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Noninvasive Monitoring of Blood Pressure Using Optical Ballistocardiography and Photoplethysmograph Approaches*

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Abstract— **A new all optical method for long term and continuous blood pressure measurement and monitoring without using cuffs is proposed by using Ballistocardiography (BCG) and Photoplethysmograph (PPG). Based on BCG signal and PPG signal, a time delay between these two signals is obtained to calculate both systolic blood pressure and diastolic blood pressure via linear regression analysis. The fabricated noninvasive blood pressure monitoring device consists of a fiber sensor mat to measure BCG signal and a SpO2 sensor to measure PPG signal. A commercial digital oscillometric blood pressure meter is used to obtain reference values and for calibration. It has been found that by comparing with the reference device, our prototype has typical means and standard deviations of 9+/-5.6mmHg for systolic blood pressure, 1.8+/-1.3mmHg for diastolic blood pressure and 0.6+/-0.9bpm for pulse rate, respectively. If the fiber optic SpO2 probe is used, this new all fiber cuffless noninvasive blood pressure monitoring device will truly be a MRI safe blood pressure measurement and monitoring device.**

I. Introduction

High blood pressures are one of the main causes of death in the world. For such patients, the blood pressure measurement is very important both in hospitals and at home. Monitoring and measurement of blood pressure can provide valuable information for hypertension diagnosis and treatment. Continuous and noninvasive blood pressure measurement is desirable. There are various noninvasive blood pressure measurement devices. Most of them are cuff based measurement devices by using the auscultation method and oscillometric method. Cuff based blood pressure measurement devices provide no information on continuous blood pressure values. It is always discomfort during the measurement due to the inflation and deflation of the cuff, which may produce pain and contribute to the patient's stress level. This pain and stress may also affect patient's real blood pressures. Cuffless based blood pressure measurement devices can solve the above problems. They can provide not only the continuous blood pressure information but also make the long term monitoring and measurement of blood pressures practical.

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There are a few research activities on various types of cuffless blood pressure measurement devices including estimation of blood pressures using a Photoplethysmographic (PPG) approach [1-2], a ring type device based on PPG and electrocardiogram (ECG) approaches [3-4], a noninvasive blood pressure measurement device using accelerometer [5], a force sensitive electromechanical film (EMFi) sensor used as a blood pressure pulse transducer [6]. In this paper, we propose a new all optical method for estimation of blood pressures based on PPG and optical Ballistocardiogram (BCG) approaches. A time delay between measured PPG signal and BCG signal is used to calculate both systolic blood pressure (SBP) and diastolic blood pressure (DBP). This cuffless blood pressure measurement device consists of an optical sensor for acquiring BCG signal and a SpO2 sensor for PPG signal. An algorithm is developed to estimate blood pressures from measured PPG and BCG signals through linear regression analysis [4,7]. If the SpO2 probe in our PPG sensor is replaced with fiber optic SpO2 probe, the proposed sensor heads will be all fiber sensor heads, which are immunity to electromagnetic interferences and no risk in RF burns in MRI room. These all fiber sensor heads are truly MRI safe sensor heads and can be placed inside MRI room while the optoelectronic parts of the measurement device can be placed outside the MRI room.

This paper is organized as follows. Section I is introduction. Section II introduces our method and system configuration. Section III presents experimental results. The conclusion is drawn in Section IV.

II. Proposed Method and System Configuration

A. All Optical Method

Figure 1 shows the block diagram of proposed method and measurement device for blood pressure measurement without using cuffs.

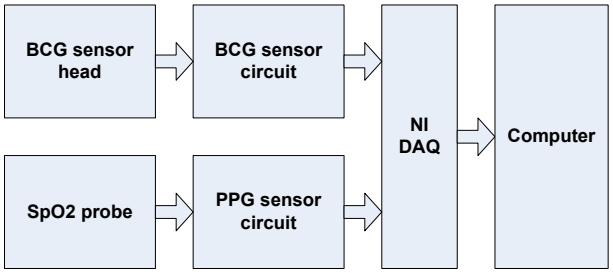

Fig.1 Block diagram of proposed method and device

There are two optical sensors used, optical BCG sensor and PPG sensor. The optical BCG sensor is used to obtain BCG

signal while SpO2 sensor for PPG signal. The information of peaks of BCG and PPG signals are used to calculate the time delay from the peak of BCG to the corresponding PPG peak. Based on this time delay, both systolic blood pressure and diastolic blood pressure are estimated. These signal processing and calculations are done in the computer. The NI DAQ card is used to acquire data from BCG sensor circuit and PPG sensor circuit. In history, BCG was a very old technique to evaluate cardiovascular health of patients [8] and has potential application as a cardiovascular diagnostic tool [9]. Unlike electrocardiogram (ECG), BCG is a contactless method where skin contact is not required. It has a capability to collect heart beating information without annoying patients and very suitable for long term monitoring and measurement [10]. Our group has been working on optical BCG sensor by using fiber optic sensor technology [11] for heart rate and BCG waveform measurement. The fiber optic BCG sensor is built based on micobending fiber sensor technology. Fig.2 shows a typical fiber optic BCG sensor head which contains a section of graded multimode fiber clamped between two microbenders.

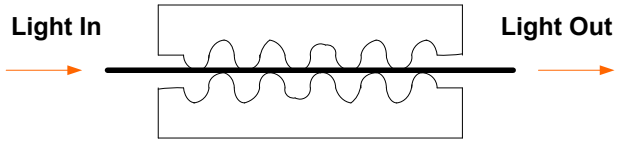

Fig.2 Microbending fiber optic BCG sensor head

The light from light source is input into one end of the BCG sensor head while the output light from other end of the sensor head is collected by a photo detector (PD) and converted into electrical signals which are acquired by NI DAQ card. As the displacement between two microbenders changes, the light intensity of the sensing multimode fiber changes with subject's body vibration caused by heart beating. So, the light intensity in the microbending fiber is modulated by the heart beating induced body vibrations. This modulated signal is extracted using algorithm as the BCG signal which is shown in Figure 3. The distinctive peaks correspond to the ejection of the blood into the vessels with each heartbeat.

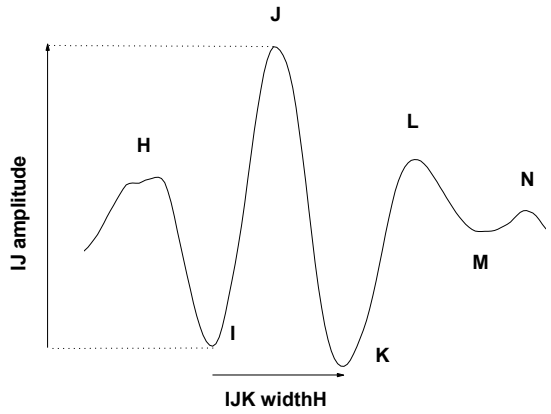

Fig.3 BCG signal acquired from a fiber optic BCG sensor

It is clear that the BCG signal measured from the fiber optic BCG sensor closely resembles the BCG waveform given in other reference [12] for example. The main components of the BCG signal, e.g., H, I, J, K, L, and N peaks, can be clearly indentified.

PPG sensors are widely used in the researches on cuffless blood pressure measurement devices [1-7]. In this paper, we use a commercially available transmission type SpO2 probe as PPG sensor head. This SpO2 probe has two light emitting diodes (LEDs) at 650nm and 940nm and one photo detector (PD). Only one LED light source at either 650nm or 940nm is used in this paper. The fingertip tissue is irradiated by the LED, and the resultant light intensity is measured by the PD placed on the other side of the fingertip tissue. We designed and built the PPG circuits for the SpO2 probe. To acquire the measured data from both BCG sensor and PPG sensor, an NI DAQ card is used. Signals are averaged, smoothened, filtered and calculated by the computer.

B. Proposed Algorithm for Blood Pressure Extraction

Figure 4 shows the main algorithm flowchart for blood pressure extraction. According to the features of BCG signals, a band pass filter is used in the range of 2-30Hz. A 5 point moving average is also applied to smoothen BCG signals. Based on LabVIEW platform, we developed a BCG peak detection algorithm to extract the J peak location of the BCG signal. In the same time, data from measured PPG sensor is smoothened and filtered in the range of 0.2-10Hz according to the features of PPG signal. The location of peak of the PPG signal is detected by a PPG peak detection algorithm. Based on information of peak locations of the BCG and PPG signals, the time delay (TD) is calculated between J peak of the BCG signal and the corresponding peak of PPG signal. Then the SBP and DBP are estimated based on the TD parameter via the linear regression analysis in the form of

$$SYS = aTD + b \quad (1)$$

$$DIA = cTD + d \quad (2)$$

where SYS is the systolic blood pressure, DIA is the diastolic blood pressure, a, b, c, d are calibration constants. Pulse rate could be estimated from the intervals of PPG peaks.

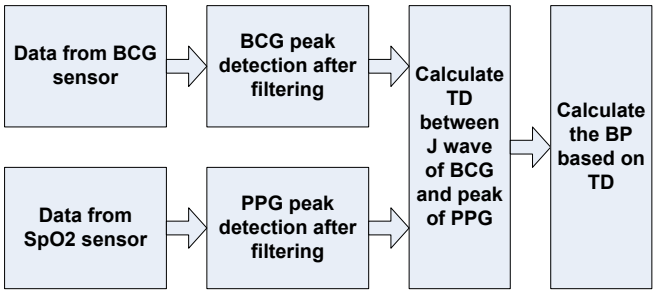

Fig.4 Main algorithm flow of the proposed method

III. Results and Discussions

Figure 5 is the photo of whole measurement system setup which consists of a fiber optic BCG sensor which is embedded inside a cushion, a PPG sensor, NI DAQ card and computer.

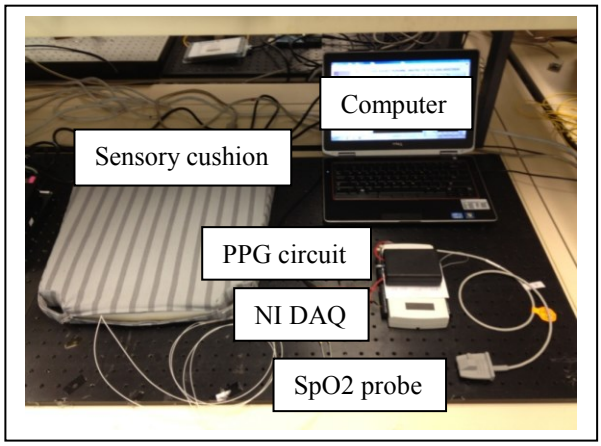

Fig.5 Photo of system setup

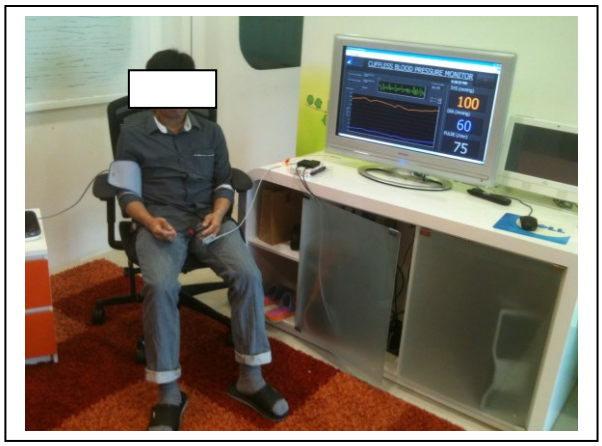

Fig.6 Photo of demo. The right arm is used by a commercial blood pressure meter for reference. The fingertip in the left hand is attached to SpO2 probe. The computer screen shows GUI of the system.

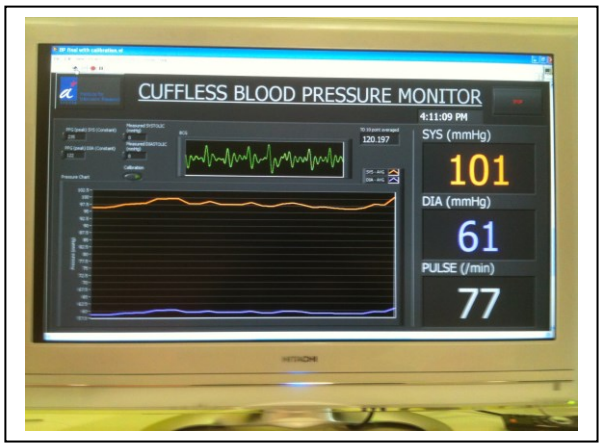

Fig.7 GUI of the system.

The software running on the computer is LabVIEW based software which is capable of monitoring and measurement of SBP, DBP and pulse rate in a continuous manner. During the measurement, the cushion can be placed on a chair as shown in Figure 6. Figure 7 shows the GUI of the system. SBP, DBP and pulse rate are displayed in the screen of the computer. It also displays the BCG waveform and histogram of SBP and DBP. The back (used for measurements) of the subject is in contact with the cushion. The cardiac beating induces body vibrations on the cushion. This in turn modulates the light intensity of the sensing multimode fiber that indicates cardiac beating. By extracting the modulated light signals, the BCG waveform is obtained as shown in Figure 7. The subject's fingertip is attached with the SpO2 probe. Only the red LED light source is used. To demonstrate our concept, five healthy subjects are participated in the experiments. Their blood pressures were regulated by exercises. First, we need to do calibration to find device's parameters, a, b, c, and d based on linear regression analysis for each individual as shown in Eq.(1-2).

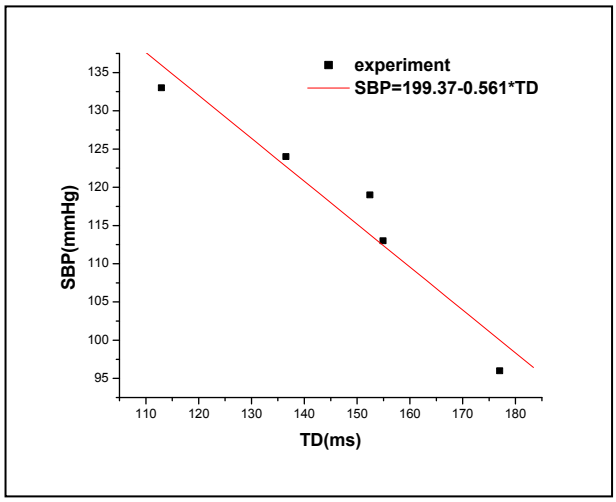

Fig.8 (a) Measured SBP as a function of TD

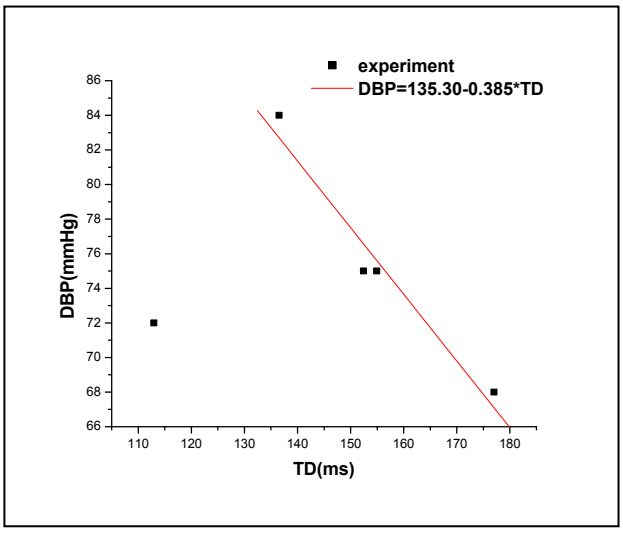

Fig.8 (b) Measured DBP as a function of TD.

Figure 8 shows measured SBP (mmHg) from commercial device as a function of calculated TD (ms) from our measurement system for a volunteer. It has been shown that the estimated TD is correlated with both SBP and DBP. In Figure 8 (b), one bad point of TD is neglected for DBP calculation. Based on the linear regression analysis, the calibration constants, a, b, c and d are obtained for this individual. Because the relationship of BCG, PPG and blood pressures are complicated by optical, biomechanical, and physiologic factors, the final calibration constants input to measurement device should be in the form of

$$SYS = (a + \Delta a)TD + (b + \Delta b) \quad (3)$$

$$DIA = (c + \Delta c)TD + (d + \Delta d) \quad (4)$$

where Δa, Δb, Δc, and Δd are correction factors for each calibration constant, a, b, c, and d. It is very easy to find these correction factors by measuring two points from low to high blood pressures during live experiments. It should be noted that the calibration constants and their correction factors are individual dependent. The proposed measurement device in this paper needs calibration for each individual before use. Table I shows measurement results from Omron device and our device in the same time for a volunteer. It can be seen from Table I that the mean and standard deviation are 9+/-5.6mmHg for SBP, 1.8+/-1.3mmHg for DBP and 0.6+/-0.9bpm for pulse rate, respectively. Because the calibration constants are considered for individual, the correlations between TD and blood pressures are very good. The measurement accuracy can be guaranteed because the variations in subject's characteristic parameters such as arm length, blood viscosity, age, weigh, etc are not existed. These characteristic parameters may affect the accuracy of blood pressure measurement according to some other studies in [4,7]. The main error of our method is from the error in the estimation of BCG peak locations. These BCG peaks are easily distorted by motion noises. An algorithm to remove these motion noises is being developed to further improve the accuracy of our method. Further investigation on hypertensive and hypotensive patients and clinical trials are needed to validate our method and device for clinical use and home use. There have been some other researches to calculate blood pressures by using similar TD between ECG peak and PPG peak [3,4,7]. In their methods, ECG probes have to be attached to subject's skin, which may not be suitable for long term continuous monitoring. In our method, however, our sensors have the potential to be used in a "contactless" manner for both BCG and PPG signal acquisitions and there is no need to directly contact to body skin.

IV. Conclusion

This paper describes a new all optical method and measurement device for measuring and monitoring blood pressures which is suitable for continuous and long term monitoring. The method is based on optical BCG and PPG approaches. We built the prototype system and developed algorithm and software based on LabVIEW platform. The preliminary results have demonstrated that the use of the all optical method and the measurement device is capable of measuring and monitoring systolic blood pressure and diastolic blood pressure in continuous and long term manner. Preliminary experimental results have shown that our device has a reasonable accuracy. Further investigation of the calibration issue and clinical trials are needed to validate our method and device for potential clinical use and home use.

TABLE I. Comparision of measurement results

Results from Omron Device			**Results from Our Device**		
SBP mmHg	***DBP mmHg***	***Pulse /min***	***SBP mmHg***	***DBP mmHg***	***Pulse /min***
146	77	113	133	73	113
135	70	108	121	72	108
128	70	107	118	71	107
129	71	103	121	70	104
108	63	79	108	62	81

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