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Pulse Oximeter Concept for Vascular Occlusion Test

Fatanah M. Suhaimi, J. Geoffrey Chase, Christopher G. Pretty, Rodney Elliott, Geoffrey M. Shaw

***Abstract*—**Microcirculatory dysfunction is very common in sepsis and may results in organ failure and increased risk of death. Analyzing oxygen utilization can potentially assess microcirculation function of an individual. In this study, a modified pulse oximeter is used to extract information signals due to absorption of red (R) and infrared (IR) light. IR and R signal are related to the overall blood volume and reduced hemoglobin, respectively. Differences between these two signals thus represent the amount of oxygenated hemoglobin. Avascular occlusion test has been conducted on healthy individuals to validate the pulse oximeter concept. In this test, both R and IR signals rapidly changed according to the occlusion process. The pulse oximeter concept presented is capable of extracting valuable information to assess microcirculation condition. Implementing this concept on ICU patients has the potential to aid sepsis diagnosis and provide more accurate tracking of patient state and sepsis status.

***Keywords*—**Microcirculation, sepsis, sepsis diagnosis, oxygen extraction.

I. Introduction

SEPSIS patients normally suffer microcirculatory dysfunction, which consequently results in organ failure [1] and increased risk of death [2]. It is characterized by heterogenous abnormalities particularly in blood flow and under-perfused capillaries, which also results in increased risk of severe infection [3], [4]. Importantly, microcirculatory distress is the only independent factor for predicting patient outcome if it is not treated within 48 hours [5]. The microcirculation is a critical physiological pathway through which oxygen diffuses to tissues and waste products are returned to be processed by the circulation. Clinically, microcirculatory dysfunction affects organs, such that tissues receive insufficient amounts of oxygen or other substrates. In sepsis, microcirculatory becomes hypoxic, a deficiency in the amount of oxygen reaching the tissue [6], [7]. As a result, tissues and organs begin to fail. The end consequence is an increased risk of the organ failure that defines sepsis.

This study presents a validation of pulse oximeter concept for assessing microcirculation function. A modified pulse oximeter is used to assess microcirculation function via assessing oxygen extraction. In this study, extraction is the rate or level of exchange of oxygen and other products by the microcirculation.

In general, pulse oximeter operation is based on measuring the absorption of red and infrared light passed through a patient's finger or ear lobe. The principle of pulse oximetry is based on the assumption that the only pulsatile absorption between the light source and the photodetector is that of arterial blood. Background, such as fluid, tissue and bone, are factored out of the measurement by monitoring the steady state of absorption from bone tissue, venous blood and arterial blood.

The light source incorporated in the oximeter probe consists of two light emitting diodes (LEDs) that emit light at known wavelengths, specifically 660nm and 940nm for red and infrared, respectively. These two wavelengths are used because oxyhemoglobin and reduced hemoglobin have different absorption spectra at these particular wavelengths. In particular, the changes in red and infrared signals are specifically investigated separately in this study. Unlike a standard pulse oximeter that combines all these signals into a single, calibrated oxygen saturation metric.

The periodic variations due to arterial pulsatility yield an alternating current (AC) component, which is very small relative to the steady state direct current (DC) component. In normal use, the change in the AC signal relative to the DC signal measured represents the absorption of oxygen into tissue. The raw red and infrared signals are processed to represent the relative absorption of reduced hemoglobin and oxyhemoglobin. From this concept, oxygen saturation and extraction can potentially be derived and thus can be used to assess the microcirculation status. This use is a significant extension from the use of pulse oximetry to measure oxygen saturation in tissues.

In this study, a vascular occlusion test (VOT) is conducted on healthy individuals to induce changes in microcirculation. Additionally, VOT has been widely used in several researches to assess microvascular changes, specifically to obtain dynamic tissue oxygen saturation [8]-[12]. Results from several researches indicate that the VOT permits the determination of tissue metabolic rate, particularly during ischemia [12], [13]. Therefore, VOT is used in this study to measure oxygen extraction, a key feature of sepsis. More important, VOT is used in this study to demonstrate and validate the pulse oximeter concept.

The goal of this study is to determine if changes in oxygen extraction, a key feature of sepsis, can be assessed under known and well understood perturbations. Such measurement if successfully captured will provide information about microcirculation dysfunction and therefore could enable better and more accurate tracking of patient state and sepsis status.

Fatanah M. Suhaimi is with the Advanced Medical and Dental Institute, Universiti Sains Malaysia, Bertam, 13200 Kepala Batas, Penang, Malaysia (phone: 604-562-2561; fax: 604-562-2468; e-mail: fatanah@amdi.usm.edu.my).

J. G. Chase, C. G. Pretty, and R. Elliott are with Department of Mechanical Engineering, University of Canterbury, Christchurch, Private Bag 4800, 8054, New Zealand (e-mail: geoff.chase@canterbury.ac.nz, chris.pretty@canterbury.ac.nz, rodney.elliott@canterbury.ac.nz).

G. M. Shaw is with the Department of Intensive Care, Christchurch Hospital, Christchurch 8054, New Zealand (e-mail: Geoff.Shaw@cdhb.govt.nz).

II. Methods

A. Test Design

In this study, vascular occlusion test has been conducted in order to validate the pulse oximeter concept and also to induce changes in extraction. The vascular occlusion test was done on healthy individuals. This study and the use of this data was approved by the University of Canterbury Human Ethics Committee, Christchurch, New Zealand.

In this test, subjects were comfortably seated with one arm rested on a table. An initial blood pressure was measured manually on the subject's arm to identify baseline perfusion pressure. After that, a pulse oximeter probe was attached to the subject's finger and subjects were required not to move their arm, hand and fingers. A sphygmomanometer was then placed on the forearm and baseline measurement was recorded for 30-60 seconds. The sphygmomanometer was then rapidly inflated until the pressure was 40 mmHg above the baseline systolic pressure to induce the occlusion. Inflation took approximately 10-30 seconds. The sphygmomanometer was then rapidly deflated after 3 minutes of occlusion. Data from pulse oximeter was continuously recorded for at least 3 minutes after the sphygmomanometer was released. Fig. 1 shows the process used in this test.

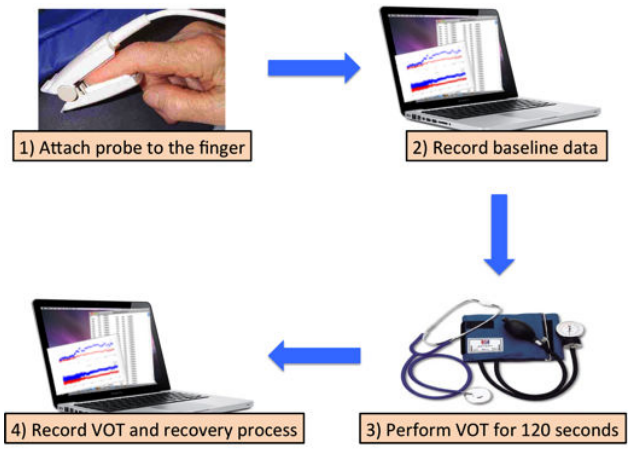

Fig. 1 Flowchart of procedure used in the vascular occlusion test (VOT)

B. Test Subject

There were 15 healthy individuals participated in this test. Table I shows the demographic and baseline characteristics of the test subjects.

C. Measurement Metrics

In general, pulse oximeter use red and infrared LEDs. These LEDs on the probe are alternately pulsed in a controlled fashion. In order to keep the photo-receiver sensors within specification, the intensity of the IR and R LED is controlled by the LED intensity control block. The output from the photodiode of the finger probe is passed through a current-to-voltage converter. The raw voltage converted signal is amplified using a second stage amplifier. The signals from these two stages are fed to two different channels of ADC. The sampling rate used in this experiment is 70 Hz. Output data is observed in a screen and captured from a serial port and stored in the PC. The DC component is obtained using a 32-point moving average of the raw signal, while the AC component is the remainder of the signal.

During the test, DC and AC signals for R and IR absorption were measured. The R signal measures reduced hemoglobin (Hb) and the IR signal measures the sum of reduced hemoglobin and oxyhemoglobin (Hb + HbO_2). During the inflation of the sphygmomanometer, both the R and IR DC signals were expected to decrease over time as less blood was flowing into the occluded area, before reaching constant values indicating a constant blood volume in the occluded area. Additionally, no pulsatile waveform should be seen during this time since no pulsation of arterial blood should exist during the occlusion. After the sphygmomanometer has been released, the R and IR DC signals were expected to rise immediately as more blood flows initially into the hand area, followed by blood redistribution and progressive desaturation. This process occurs until the blood flowed has been normalized.

TABLE I
Demographic and Baseline Characteristics of Test Subjects

Demographic characteristics	Median [IQR] [a]
Age (years)	26 [23 – 30]
Gender (%)	
Female	40
Male	60
Dominant Hand (%)	
Right	93
Left	7
Weight (kg)	61 [46 – 72]
Height (cm)	166 [155 – 177]
Baseline characteristics	
Systolic blood pressure (mmHg)	110 [100 - 110]
Diastolic blood pressure (mmHg)	60 [60 - 64]
Heart rate (beats/minute)	65 [59 - 71]

[a]IQR is interquartile range

III. Results

Fig. 2 shows the DC and AC components of the R and IR pulse oximeter signals during a VOT on Subject 14. The VOT process can be divided into three stages, which are the baseline (resting), vascular occlusion, and recovery. X and y-axes represent time in seconds and amplitude in volts, respectively. In Fig. 2, T1 represents the starting time of occlusion process whereas T2 represents the starting time of releasing the sphygmomanometer. Fig. 2 represents one of the examples of DC and AC signals of red and infrared collected from this study. Generally, most of the test subjects have similar AC and DC profile pattern as in Fig. 2.

In Fig. 2, DC R and IR signals drop hugely during vascular occlusion relative to the baseline. As the vascular occlusion progressed, both DC IR and DC R signals were settled to almost constant. Both R and IR signals increased immediately after the sphygmomanometer was deflated and greater changes

of amplitude in the IR signal can be observed initially as compared to the R signal. However, both signals intersect during recovery and DC R was higher than DC IR throughout recovery.

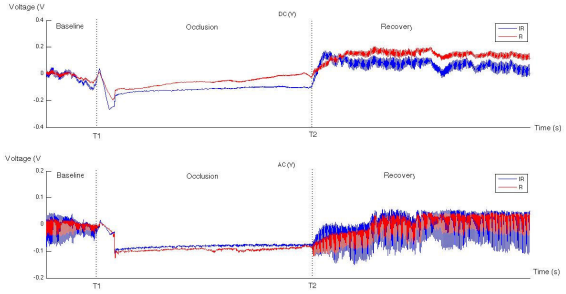

Fig. 2 DC and AC components of red and infrared during vascular occlusion test on Subject 14

Fig. 3 shows the scaled AC components of IR signals on Subject 14 for a 15 second interval during the baseline, vascular occlusion and recovery phases. During the vascular occlusion, represented in the middle panel of Fig. 3, no heartbeat was detected, as expected. This is because the heartbeat has been blocked due to the occlusion process that also results in blood flow ceased and limit the blood volume redistribution. Additionally, AC amplitude and beat-to-beat interval were slightly increased during recovery compared to the baseline. There were 17 peaks of AC signal observed during baseline whereas 15 peaks during recovery for a same time interval, as shown in top and bottom panels of Fig. 3. However, the changes are not very significant.

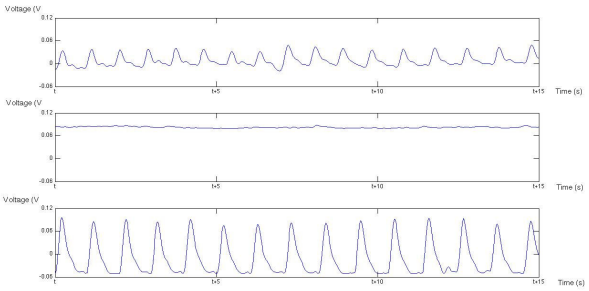

Fig. 3 Infrared AC signals of Subject 14 for 15 seconds interval of baseline, vascular occlusion and recovery

Table II shows the average value of oxygen extraction in volts and percentage measured during baseline and recovery for all 15 subjects during the VOT. Extraction is measured as the amount of oxygenated hemoglobin, HbO_2, that is the difference between IR and R DC signals. Median oxygen extraction at baseline and recovery are 0.03 and 0.05 volts, respectively. Median change in oxygen extraction is 0.01 volts. Most of the subjects had increased oxygen extraction at the recovery with respect to their baseline, as expected. However, the changes in oxygen extraction from the baseline to the recovery were relatively small, and some individuals had lower oxygen extraction at recovery compared to their baseline.

TABLE II
AVERAGE VALUE OF OXYGEN EXTRACTION AND CHANGE IN OXYGEN EXTRACTION

Subject no	HbO_2Baseline		HbO_2Recovery		Δ HbO_2	% Absolute	% Relative
	Volts	%	Volts	%	Volts		
1	0.03	60.0	0.05	62.5	+0.02	+2.5	4.2
2	0.02	33.3	0.09	56.3	+0.07	+23.0	69.1
3	0.02	66.7	0.04	100.0	+0.02	+33.3	49.9
4	0.09	52.9	0.08	42.1	-0.01	-10.8	20.4
5	0.04	44.4	0.02	20.0	-0.02	-24.4	55.0
6	0.07	58.3	0.10	58.8	+0.03	+0.5	0.9
7	0.02	28.6	0.02	25.0	+0.00	-3.6	12.6
8	0.02	50.0	0.05	55.6	+0.03	+5.6	11.2
9	0.06	40.0	0.06	35.3	+0.00	-4.7	11.8
10	0.03	33.3	0.02	16.7	-0.01	-16.6	49.9
11	0.09	90.0	0.09	47.4	+0.00	-42.6	47.3
12	0.01	50.0	0.02	50.0	+0.01	+0.0	0.0
13	0.06	42.9	0.08	47.1	+0.02	+4.2	9.8
14	0.04	50.0	0.05	50.0	+0.01	+0.0	0.0
15	0.03	37.5	0.10	58.8	+0.07	+21.3	56.8
Median	0.03	50.0	0.05	50.0	0.01	0.0	12.6
IQR[a]	0.02-0.06	38.1-57.0	0.03-0.09	37.0-58.2	0.00-0.03	-9.3-5.3	5.6-49.9

[a]IQR is interquartile range

IV. DISCUSSION

During vascular occlusion, DC components of both the R and IR signals rapidly decreased as a result of less blood flow into the occluded area and consequently reduced total blood volume in this particular area. This process continues slowly until total vascular occlusion is achieved. Additionally, small

volumes of blood may potentially shift within the vascular compartments as vasomotor tone decreases during this induced ischemia. However, these volume shifts are very insignificant compared to the total blood volume and highly variable depending on individual responses.

During ischemic challenge, the DC IR signals that represent total blood volume are almost constant for most test subjects. Nevertheless, the blood compartment volumes will vary significantly amongst individuals due to several factors such as variation in capillary integrity, inflow vasomotor tone, and arterial pressure. This variability will consequently lead to variability in the effect of the VOT among individuals.

After the sphygmomanometer is deflated, both the R and IR signals rapidly increased as a result of large amount of blood flow into the occluded area, which then begins a recovery process. The recovery process represents the expected microvasculature response in which, the determinants of reoxygenation includes capillary integrity, local blood volume, local vasomotor tone, perfusion pressure, tissue oxygen saturation and total hemoglobin [11]. Higher amplitudes of AC IR observed during recovery compared to the baseline indicate higher total blood volume during recovery as an effect of reperfusion after the vascular occlusion process.

In general, the description mentioned earlier is largely similar for all test subjects, showing that the basic changes expected were visible via these signals. Assuming perfusion pressure is adequate in this test, the main criterion of microvasculature response is thus total hemoglobin and tissue oxygen saturation.

Oxygen extraction is expected to change slightly during the VOT due to the greater blood flow during recovery compared to baseline. However, variations of oxygen extraction in Table II are largely due to the effect of the vascular occlusion process differing between individuals. Generally, the VOT is used to evaluate the response of a system to a pre-determined stress in terms of local metabolic demand and reperfusion response in a healthy individual [14]-[16]. However, variation in metabolic rates may exist depending on individual experience during ischemic challenge [11].

Overall, the vascular occlusion tests show very similar patterns for R and IR signals and for both AC and DC components across different healthy individuals. Repeating the test in the same individual also results in a similar pattern indicating repeatability across individuals, particularly using the pulse oximeter used in this study. The VOT results show that the pulse oximeter concept used able to assess changes in extraction due to ischemia. However, these changes vary across individuals depending on individual experience, microvasculature response and reoxygenation factors.

V. Conclusions

Microcirculation function plays a very important role in the evolution of sepsis. This is because sepsis directly affects microcirculatory function by reducing microcirculatory oxygen transport and tissue oxygen utilization. Assessing oxygen saturation and extraction can potentially describe and evaluate microcirculation function.

The pulse oximeter sensor concept presented is capable of extracting valuable information to assess metabolic and microcirculatory extraction and condition. Independent signals from pulse oximeter can be used to assess oxygen saturation and consequently to analyze the oxygen transport and utilization. More important, the tests used in this study validated the concept of this pulse oximeter based sensor approach to assess underlying changes in microvasculature response and oxygen extraction. Thus, implementing this concept and method on ICU patients has the potential to aid sepsis diagnosis and provide more accurate tracking of patient state, sepsis status and response to treatment.

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