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Evaluation of a multimode photoplethysmographic sensor during cuff-induced hypoperfusion

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***Abstract*—Photoplethysmography (PPG) is a technique widely used to monitor volumetric blood changes induced by cardiac pulsations. Pulse oximetry uses the technique of PPG to estimate arterial oxygen saturation values(SpO_2). In poorly perfused tissues, SpO_2 readings may be compromised due to the poor quality of the PPG signals. We have developed a new multimode PPG measurement system which utilizes a reflectance PPG probe that operates in reflectance, transmittance and transreflectance mode simultaneously aiming to improve the quality of the PPG signals in cases of poor peripheral perfusion. In order to evaluate the performance of the probe, experiments were performed in healthy volunteers. A blood pressure cuff was used to induce systematic and controlled artificial hypoperfusion while PPG signals were recorded using all three modes. It was found that the amplitude of the transreflectance signal was significantly greater than the other two conventional PPG sensors at all occlusion pressures, suggesting the potential for improved signal acquisition in patients with peripheral hypoperfusion.**

***Index Terms*—Photoplethysmography, multimode, hypoperfusion, pulse oximetry.**

I. Introduction

PHOTOPLETHYSMOGRAPHY is a non-invasive electro-optical technique widely used in the study and monitoring of the pulsations associated with changes in blood volume in a peripheral vascular bed [1]. The general consensus is that the pulsations come from the site of maximum pulsation within the arteriolar vessels where pulsatile energy is converted to smooth flow just before the level of the capillaries [8]. Photoplethysmography is based on the absorption properties of vascular tissue when it is transilluminated by light. It is possible for the tissue to be directly transilluminated where the light source is on one side of the tissue and the detector on the other side (transmittance mode) or where the light source and the photodetector can be positioned side by side (reflectance mode). The transmission mode is limited to areas such as the finger the ear lobe or the toe where the reflection mode allows measurements on virtually any skin area [3].

The intensity of the light that reaches the photodetector in either reflectance or transmittance mode is measured and the variations in the photodetector current are assumed to be related to blood volume changes underneath the probe [5], [4]. These variations are amplified and recorded as the photoplethysmographic signal, used in the estimation of arterial oxygen saturation (SpO_2) by pulse oximetry. Pulse oximeters estimate arterial oxygen saturation non-invasively by illuminating vascular tissue with red light and near infrared radiation. The pulsatile photoplethysmographic (ac PPG) signal associated with cardiac contraction is assumed to be attributable solely to the arterial blood component. The amplitudes of the red and infrared ac PPG signals are sensitive to changes in arterial oxygen saturation because of differences in the light absorption of oxygenated and deoxygenated hemoglobin at these two wavelengths [9]. The arterial blood oxygen saturation may be estimated from the ratios of these amplitudes, normalized by dividing by the total detected intensity (the dc signal). Hence, the technique of pulse oximetry relies on the presence of an adequate peripheral arterial pulse [2]. False measurements have been reported while using a transmittance mode PPG probe in cases of poor peripheral perfusion. Delay in the estimation of SpO_2 by transmittance pulse oximeters has also been reported [6], [10] in cases of low peripheral perfusion. In order to overcome some of these limitations, we are proposing the design and development of a multimode finger phtotoplethysmographic sensor capable of operating simultaneously as a reflectance and transmittance PPG sensor. Such a sensor will "harvest" both the light transmitted and reflected from the vascular bed and therefore enhance its performance in cases of poor peripheral perfusion. This study will introduce the development of the proposed technology in brief and then investigate in detail its performance under conditions of controlled induced hypoperfusion in healthy volunteers.

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II. Materials and Methodes

A. Instrumentation of the multimode PPG system

1) Probe: The custom made multimode PPG finger probe [7] consists of two surface mount ceramic type infrared LEDs with peak emission wavelength of 880 nm, and two red LEDs with peak emission wavelength of 660 nm. Each pair of LEDs is mounted on the diagonal corners of the PCB board and driven asynchronously with 20 mA current. The control pulses generated by the data acquisition card switch on and off each pair of LEDs with a frequency of 500 Hz and a duty cycle of 25%. Two photodiodes are used, one of which is placed on the same plane as the LEDs, detecting the backscattered light and serving as a reflectance PPG probe, as shown in Figure 1. The other photodiode is mounted on the opposite side detecting the transmitted light from the tissue and serving as transmittance PPG probe. This geometrical placement of the optical components allows the probe to operate simultaneously in both transmittance and reflectance mode. A used commercial pulse oximeter finger clip is employed to enclose all the optical components.

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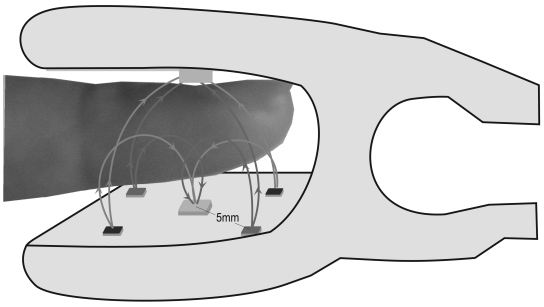

Figure 1. Multimode photoplethysmography probe.

2) Processing system and data acquisition: The PPG processing unit is designed to monitor reflectance, transmittance and transreflectance PPGs simultaneously (Figure 2). The detected current by the reflectance and transmittance photodiodes is converted into voltage by their respective differential transimpedance amplifiers. The outputs of both reflectance and transmittance transimpedance amplifiers are connected to the inputs of a summing amplifier to produce a new transreflectance output. All three outputs representing the three modes are then passed through identical processing stages. The mixed PPG signals at the output of the transimpedance amplifier is firstseparated into their respective red and infrared PPG signals by using a demultiplexer. The modulated ac part of each red and infrared signal is extracted using a band-pass filter (passband 0.5 Hz to 10 Hz) and the dc part is filtered using a low-pass filter (cut-off frequency 0.5 Hz). All the ac signals from the three modes are amplified using an inverting amplifier. A 16-bit data acquisition card (DAQPad-6015, National Instruments Inc., USA) is used to digitize all twelve signals, six ac and six dc PPG signals. National Instruments LabVIEW was used to acquire these signals at a sampling rate of 1 kHz. Matlab was used for further processing and analysis of the data.

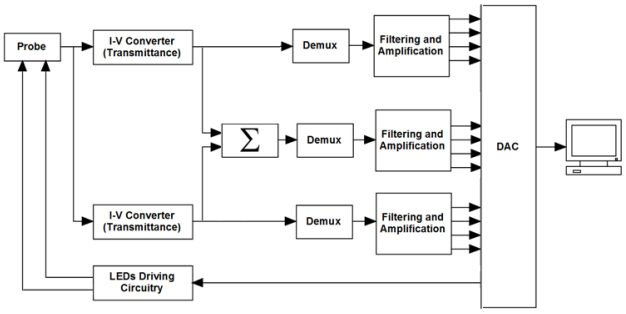

Figure 2. Block diagram of the multimode PPG processing system.

B. Measurements

The experimental protocol for this study was approved by the institutional Ethics Committee of City University London. Seven non-smoking healthy volunteers were recruited and each volunteer signed a consent form prior to the experiment. The subjects were asked to abstain from eating, drinking and exercise for at least two hours before the experiment.

At the start of the experiment, the subject was told to sit comfortably on a chair. Heart rate, systolic and diastolic blood pressure of each subject was monitored using an automatic blood pressure monitor device (HEM-907, Omron Healthcare, Hoofddorp, The Netherlands) prior to the acquisition of PPG signals. A sphygmomanometer blood pressure cuff was then wrapped around the brachial artery of the right arm. The index finger of the same arm was placed in the custom made multimode PPG probe. PPG recording commenced prior to any occlusion. Artificial hypoperfusion was then induced by gradually occluding the brachial artery using the sphygmomanometer. The pressure was exerted with increments of 15 mmHg and PPG signals recorded from all three modes for a period of 30 seconds. Once the previously recorded systolic pressure was reached, the pressure in the sphygmomanometer cuff was released and PPGs recorded for a further 30 seconds.

Peak detection algorithm was used to determine the ac PPG amplitudes. The mean of the PPG amplitudes recorded for each 30 second epoch for each occluding pressure for both wavelengths were then calculated. Paired Student's t-tests were used to determine whether there were statistically significant differences in amplitude between different modes for all occlusion pressures. A value of $p <= 0.05$ was considered statistically significant.

III. Results

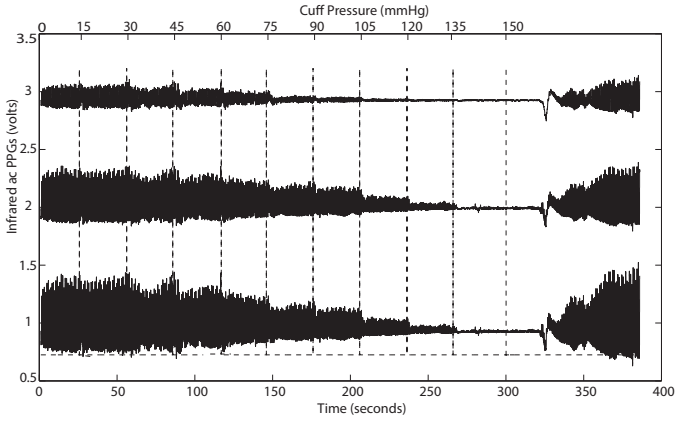

Figure 3. Infrared ac PPG signals of a subject for the entire duration of the experiment, recorded from the reflectance (top), transmittance (middle) and transreflectance (bottom) PPG system.

Good quality PPG signals were obtained from all seven volunteers at the majority of the occluding pressures with some deterioration in both the amplitude and the morphology of the PPGs at higher pressures. Twelve PPG signals were recorded from the reflectance, transmittance and transreflectance PPG system, i.e. six ac (three red and three infrared signals for each mode) and six dc (three red and three infrared signals for each mode) PPG signals. Figure 3 shows an example of infrared ac PPG signals from one volunteer, acquired for the complete duration of the experiment. Each vertical tick in the figure represents an increment of 15 mmHg of pressure exerted on the brachial artery. In Figure 3 the traces at the top, middle and bottom depict PPG signals from the reflectance, transmittance

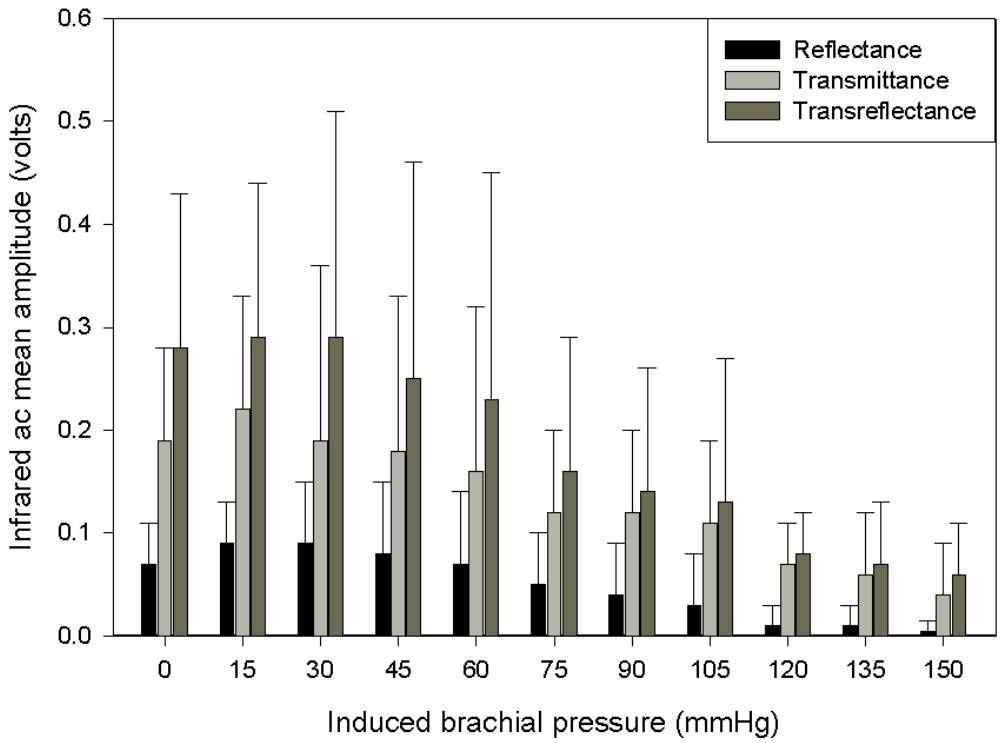

Figure 4. Mean (± SD) of infrared reflectance, transmittance and transreflectance ac PPG signals.

and transreflectance modes respectively. It can be seen that the amplitudes of all the waveforms decreased as the brachial artery was occluded gradually. The PPG amplitudes of the reflectance PPG signal (top) was smaller than the transmittance (middle) and transreflectance (bottom) PPG signals at all pressure values. The transreflectance PPG signals (bottom) were larger in amplitude when compared with the other two modes at all occlusion pressures.

Figure 5 shows a graph of mean infrared PPG ac amplitudes from one subject plotted against occlusion pressure. From the figure it can be seen that the rate of decrease in PPG amplitude became more apparent after the pressure reached 75 mmHg (approximately 50% occlusion). It can also be seen that at all arterial occlusion pressures, the mean transreflectance infrared ac values were greater compared to those acquired using the reflectance and transmittance modes.

Group	P values
Reflectance and transmittance	< 0.001
Reflectance and transreflectance	< 0.001
Transreflectance and transmittance	< 0.001

Table I
RESULTS OF PAIRED T-TESTS.

Figure 4 shows a bar chart of the mean ± SD of the mean infrared ac PPG amplitudes at all occlusion pressures from all seven volunteers. It can be seen that the mean transmittance PPG amplitudes were greater than the reflectance PPG amplitudes at all pressures. Furthermore, at all occlusion pressures, the mean transreflectance PPG amplitudes were greater than those recorded for the other two modes. Table I shows the

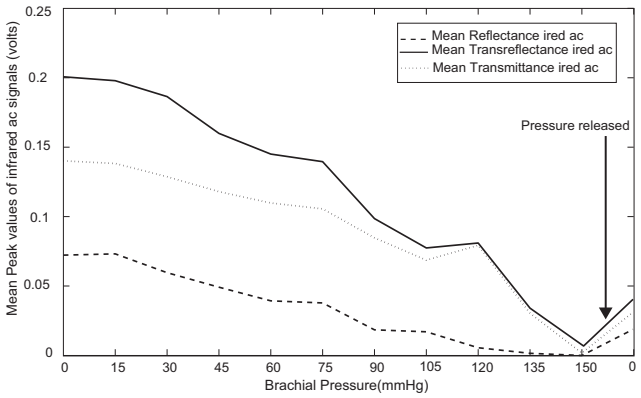

Figure 5. Mean values of the amplitudes of infrared PPG signals recorded from reflectance, transmittance and transreflectance modes at different occlusion pressures.

results of the three paired t-tests. It can be seen that there were significant differences between the amplitudes recorded for all three modes, when all pairs of modes were compared.

IV. CONCLUSIONS

The newly developed multimode PPG probe and processing system was evaluated in conditions of induced hypoperfusion. PPG signals from the two conventional modes (transmittance and reflectance) and the new transreflectance mode were recorded simultaneously. Good quality PPG signals were obtained from all volunteers at almost all induced brachial pressures. The results show that infrared PPG signals acquired

using the transreflectance mode are invariably greater in amplitude than those obtained using conventional transmittance or reflectance modes.

This pilot study suggests that the transreflectance mode might produce reliable PPG signals with good signal to noise ratio at high occlusions and therefore enable the accurate estimation of blood oxygen saturation in cases of poor peripheral perfusion. Further studies in cases of real clinical hypoperfusion are planned in order to evaluate this hypothesis.

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