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A novel non-invasive trans-reflectance photoplethysmographic probe for use in cases of low peripheral blood perfusion

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Abstract—The acquisition of reliable and meaningful photoplethysmographic (PPG) signals using conventional pulse oximetry technology may be compromised by conditions of low tissue perfusion. We have developed a novel ‘trans-reflectance’ PPG measurement system which combines reflectance and transmittance together into a single mode. For comparison purposes the system also enables the independent display of reflectance and transmittance PPG signals simultaneously. Preliminary experiments were performed on volunteers to assess the performance of the probe, where, artificial hypoperfusion was created in individuals and data was recorded with the newly developed trans-reflectance photoplethysmographic mode, and the conventional transmittance and reflectance PPG modes. The PPG signals recorded during hypoperfusion using the trans-reflectance mode were of good quality with higher signal-to-noise ratio than those obtained from the transmittance and reflectance modes.

Index Terms—Photoplethysmography, trans-reflectance, hypoperfusion, pulse oximetry.

I. INTRODUCTION

PHOTOPLETHYSMOGRAPHY is a non-invasive electro-optical technique widely used in the study and monitoring of pulsations associated with changes in blood volume in a peripheral vascular bed [5], [4], [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 transmittance mode is limited to areas such as the finger, the earlobe or the toe where the reflectance mode allows measurements on virtually any skin area [9], [7].

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 [9], [10], [2]. These variations are amplified and recorded as a voltage signal called the photoplethysmograph (PPG). Photoplethysmography is used in the estimation of arterial

oxygen saturation (SpO_2) by pulse oximetry. Pulse oximeters estimate arterial oxygen saturation non-invasively by shining light at two different wavelengths, red and near infrared, through vascular tissue. 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 [11]. From the ratios of these amplitudes, and the corresponding dc photoplethysmographic components, arterial blood oxygen saturation is estimated. Hence, the technique of pulse oximetry relies on the presence of an adequate peripheral arterial pulse, which is detected as a photoplethysmographic (PPG) signal [7]. When peripheral perfusion is poor, pulse oximeter readings become unreliable or cease altogether [6], [3]. In order to overcome some of the limitations of the commercial transmittance or reflectance pulse oximeters that appear in cases of poor PPG pulsation, a novel trans-reflectance (dual mode) finger photoplethysmographic probe was proposed that will operate simultaneously as a reflectance and transmittance PPG probe. Such a probe will “harvest” both the light transmitted and reflected from the vascularized tissue and could potentially enhance its performance in cases of poor peripheral perfusion. This paper describes the technological development of the probe, and the processing and data acquisition system. A preliminary evaluation of the system was performed in volunteers. Low perfusion states were artificially induced by asking volunteers to place their hands in iced water. Results from this preliminary study are presented.

II. MATERIAL AND METHODS

A. Trans-reflectance PPG probe

The trans-reflectance finger probe consists of two photodiodes and four LEDs, as shown in Figure 1. The geometrical placement of the optical components enables the probe to operate simultaneously in both reflectance and transmittance modes. The conventional pulse oximetry wavelengths are used with two LEDs of peak emission wavelength 660 nm and the other two with a peak emission wavelength of 880 nm. One of the photodiodes which is placed in the same plane as the LEDs serves as a detector for the reflected light whereas the second photodiode which is placed on the opposite side serves as a detector for the transmitted light. Each LED is

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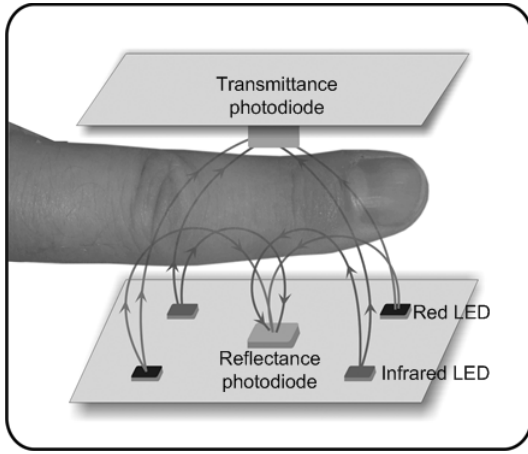


Figure 1. Trans-reflectance photoplethysmography probe.

driven asynchronously with 20 mA current. The duty cycle of the control pulses which switch on and off each LED is 25%. All optical components are packaged in a conventional pulse oximeter finger clip. A time multiplexing algorithm is implemented in LabVIEW (National Instruments Corporation, Austin, TX, USA) to switch the LEDs on and off at a frequency of 500 Hz. The trans-reflectance PPG probe also incorporates a k-type thermocouple temperature sensor for measuring finger skin temperature.

B. PPG processing and data acquisition system

Figure 2 shows the PPG processing system. The system is designed to enable simultaneous monitoring of reflectance, transmittance and trans-reflectance PPGs, allowing comparison of all three modes. All three mode channels are identical. The outputs from the reflectance and transmittance

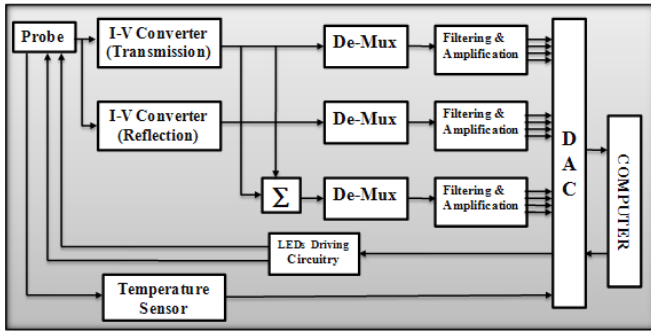


Figure 2. Block diagram of the PPG processing system.

photodiodes are connected to two differential transimpedance amplifiers (I-V Converter). For the trans-reflectance channel the outputs of both reflectance and transmittance I-V converter are summed together using a summing amplifier. All three voltage outputs representing the three modes then follow an identical process and therefore the rest of the processing system will be described assuming only one channel. The mixed voltage output of the I-V converter is connected to a demultiplexer (De-Mux) in order to separate the red and infrared PPG signals for each mode. The PPG signals are then

filtered into their respective red and infrared ac and dc PPGs using band-pass (pass-band, 0.5 Hz to 10 Hz) and low-pass filters (cut-off frequency, 0.5 Hz). The red and infrared ac PPG outputs are then amplified using an inverting amplifier with a gain of 30. The output of the temperature sensor is linearized using an AD594 (Analog Devices, Inc) to produce an output of 10 mV/°C. The red and infrared ac and dc PPGs from all three channels and the temperature signal are then digitized using a DAQPad-6015 16-bit data acquisition card (National Instruments Corporation, Austin, TX, USA). A virtual instrument was implemented in LabVIEW to display and record the PPG signals on a personal computer.

C. Preliminary evaluation on healthy volunteers

PPGs and temperature signals were acquired from five healthy volunteers at Biomedical Engineering Research Laboratory, School of Engineering and Mathematical Sciences, City University London. The subjects were asked to abstain from eating, drinking, smoking and exercise for at least two hours before the experiment. At the start of the experiment, the subjects were asked to place their hand into a bucket of iced water, until the skin temperature of the hand reached 15 °C. The hand was then removed from the iced water and the custom made PPG probe was placed on the index finger of the cold hand and PPG signals from all three modes were collected simultaneously. The ac PPG signals at both wavelengths from all three modes were normalized by dividing the ac component of each signal by the dc (total intensity) component. Meanwhile the skin temperature was also recorded. The measurements continued until the skin reached a steady temperature.

III. RESULTS

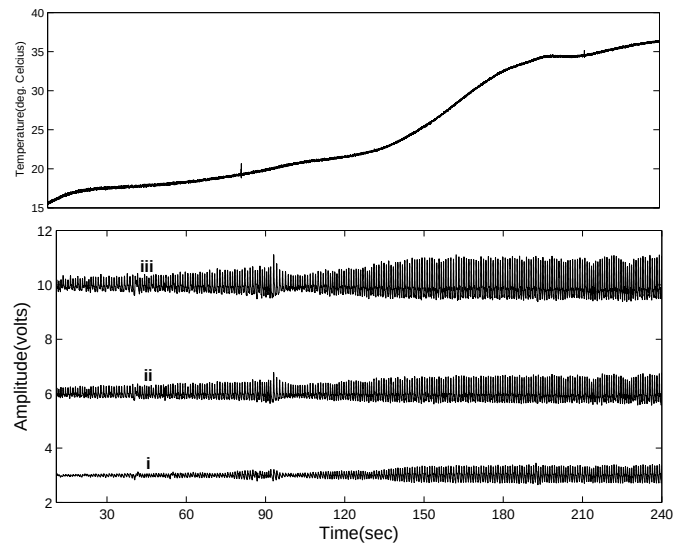


Figure 3. Temperature (top) and three normalized infrared PPG signals (bottom), recorded simultaneously from the index finger using the trans-reflectance PPG probe. The waveforms i, ii, and iii show reflectance, transmittance, and trans-reflectance infrared ac PPG signals respectively.

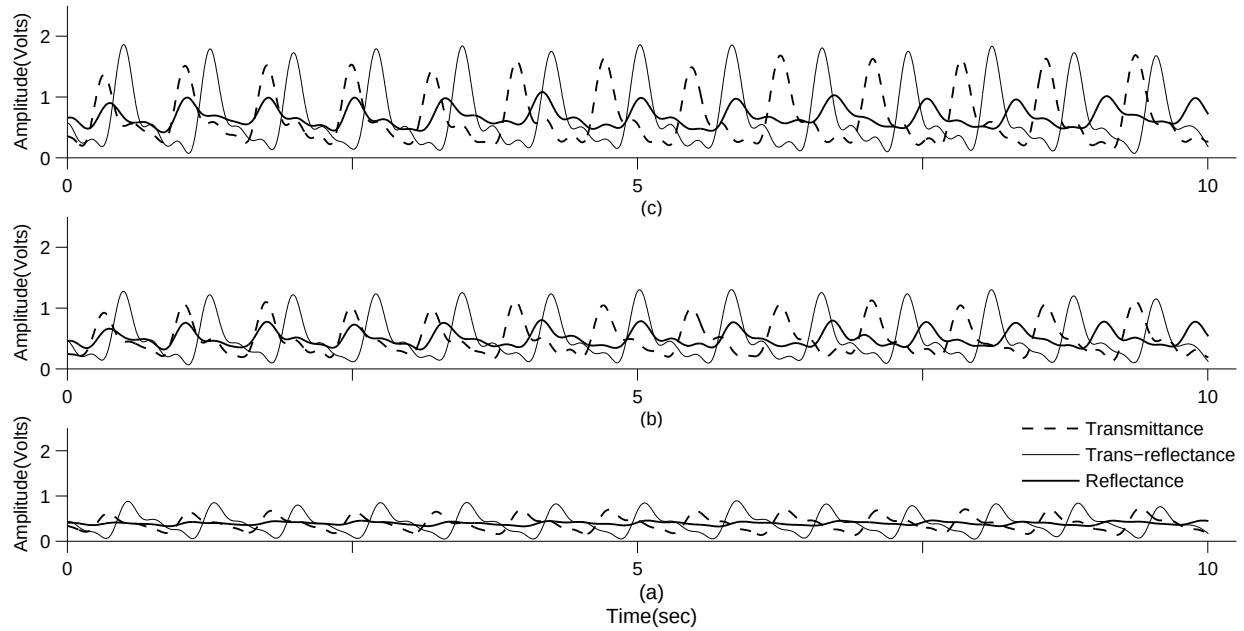


Figure 4. 10-second samples of normalized infrared PPG signals recorded from the hand at a skin temperature of (a) 16°C, (b) 20°C and (c) 24°C.

Thirteen signals were recorded, which included four PPG signals from each mode: transmittance, reflectance, and trans-reflectance acquired from the custom made trans-reflectance PPG system, and a temperature signal recorded from the thermocouple. The upper trace in Figure 3 shows the temperature of the finger during the monitoring period recorded from one volunteer. Three normalized infrared PPG signals (one for each mode) recorded from the index finger using the newly developed technology are shown in Figure 3 (lower traces). The signals (i), (ii), and (iii) show the normalized reflectance, transmittance, and trans-reflectance infrared PPG signals respectively. It can be seen that all three signals increased in amplitude as the skin temperature increased. At low temperature, where vasoconstriction presumably occurred, a noticeable difference in the amplitude of the reflectance and transmittance PPG probe signals was observed. The infrared trans-reflectance component (iii in Figure 3) was greater in amplitude than both signals obtained from the transmittance and reflectance modes. At the start of the monitoring period, the amplitude of the reflectance signal was extremely small. From Figure 3 it can be observed that the PPGs of the trans-reflectance mode were of high signal-to-noise ratio at all finger temperatures. The amplitude of the transmittance PPG signal was larger than the reflectance PPG signal but lower than the trans-reflectance PPG signal at all temperature values. Our observations on the PPG signals from the reflectance and transmittance mode were in agreement with other studies in the field [9], [1].

Figure 4 depicts normalized PPG signals (for ten seconds) recorded from the 'cold' index finger of a volunteer at three different temperatures. Figure 4a shows PPGs from the three modes at 16 °C and similarly Figures 4b and 4c show PPGs from the three different modes at temperatures 20°C and 24°C respectively. Clearly the trans-reflectance PPG signals have

the larger amplitude than the other two modes at all three temperatures.

IV. CONCLUSIONS

A new non-invasive trans-reflectance PPG probe was developed. The PPG probe had also the capability to operate in reflectance and transmittance modes as well. In order to compare the performance of the trans-reflectance PPG mode, all three modes were run simultaneously in an artificially induced finger hypoperfusion using an ice bath. Good quality PPG signals were recorded from the newly developed trans-reflectance probe. The results show that the trans-reflectance mode was more sensitive to blood pulsation than the reflectance and the transmittance mode during peripheral hypoperfusion. Furthermore the amplitude of the signals obtained from the trans-reflectance mode were greater than those from the other two modes suggesting that the trans-reflectance signals may be more suitable for estimation of oxygen saturation in cases of poor peripheral perfusion where PPG signals from the reflectance or the transmittance mode can become unreliable. Following further assessments in volunteers, oxygen saturation derived from the trans-reflectance mode will be compared with values obtained from the reflectance and transmittance modes.

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