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Evaluation of a combined reflectance photoplethysmography and laser Doppler flowmetry surface probe

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***Abstract*— this study presents evaluation of a system combining laser Doppler flowmetry and photoplethysmography (PPG) in a single probe for the simultaneous measurement of perfusion and blood flow in the finger. A cuff sphygmomanometer was used to partially occlude the arteries supplying the hand to investigate the effect of low pressure on photoplethysmographic and laser Doppler signals and also on calculated arterial blood oxygen saturation values (SpO_2). Red and infrared PPG and Doppler signals were recorded from six healthy volunteers at various pressures. Good quality signals were recorded in all subjects at low cuff pressures; however both PPG and Doppler signals showed a gradual decrease in amplitude at higher pressures. SpO_2 values calculated from the PPG signals showed higher deviation from measurements made on the contralateral hand using a commercial pulse oximeter at higher cuff pressures.**

I. Introduction

Blood oxygen saturation level is very important in clinical physiological monitoring. In medicine, oxygen saturation indicates the percentage of hemoglobin binding sites in the bloodstream occupied by oxygen [1]. Various techniques measure the skin blood flow including Photoplethysmography and laser Doppler flowmetry (LDF). Photoplethysmography is a method of monitoring changes in transmission of light through tissue due to pulsation of small arteries while laser Doppler flowmetry (LDF) measures microcirculatory blood cell velocity and flux [2].

The results presented here are part of a wider study to combine LDF and PPG into a surface probe intended for evaluation of peripheral blood flow in abdominal tissue during bowel operations. Bowel viability assessment is essential in gastrointestinal surgery, and must be evaluated frequently during and after abdominal operation otherwise it can be lead to intestinal ischemia and necrosis associated with an increased length of hospital stay, significant postoperative morbidity and mortality. Although numerous techniques of intraoperative bowel viability assessment like pulse oximetry, polarographic measurement of oxygen tension, near-infrared and visible light spectrophotometry (NIRS & VLS) and intravital microscopy are available, only a few are applicable in bowel surgery. The majority of methods are still far from ideal [2]. An optical sensor for assessment of the perfusion of the bowel has been proposed which may be placed on the bowel allowing the perfusion status and blood oxygen level before and after rejoining two parts of bowel together to be assessed. The sensor could indicate the presence and magnitude of the circulation so allow early warning of ischemia to the surgeon before damage occurs.

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A. Photoplethysmography (PPG)

Photoplethysmography, (PPG) a non-invasive electro-optic method provides information on the blood volume changes in the body caused by cardiovascular pulsations in the bed of tissue [3]. A photoplethysmogram is obtained by illuminating a part of the body of interest and acquiring either the reflected or transmitted light. Photoplethysmography (PPG) involves two basic forms of optoelectronic which one for emitting monochromatic light into tissue and the other for collecting the light reflected back, or through, and not absorbed by tissue and blood. The intensity of light from emitter, which reaches the photodiode detector, will be measured to determine the blood volume changes. Variation in the signal correlates to several parameters of which pulsatile changes in blood flow and blood volume are regarded as most important [4]. Typically PPG is a non-invasive technique and operates at red and infrared wavelength [5].

The PPG signal consists of two types of waveforms including a dominating DC-part and a pulsatile AC-part. AC component is a pulsatile waveform, which represents the pulsing of the blood in the arteries while DC component is a comprised of the absorption from the non-pulsing arterial blood, the venous and capillary blood. The AC-part is usually filtered out and amplified.

There are two main PPG operational configurations; the first one is transmission mode operation where the tissue sample (e.g. fingertip) is placed between the source and detector. And the second one is reflection mode operation where the LED and detector are placed side-by- side [6].

B. Laser Doppler flowmetry (LDF)

The Doppler effect is utilized in laser Doppler flowmeters for measuring microvascular blood flow. In brief, a beam of laser light, carried by a fiber-optic probe attached to or inserted into the investigated tissue, interacts with moving components of tissue such as red blood cells [7] and is Doppler shifted while light interacting with static objects is unchanged. The light is then scattered and partly absorbed by the tissue to be investigated. The light is picked up by a returning fiber, converted into an electrical signal that is processed to provide an estimation of blood flux, which is the product of the velocity and the number of red cells in the volume of tissue interrogated by the probe [8]. Laser Doppler flowmetry (LDF) and photoplethysmography (PPG) are both well-established non-invasive optical methods for measuring changes in skin blood flow [9]. Through application of both these methods, the tissue blood flow in different tissue layers can be inferred. As laser Doppler flowmetry can study the

more superficial blood flow [10] and PPG can assess the blood flow deeper in the tissue [11], the combination of LDF and PPG was chosen in order to be able to explore the most superficial blood flow using LDF as well as blood flow in deeper tissue layers using PPG [3].

This study aimed to evaluate this system's ability to differentiate between states of normal and compromised perfusion. Both LDF and PPG measurements were made from the finger using a sphygmomanometer cuff on the arm to induce graded perfusion states by inflating the cuff to various pressures causing partial occlusion of the brachial artery. The LDF and PPG signals were measured for a series of pressures from zero to 135 mmHg. SpO_2 values were also calculated from the acquired PPG signals. It is hoped that using laser Doppler flowmetry and photoplethysmography in a combined probe, improvement in the investigation of tissue viability will be possible, and the results will lead to refinements in future measurements made form intestinal tissue.

II. MATERIALS AND METHODS

A. Photoplethysmographic reflectance probe

The reflectance probe used in this study consisted of a central photo detector surrounded by two light sources for PPG (and a LDF fiber tip). Two combinations of wavelengths of light and the same distance from light source to detector will be used: infrared (IR) 880nm and red (R) 628nm.

B. Doppler laser probe

The VP8c titanium laser Doppler disc probe (Moor Instruments Ltd., UK) will be used as the laser Doppler probe in this research. The probe is connected to a laser Doppler monitor (Moor Instruments, Ltd., UK). The combined probe has been shown in Fig. 1. Fig. 2 shows the block diagram of the PPG systems. It consists of a timer, LED driver, photodiode detector, amplifier, demultiplexer and a band pass filter circuit.

C. Evaluation of the system

Three main parts of the measurement system developed for the present research include: (a) Probe (b) Instrumentation: this is housed in a box with dimensions 30x28x9 cm containing: power, LED current source and a custom-made signal processing circuit to separate the photoplethysmographic signals into its AC (rapidly varying or 'pulsatile') and DC (slowly varying) components and to amplify each component. The drive current (as stated on the LEDs datasheet) used for switching the LEDs was 50 mA using a current-limiting resistor in series with the LEDs of value R = 220 Ω and a voltage supply of 12 V. (c) Data acquisition system: The AC PPG and DC PPG signals are sampled by an analogue to digital converter installed into a notebook computer. Software (known as a virtual instrument or 'VI') implemented in LabVIEW (National Instruments Corporation, Austin, TX, USA) reads the AC and DC signals, displays the AC PPG waveform and records both signals for later analysis. The PPG signals (AC and DC), and the flux signal from the laser Doppler flowmeter will be acquired and recorded with the DAQ card at a sampling frequency of 200 Hz using a specially developed LabVIEW program. The PPG (AC signal) was separated from the total intensity (AC+DC) signal using filters incorporated into the measurement circuitry. The Doppler monitor has an analog output so signals can be obtained and displayed using LabVIEW.

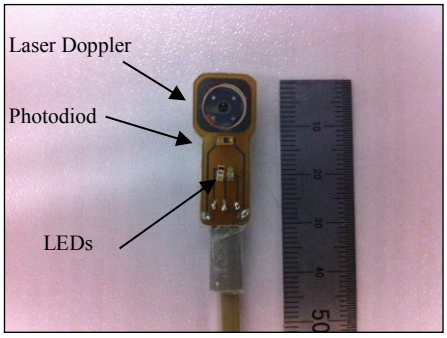

Figure 1. Photograph of the combined probe with two LEDs, one photodiode and the laser Doppler probe tip of 8 mm diameter.

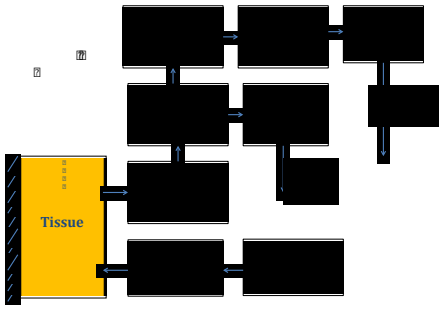

Figure 2. The block diagram of the PPG systems

III. EXPERIMENTAL METHOD

Six healthy volunteers (2F, 4M; mean age 25 ± 3) who had not been taking any regular medication and were free of any significant medical problems participated in this study. A pressure cuff attached to a manual sphygmomanometer was placed around the left arm of a volunteer. The experimental probe was attached to the left index finger. One minute of simultaneous PPG and Doppler flux measurements were taken with the cuff deflated. The cuff was then inflated in 15 mmHg steps up to 135 mmHg. One minute of PPG and Doppler measurements was again taken at each pressure. The cuff was deflated for 30 seconds between each measurement to allow re-perfusion of the hand and to avoid unnecessary discomfort for the volunteer subjects.

IV. DATA ANALYSIS AND STATISTICS

From the PPG signals, the peak-to-peak amplitudes of the AC red (R_{AC}) and infrared (IR_{AC}) signals were calculated for each cardiac cycle (heartbeat) and the mean value of these amplitudes determined for all signals during each one minute measurement period. DC values for red (R_{DC}) and infrared (IR_{DC}) calculated by subtracting the AC signal from the total signal (AC+DC). The amplitudes of laser Doppler

for all six volunteers were also measured during the hypoperfusion process for about one minute with calculation of peak-to-peak amplitude of the laser Doppler signals. The SpO_2 values were also calculated using the following formula: $SpO_2=110–25\ R_R$

where,

$$R_R=\frac{R_{AC}/R_{DC}}{IR_{AC}/IR_{DC}}$$

V. RESULTS

PPG and Doppler signals were detected from the combined probe from the index finger in all volunteers. The AC red and infrared PPG and Doppler traces in one volunteer at zero, 75 mmHg and 135 mmHg pressures for 10 second are shown in Fig. 3, 4 and 5 respectively. In all Figures AC infrared (IR_{AC}) PPG is shown in the first graph, AC red (R_{AC}) PPG is the middle graph and the last graph is related to laser Doppler. By comparing Fig. 3, 4 and 5, it is clear that there are significant differences between IR_{AC} and R_{AC} PPG and Doppler signals at each of the cuff pressures represented by the graphs. In fact at 75 mmHg, the finger PPG signals are significantly reduced for all subjects compared to the signals obtained at zero pressure and with a further increase of the cuff pressure to approximately 120 mmHg all signals ceased due to no blood flow to the finger (see Fig. 6 at pressure 120 mmHg). In Figures 6, 7, and 8, the amplitude of AC red and infrared signals along with the Doppler signal in various pressures in all subjects is shown. As the cuff is gradually deflated, the brachial artery will be occluded gradually, due to the decrease in the volume of blood through the arm. As a result, less blood can reach the finger producing low amplitude signals for all measurements. This effect is obvious in changes in the amplitude of IR_{AC} and R_{AC} PPG and Doppler signals from the finger probe. The IR_{AC} and R_{AC} amplitude reduced by 58.96% and 37.58% respectively at 75mmHg compared to zero cuff pressure. The laser Doppler amplitude fell by 60.14% at 75mmHg cuff pressure compared to zero cuff pressure. Figure 9 shows the calculated SpO_2 at different cuff pressures. It can be seen the values of SpO_2 become erratic at cuff pressures greater than 75 mmHg, with all but one subject showing apparent desaturation at high cuff pressures.

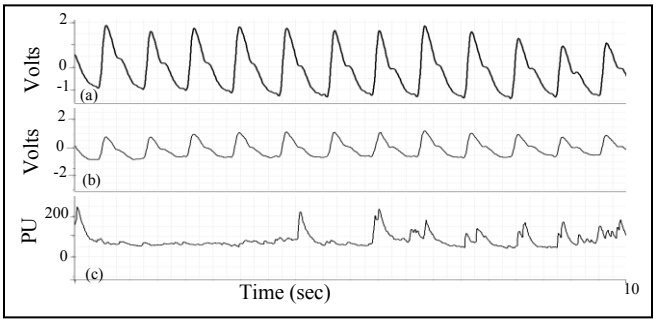

Figure 3. (a) IR_{AC} ,(b) R_{AC} and (c) laser Doppler signals at zero mmHg for 10 second.

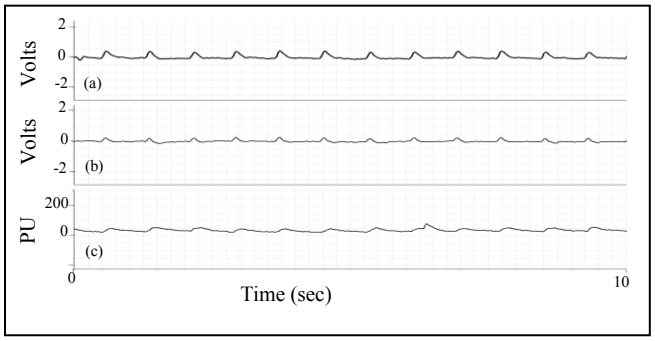

Figure 4. (a) IR_{AC} ,(b) R_{AC} and (c) laser Doppler signals at 75 mmHg for 10 second.

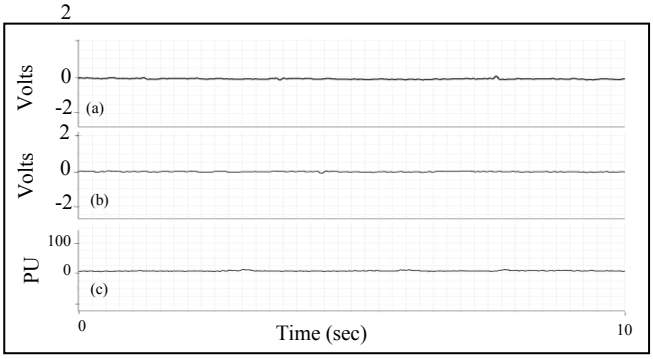

Figure 5. (a) IR_{AC} , (b) R_{AC} and (c) laser Doppler signals at 135 mmHg for 10 second.

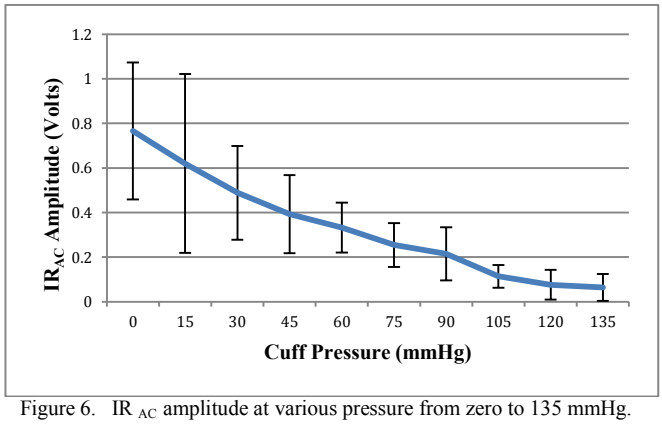

Figure 6. IR_{AC} amplitude at various pressure from zero to 135 mmHg.

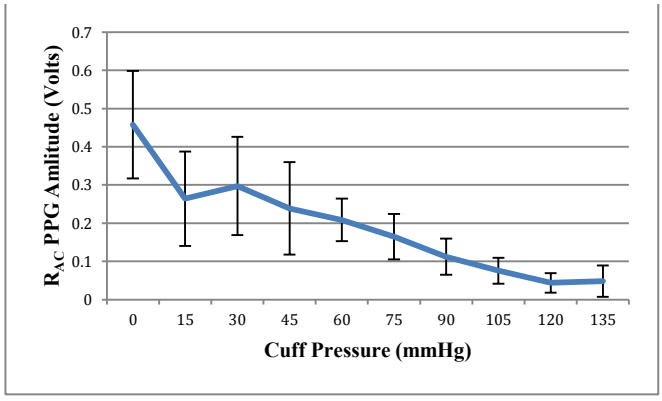

Figure 7. R_{AC} amplitude at various pressure from zero to 135 mmHg.

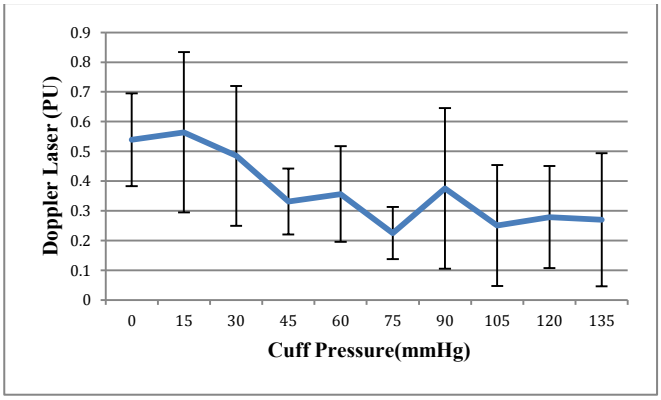

Figure 8. Laser Doppler amplitude at various pressure from zero to 135 mmHg.

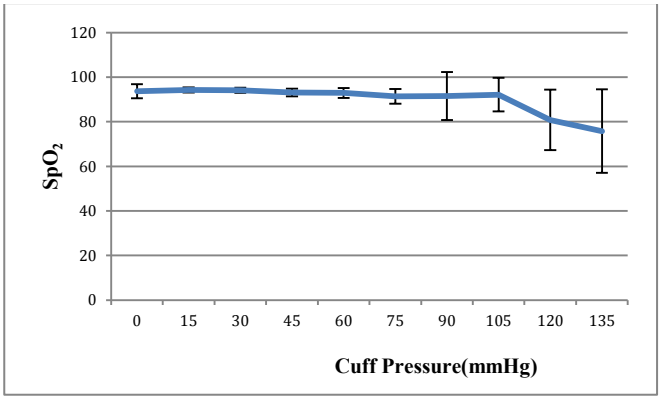

Figure 9. Blood oxygen saturation (SpO_2) during hypoperfusion from zero to 135 mmHg.

VI. Discussion and Conclusion

Finger PPG and Doppler signals were measured in six volunteers in various pressures from zero to 135 mmHg. During hypo-perfusion as the cuff pressure increases, the amplitude of the PPG and Doppler signals decrease with increasing pressure as expected due to occlusion of the brachial artery. From the signals obtained at different pressures, it can be seen that the mean AC red and infrared PPG and Doppler amplitude is considerably reduced in states of simulated ischemia in the finger tissue. The decrease in the amplitude of the PPG signals and Doppler coincides with the observed changes in blood oxygen saturation in all subjects. These findings suggest that both PPG and LDF individually are sensitive indicators of ischemia although the percent fell in amplitude of Doppler was greater than PPG between zero and 75mmHg cuff pressure. This result suggests that PPG is more sensitive to ischemia than Doppler.

A measurement system combining both modalities would provide more information than PPG or Doppler alone. Loss of both signal types would provide stronger evidence of ischemia than either single measurement. The extra information gained from the oxygen saturation calculated from the PPG signals could provide further information regarding the health of the tissue. The differences and similarities between finger and bowel measurements are not yet known as measurements were only taken from one site (the fingertip).

The aim of this experiment was to test a combined opto-electronic measurement technique based on PPG and LDF technology in conditions of reduced perfusion as may occur during ischemia of the gut or other internal tissue. This study is a part of wider study, which aims to evaluate this measurement system in patients undergoing bowel resection. The effectiveness of the system for assessing bowel viability will shortly be evaluated in a clinical trial. The combined sensor will be laid on the surface of the bowel during open laparotomy, before and after removal of ischemic or cancerous bowel tissue. PPG and LDF measurements will be made from ischemic and healthy tissue, providing comparison of the presence and magnitude of perfusion in different regions. A combined sensor could allow early warning of ischemia to the surgeon before damage occurs.

Furthermore, the proposed biosensor can be used during many kinds of surgery, for example, gastric pull-up in esophageal cancer where there are often serious doubts about the blood supply to the gastric tissue due to rotation or other displacement of the tissue mass. In addition, the sensor could find application in colon bypass or in patients with colon volvulus, torsion of testis etc.

References

[1] Allen J., "Photoplethysmography and its application in clinical physiological measurement," Phys meas, vol. 28, R1-R39, 2007.

[2] Linas Urbanavicius, Piet Pattyn, Dirk Van de Putte, Donatas Venskutonis, "How to assess intestinal viability during surgery: A review of techniques," World J Gastrointest Surg, pp. 59-69, 2011.

[3] Uliasz M. et al., "Sonography of small bowel, colon and appendix in children with cystic fibrosi," Med Wieku Rozwoj, vol 14, no. 1, pp 15-27, Jan-Mar 2010.

[4] Nuria Oliver & Fernando Flores-Mangas, "HealthGear: A Real-time Wearable System for Monitoring and Analyzing Physiological Signals," Journal of communication, vol. 2, no. 2, Mar. 2007.

[5] Hsiu H, Hsu CL, Wu TL., "Effects of different contacting pressure on the transfer function between finger photoplethysmographic and radial blood pressure waveforms," Proc Inst Mech Eng H., vol. 225, no. 6, 575-83, Jun. 2011.

[6] Cong-Zhia; Zheng, Yong-Pinga, "Comparison between reflection-mode photoplethysmography and arterial diameter change detected by ultrasound at the region of radial artery Wang," Blood Pressure Monitoring, vol. 15, no. 4, pp 213-219, Aug. 2010.

[7] T. L. Goode and H. J. Klein, "Miniaturization: An Overview of Biotechnologies for Monitoring the Physiology and Pathophysiology of Rodent Animal Models," ILAR Journal, vol. 43, no. 3, 2002.

[8] Wong DM, et al. "Agreement between arterial partial pressure of carbon dioxide and saturation of hemoglobin with oxygen values obtained by direct arterial blood measurements versus noninvasive methods in conscious healthy and ill foals," J Am Vet Med Assoc., vol. 239, no. 10, pp 1341-7, 2011.

[9] JM Goggin et al., "Ultrasonographic measurement of gastrointestinal wall thickness and the ultrasonographic appearance of the ileocolic region in healthy cats," Journal of the American Animal Hospital Association, vol 36, no. 3, pp224-228, May 2000.

[10] Jean Micheels et al., "Laser doppler flowmetry. A new non-invasive measurement of microcirculation in intensive care?," vol. 12, no. 1, pp 31–39, May 1984.

[11] Zhang Q., Linderg, L., Kadefors, R. and Styf, J. "A non-invasive measure of changes in blood flow in the human anterior tibial muscle," Eur J Appl Physiol, pp. 448-45, 2001.