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A Novel System for Continuous Peripheral Arterial Pressure-Volume Loop Measurement

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***Abstract*—This study develops a system to obtain continuous blood pressure signal and impedance plethysmography (IPG) signal, simultaneously. Based on the principle of impedance measurement, the peripheral vessel volume change can be computed from the IPG signal. Equipped with simultaneous information of pressure and volume, a pressure-volume (PV) loop can be constructed. It is well known that the left ventricular pressure-volume loop contains a number of feature points indicating the performance of cardiac function. Therefore, in this study, the same principle is used to try to discuss the peripheral vessel pressure-volume loop. Ten volunteers were recruited for this study. Subjects went through the cold pressor test by immersing their left foot into ice water. Blood pressure signal and impedance changed were recorded using a custom-made system. The results illustrated that the pressure-volume loop, as it was expected, demonstrated a contraction phenomenon after stimulation in five out of ten subjects. The areas of those pressure-volume loops reduced as much as 70% in some subject. However, loop responses to stressors varied from subject to subject and the slope of the loop did not alter significantly. In conclusion, the proposed system is a potential way to measure and to investigate the compliance and characteristic of peripheral blood vessel.**

I. Introduction

Arterial compliance has been used to evaluate the prognosis of hypertension during or after the medical interventions [1]. The Windkessel model predicts an exponential decay of aortic pressure during diastole period when the flow is zero. This decay is characterized by the decay time. Thus, it is possible to estimate the arterial compliance from blood pressure waveform. In the past few years, there were numeral methods being proposed to estimate the total arterial compliance from blood pressure waveform including the decay time method, the area method and two areas method [2]. On the other hand, by measuring the different between pulse wave arrival times at two different locations, the pulse wave velocity (PWV) is now clinically accepted as a reliably method to estimate the total arterial compliance. All these methods can only provide single compliance estimation in one cardiac cycle. However, it is believed that the arterial compliance does not remain constant during the cardiac cycle. The arterial properties during systolic is drastically different from that during diastolic.

The compliance of an artery describes the ability to store a varying amount of blood and it is defined as the change in blood volume for a given change in blood pressure. Thus, to accurately assess dynamic change of arterial compliance one need both pressure and volume information simultaneously during each cardiac cycle.

To obtain the blood pressure waveform, noninvasively, a continuous blood pressure monitoring technique was proposed by the author [3]. The system uses low cuff pressure and is capable of observing blood pressure waveform noninvasively for long period of time. On the other hand, the blood volume change can be obtained, conveniently and cheaply, using impedance plethysmography. In 2003, Groothuis et al. [4] used 30 mmHg or higher cuff pressure to obstruct the venous return in the forearm and conformed that it is possible to obtain forearm blood flow. Although, ultrasound technique is the most common noninvasive way to estimate the blood volume, it is not only inconvenient but also very difficult to become lightweight and portable. Van de Water et al. used IPG principle to measure the blood flow in a hind limb of a dog and reported that the correlation of $r = 0.962$ was obtained when they were compared with electromagnetic flowmeter measurements [5].

Thus, this study combines IPG and continuous blood pressure measurements together to construct a lightweight system for peripheral blood vessel characteristic evaluation. The main advantage of this proposed system is its capability of obtaining blood pressure signal and blood volume change simultaneously. With these two concurrent signals, the peripheral arterial pressure-volume (PV) loop can be constructed. Similar to the left-ventricular pressure-volume loop, the arterial pressure-volume loop is also a closed loop as it was reported by Quick et al. [6]. The tracks of the loop, the slope, shape and area of the loop will change due to the variation of blood vessel.

II. Methods

A. Impedance Plethysmography (IPG)

By measuring the electric impedance at the body surface,

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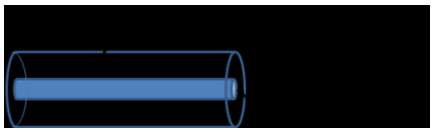

Fig. 1. Two-compartment model. The blood vessel compartment is surrounded by an isotropic tissue compartment to form a uniform cylinder

impedance plethysmography is a simple and easy method to estimate the changing tissue volume in the body. To estimate the blood volume in the limb, two-compartment model can be used. In the model, a blood vessel compartment is surrounded by an isotropic tissue compartment to form a uniform cylinder (Figure 1). By Ohm's law, the resistance of this cylinder is given as: $1/R = 1/Rt + 1/Rb$ where Rt and Rb are the resistance of the tissue compartment and blood compartment, respectively. When resistivity, ρ, is assumed to be constant, the resistance, R, is inversely related to the volume as:

$$V = \rho \times \frac{l^2}{R} \tag{1}$$

where l is the length of the cylinder.

When using high frequency alternating current and assuming the tissue volume does not change during the measurement period, the impedance change is due to the blood volume change and can be estimated by the following equation:

$$\Delta V = -\frac{\rho l^2}{Z^2} \times \Delta Z \tag{2}$$

In the realization of IPG circuit, there are two major blocks: a high-frequency constant current source and a ΔZ amplification circuit. Considering the resolution and patient safety, a 100 KHz, 4 mA (rms) constant current source is used in this system. In addition, to protect the subject, this system employs a delay device in front of the output terminal to ensure that the current is not delivered until one second after the system is turned on. An instrumentation amplifier amplifies the modulated impedance signal that is extracted by the two inner electrodes. It then passes through an 80 kHz highpass filter followed by a 120 kHz lowpass filter before it is demodulated. A 100Hz lowpass filter is used to reduce the high frequency components that are generated by the half-wave-rectifier demodulation circuit. After demodulation and amplification, the thoracic impedance signal Z can be separated into two distinct parts. The time varying component designated as ΔZ is obtained by highpass filtering the thoracic impedance signal. On the other hand, the near DC component is known as Z_0 [7].

B. Continuous Noninvasive Blood Pressure Measurement

Continuous noninvasive blood pressure waveform can be obtained using the two-cuff non-invasive blood pressure waveform monitor system. A detail description of the method and circuit can be found in the previous publication [3]. In short, the system uses dynamic feedback to maintain constant low cuff pressure at 40 mmHg. Thus, long term continuous blood pressure waveform monitoring is possible. Two instrumentation amplifiers amplify the pressure signals from pressure sensors inside the two pressure cuffs. The amplified pressure signal can be separated into two distinct parts. The microcontroller (MSP430F149, Taxes Ins., USA) uses the very low frequency component to perform servo control of the cuff pressures around 40mmHg by adjusting inputs voltage of the two air pumps. The microcontroller monitors the cuff pressure continuously. Whenever the cuff pressure deviated more than 1mmHg from the pre-determined pressure range, the controller adjusts the amount of airflow from the pump in order to maintain constant cuff pressure dynamically.

On the other hand, the time varying components are obtained by subtracting these very low frequency components from the pressure signal using two subtraction circuits. Two 30Hz lowpass filters reduce noise and high frequency components that are generated by pressure adjustment. In this study, only the pressure signal form the upper arm was used to construct the pressure-volume loop.

C. System Hardware

To construct the peripheral pressure-volume loop, authors propose to combine the continuous blood pressure monitoring device with IPG to obtain continuous pressure and volume signals simultaneously. The system also include: the analog to digital converter, the digital signal processing module, the peripheral devices, the system power supply, the data storage memory, and the RS232 interface circuit (Figure 2.)

For IPG measurement, the tetrapolar electrode system is used. A low intensive high frequency constant current is injected into the subject's forearm through the two outer electrode bands. The two inner band electrodes sense the small impedance change, during each cardiac cycle. The impedance signal is then amplified, processed and used in the estimation of blood volume change. Additionally, these four electrodes are combined with the two pressure cuffs for easy operation.

D. Experiment

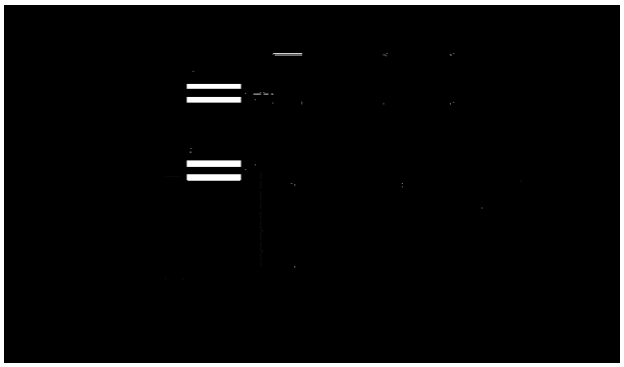

Fig. 2. Block diagram of the proposed system.

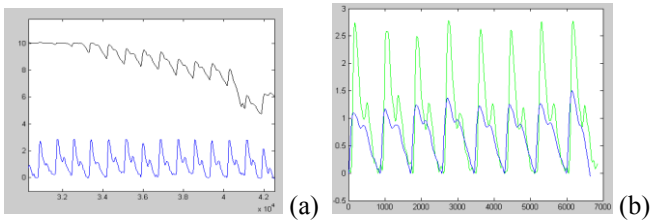

Fig. 3. The extracted continuous blood pressure signal and IPG signal. (a) before detraining and (b) after detraining.

Ten volunteers were recruited for this study. At the beginning of the experiment, two appropriately sized blood pressure cuffs were attached to the subjects' left upper arm and wrist. In the inner side of these pressure cuffs, two IPG band electrodes were attached for impedance measurement. Subjects were instructed to sit quietly in a comfortable chair. Following the baseline period, subjects performed the cold pressor task by placing their left foot in a container of 4°C water for a maximum of 2 min or until the task became too painful to tolerate. Continuous blood pressure signals from the two pressure cuffs and IPG signal were acquired throughout the task period using the proposed hardware. At the end of task, subjects were instructed to remove their foot from the water, and then signals were obtained for 1 min of the post-task recovery period.

E. Signal Processing

In general, the PV loop is generated by plotting the blood pressure against the blood volume for one complete cardiac cycle. As indicated by equation 2, the ΔZ signal is directly proportional to the changes of blood volume. Thus, in this study, the blood pressure was plotted against the impedance signal, ΔZ, instead. To generate the PV loop, first, specific section of blood pressure signal was extracted from the continuous blood pressure signal. The selected pressure signal was then detrained after filtering (Figure 3.) Signal from five or more complete cardiac cycles were manually extracted and were ensemble averaged to generate averaged pressure and averaged volume signals. The pressure signals were plotted against ΔZ signals to create multiple PV loops for that section.

III. RESULTS

Figure 4 illustrates the completed system. Four band electrodes are placed underneath the two pressure cuffs for impedance signal measurement. A typical PV loop of a subject during baseline is depicted in Figure 5. The loop,

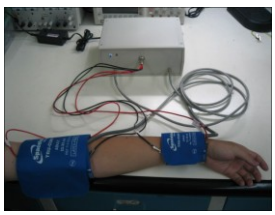

Fig. 4. The completed system hardware. Four band electrodes are attached to the subject's arm underneath the blood pressure cuffs..

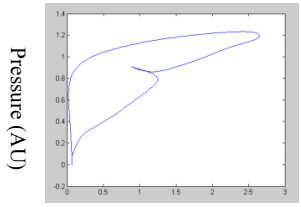

Fig. 5. The pressure-volume loop. The pressure is plotted again ΔZ after ensemble averaging over five cardiac cycles.

unlike the left ventricular pressure volume loop, starts at the lower left corner and is inscribed in a clockwise direction which is similar to the arterial system PV loops described by Quick et al [6]. In the very early systolic period, pressure increases but there is little change in volume. Afterward, volume continuous to increase as pressure hesitates at the end of early systolic. In late systolic, volume and pressure decrease in synchronous. Finally, in diastole, the pressure and volume fall monotonically after an initial increase.

The PV loops of a subject during different phases of the experiment, including baseline, during the cold pressor task and after the cold pressor task are illustrated in Figure 6. The results shown that the PV loops, as it was expected, demonstrated a contraction phenomenon after stimulation. This contraction phenomenon appears in five out of ten subjects. The areas of those pressure-volume loops reduced as much as 70% in some subject. However, the slope of the loop did not alter significantly. Additionally, it is known that changing resistance will translate the loop along the pressure axis and changing compliance will change the orientation of the loop [6]. In our results, due to the detrain operation, all pressure signal were normalized and there were no translation observed. Additionally, after ensemble averaging, some of the PV loop does not form a closed loop due to the varying cycle length.

IV. DISCUSSIONS

Heart function is a very important piece of information for cardiologists in evaluating the status of patients before, during and after treatments. Left-ventricular pressure-volume loop is a well established and comprehensive ways to assess the heart functions. However, due to its invasive nature, it is not possible to perform PV loop examination routinely. Additionally, In addition to the heart function, the peripheral properties affect the preload and afterload conditions in the heart working cycle.

The peripheral arterial pressure-volume loop may not provide comparable information as in the LV pressure-volume loop. However, it can reveal the dynamic characteristic of peripheral blood vessel. The PV loops obtained in this study suggest that the properties of blood vessel went through significant changes during the cold pressor test. However, due to the fact that the pressure and volume signals of this study are not fully calibrated, the loop translation phenomenon cannot be observed.

Cold pressor is known to increase the total peripheral resistance, systolic blood pressure, diastolic pressure and heart rate, significantly [8]. And the blood pressure reaction to cold pressor test was regarded as a useful indicator of future hypertension [9]. Thus, this study chooses cold pressure as the stressor to alter subject's physiological condition. However, blood pressure response to stressors greatly varied from subject to subject and from test to test within the single subject [9]. Our results also reflect huge inter subject and intra subject variations and only five out of ten subjects showed similar PV loop pattern during the test. Additionally, the PV loops at difference stage of cold pressor test illustrated drastically changed loop shape and even the loop direction in some subjects.

V. Conclusion

In conclusion, this study developed a system that can measure forearm blood pressure signal and blood volume signal simultaneously. Using these two signals, the pressure-volume loop can be created. The shape, area, and slope of this loop are expected to provide valuable information about peripheral arteries in the measurement region. Experiment was conducted to alter the condition of ten volunteers. As expected, the shape of the loop changed dramatically during cold pressor test. The results indicate that changes of peripheral arterial blood vessel property are dynamic and can be studied using this PV loop technique in the future.

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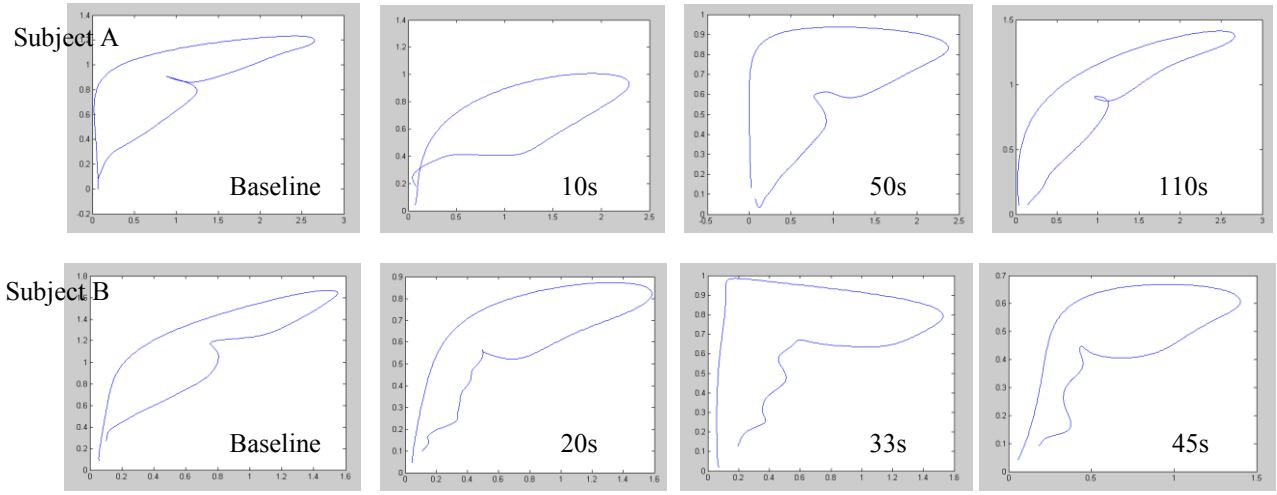

Fig. 6. The PV loops of two subjects during difference phases of the cold pressor task. After ensemble averaging, some of the PV loop does not form a closed loop due to the varying cycle length. The PV loop area of subject A reduced as much as 70% in 110 s in to the task. However, the slope of the loop did not alter significantly.