phantom can be seen in Fig. 1.
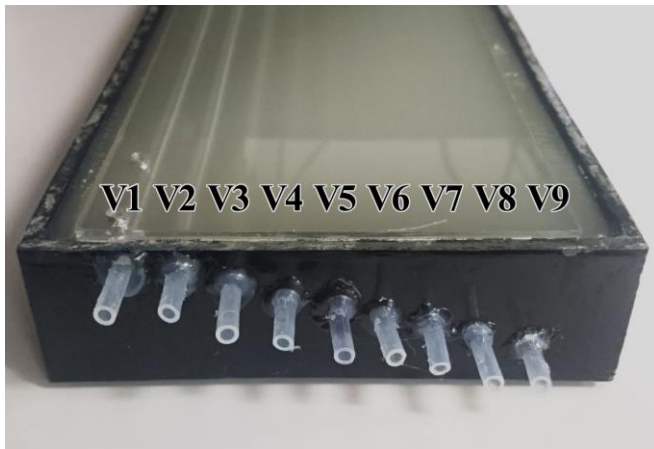

Figure 1. Homogenous pulsatile phantom with multiple vessels and increasing depths from 3.2 mm (V1) to 24.4 mm (V9). See Table 1 for all Vessel depths.

B. Development of Optical Sensor and Processing System

In order to conduct the investigation of the penetration depth of light, the detector (Vishay Intertechnology, PA, USA TEMD502OX01) and emitter (930 nm) (Kingbright, Taipei, Taiwan) were separated onto individual boards held apart on individual arms on a motor-controlled translation bridge. A microcontroller-controlled stepper motor varies the separation distance between the arms.

The reflectance PPG sensor was attached to a custom-built PPG processing system, "ZenPPG". ZenPPG is a dual-wavelength, dual-channel research PPG system developed by the Research Centre for Biomedical Engineering at City, University of London [17] [18]. The main functionalities of the ZenPPG are the acquisition of raw PPG signals (AC + DC), adjustment of light intensities and the ability to drive custom-made and commercial PPG sensors. The ZenPPG is interfaced via LabVIEW software (National Instruments, TX, USA) which provides digital control of the current source and real-time visualization and recording of the acquired signals.

C. Artificial Arterial Blood Network

An electronically-controlled pump (Harvard Apparatus, MA, USA) was used to produce the pulsatile flow. The Pump allowed control over the heart rate (BPM), systole and diastole per stroke %, and stroke volume. An external pressure transducer (Harvard Apparatus, MA, USA) was added to the artificial arterial vasculature. With the pump set to the appropriate values for average blood flow, the pressure wave produced was measured to be very close to that seen in humans (131/78 mmHg). To manipulate the pressure waveform to the desired morphology, adjustable resistance clamps were added along the artificial arterial network system.

The arterial network was connected to a circuit of tubes to step down the diameter of the tubes gradually. Once the phantom was at room temperature it was connected into the pump system, with the pressure transducer connected at its inflow.

D. Investigation Protocol

The bridge arms holding the emitter and detector were placed above the top surface of the phantom's first vessel and brought together to the closest possible separation distance (2 mm, center-to-center). All open areas of the phantom were covered by a black material to block ambient light. The translation bridge automation procedure initiated the automatic and sequential recording of 60 seconds of data for each separation distance along the chosen vessel in 0.1 mm steps until the distance reached 8 mm separation. The phantom was disconnected from the arterial network circuit and the measurement sequence was repeated for the remaining 8 vessels. The whole system configuration can be seen in Fig. 2. The raw PPG data was analyzed in an offline custom MATLAB script.
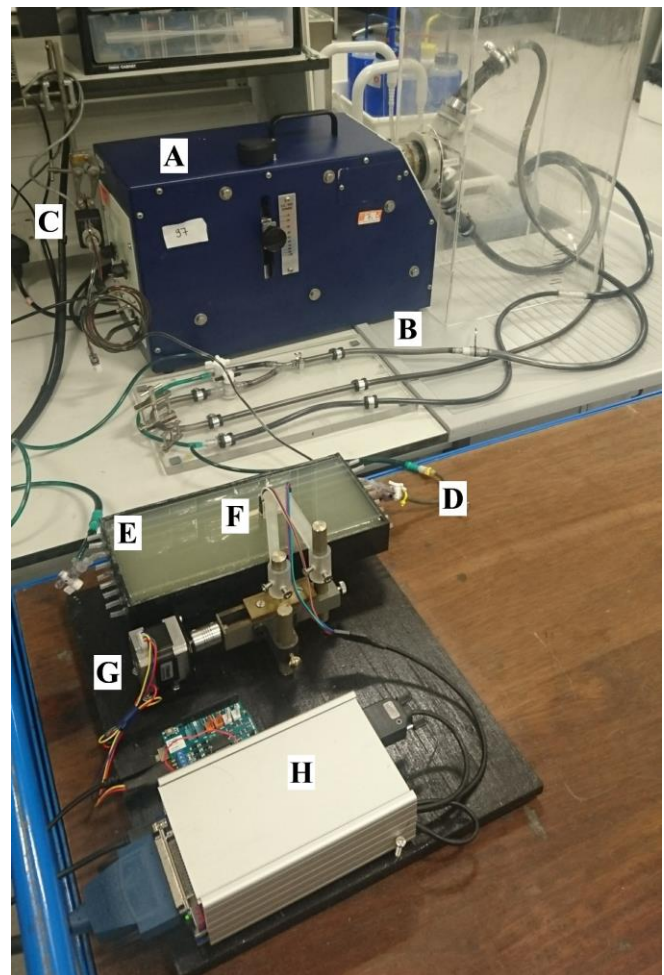

Figure 2. *In-vitro* investigation setup. The pulsatile pump (A) connected to the arterial network (B) with a pressure transducer (C) attached at the inflow of the phantom (E). The emitter and detector were held by the bridge (F). The separation distance between them is controlled by the translation bridge (G) and the signal was acquired by the ZenPPG (H).

III. Results

The obtained signals were down-sampled and filtered using band-pass FIR filter (0.5 to 5 Hz). Fig. 3 displays an eight second window of the filtered signals from each vessel depth with an emitter-detector separation distance of 4 mm. The signal recorded at V1 exhibits a typical PPG waveform, with a clear dicrotic notch. As V1 is closest to the sensor with a depth of 3.2 mm, the signal has the highest amplitude of 4.3 Vpp. This amplitude reduces as the vessel depth increases.
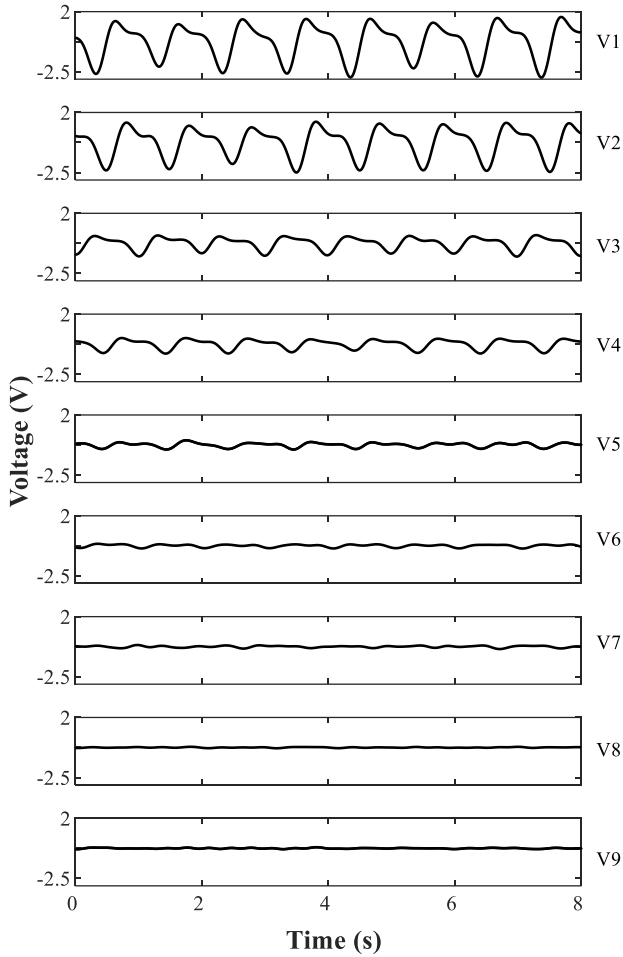

Figure 3. An eight second window of the filtered PPG signals at 4 mm separation distance for all nine vessels.

To gauge the quality of each PPG signal at each vessel depth for all separation distances, the RMS amplitude was calculated, as shown in Fig. 4. High quality signals with large amplitude were found in V1 at 3.8 mm separation distance. For V3 the peak is at 4.35 mm separation distance and for V4 at 4.4 mm. This trend, where the optimum distance increases as a function of vessel depth increase, fades at V5 (12.5 mm). In Fig. 4, as the optimal peak shifts to the right (separation distance increasing), the shape of the maximum peak broadens until no peak is noticeable in the response at V5.

Vessels V1, V2, V3, and V4 all produce clear PPG's with signal-to-noise ratios (SNR) above 22 dB (see Table 1). Although V5, V6, and V7 still show discernible PPG

Vessel	Depth (mm)	Maximum Signal-to-Noise Ratio (dB)
V1	3.2	28.16
V2	4.6	26.35
V3	7.9	23.07
V4	10.5	22.19
V5	12.5	14.79
V6	15.1	13.21
V7	17.4	9.83
V8	21.1	2.77
V9	24.4	1.82

waveforms, their amplitude has reduced significantly. Vessels V8 and V9 produce undetectable PPG signals.

Therefore, it can be concluded that for vessel depths less than 10.5 mm IR PPGs can be detected optimally when the separation distance between source and detector is between 3.8 mm and 4.4 mm. Vessels deeper than 10.5 mm produce PPGs but with low SNRs below 20 dB, which could compromise any qualitative or quantitative signals analysis when using these signals.
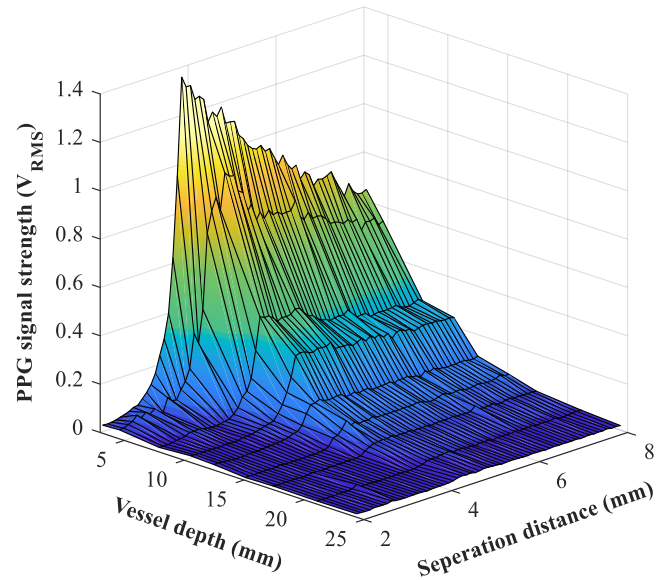

Figure 4. A 3D surface plot of the PPG signal strength against both variable parameters. Separation distance (mm) (x-axis). Vessel depth (mm)(y-axis). Root-mean-square of PPG Signal (z-axis).

IV. Conclusion

In this paper, a homogenous phantom and a novel PPG sensing system were developed to investigate the light tissue interaction relationship in reflectance PPG at different vessel depths and emitter-detector separations. The phantom and the novel PPG sensing system was connected in an *in-vitro* circulation network driven by a pulsatile pump.

In the investigation of separation distance vs. vessel depth the observed PPG signals diminish in power as vessel depth increases but can be compensated slightly by increasing the separation distance of the IR emitter and detector. Beyond a

vessel depth of 10.5 mm this compensation is no longer possible, therefore it can be concluded that for this type of vessel in this type of phantom light penetration in the IR region (930 nm) is at its' maximum. Such rigorous light-tissue interaction *in vitro* studies add significantly to the fundamental knowledge of photoplethysmography and can contribute further in the field of research aiming to unravel the origin on the PPG.

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