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A New Method to estimate Arterial Blood Pressure using Photoplethysmographic Signal

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Abstract— **Preceding studies have shown photoplethysmographic (PPG) signal resembles blood pressure (BP) wave and varies. Some investigators also have studied this relationship to explain complex hemodynamic characterization. The purpose of this study is to make a trial of finding arterial BP (ABP) using PPG signal. This new attempt is based on the theory that BP consists of the change of blood volume (BV) and the resistance of vessels. This study proposes a method to estimate BP from PPG signal and points to be considered when we use this method. Therefore we can classify cardiac output (CO) and the blood vessel resistance (VR) by analyzing PPG signal. Signals were obtained from the tails of three healthy dogs and the fingers of six patients who have changes of BP. In the animal test, we first found the correlations between PPG signal and BP, and then we could reconfirm the relationship in the clinical test. PPG signal could be influenced by the pressure (P) that occurred between the index finger and the sensor and the temperature (T) of the interest region, so we examined these influences with six healthy subjects. From the experimental results, we suggest the relationship of the estimation of BP from PPG signal. When PPG signal is normalized by P and T, this PPG signal offers more accurate estimation of BP. This study could be able to provide a new BP measurement system that has not only convenience but also accuracy.**

I. Introduction

According to hemodynamics, a rising of BP can explain with a rising of CO and/or a rising of peripheral VR. However, BP is generated by processes of complex internal factors in human and any factor is impossible to represent the whole incidence mechanism of BP [1]. So a new method that can analyze CO and VR without the analysis of whole factors is developed and selected to estimate ABP.

In the study of Takazawa et al., they showed not only PPG signal is similar to BP wave but also mechanism of vasoconstrictions and vasodilations [2], [3]. From these backgrounds, a basis that presents BP is led by analyzing CO and VR using PPG signal.

PPG signal is measured by using a light source. When a light source radiates on the skin, it is absorbed into arterial blood, venous blood, tissue and etc. Therefore, the pulsed part is affected by the cardiac contraction and relaxation and the non-pulsed part presents the absorption for non-pulsed arterial blood, non-pulsed venous blood, tissue and etc. [4]. Specially, the value of non-pulsed arterial blood presents the residual blood during the cardiac relaxation [5]. The change of BV in finger is generated by vasoconstrictions and vasodilations in affected tissue by sympathetic nervous system [6]. For instance, vasoconstrictions are results of tissue hypovolemia and the low flexibility (high resistance) of arteries. Therefore, the analysis of BV and VR becomes an item that can detect the relationship of BP [7]–[11].

PPG signal is a function of time and is varied by physiological states of subjects. To give the propriety for detecting PPG signal, it has to be normalized with information of external P and finger T [12], [13].

This study has a purpose for providing patients' convenience and easy accesses in measuring BP as well as developing a new independent convenient healthcare system with physiological information. To minimize occurred errors, when BP is estimated by only single factor, BP is estimated by defining mechanisms of the generation of BP. The evaluation of experimentations is performed with the physiological investigation and verification in animal tests and clinical tests. The reproducibility is verified with external factors' tests.

II. Hardware and System

A. Sensors

In this study, sensor devices were classified into two classes. One was for the relationship between PPG signal and BP, the other was for the relation between PPG and physiological conditions. Fig. 1 shows cross sections of these two sensors. Sensor 1 was designed for acquiring data at dogs' tails and index fingers and Sensor 2 was designed for reflecting T and P in the measured region. Optical sensors were made of LEDs which could radiate 640 nm and 940 nm wavelengths and a photo detector (PD) which had the center frequency response on 900 nm.

B. Data Acquisition and Analyzing

To acquire data, we used a Power Lab (AD Instrument Co.)

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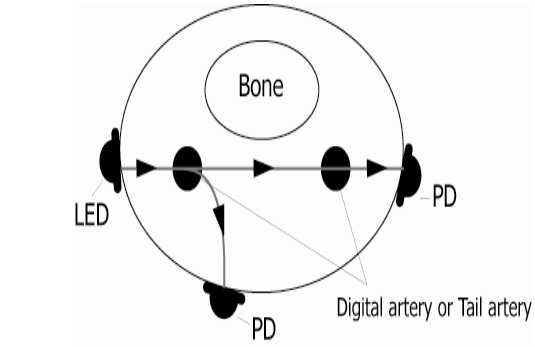
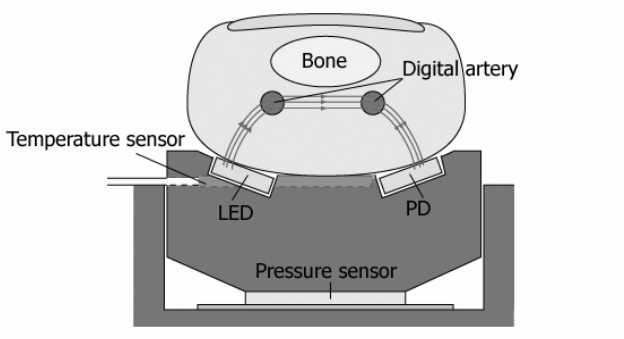


(a)



(b)

Fig. 1. Cross sections of sensors. (a) Illustration showing the cross section of the tail or the finger. (b) Illustration showing the cross section of the finger.

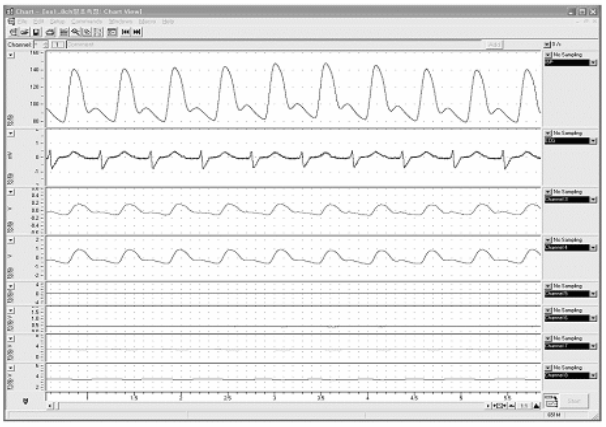


Fig. 2. Power LAB data acquisition window.

and acquired invasive BP, ECG, reflected red BV data, reflected red VR, reflected infra-red BV, reflected infra-red VR, T and P data. Fig 2 shows an acquisition program that is the Chart4 for the window. The sampling rate was 200 Hz. The data acquisition was for comparing and analyzing data. The data processing was operated off-line. We used software which is LabVIEW 7.1 for Windows XP.

III. Test and Result

These tests were progressed at the thoracic surgery, the critical care medicine and the animal experiment laboratory in Wonju Christian Hospital.

First of all, we checked the relationship between BP and PPG signal with animal tests and then we reconfirmed the discovered relationship with clinical tests. Next the relationship of PPG signal about T and P were compared with the second clinical tests for influences of external factors. Finally a new method to estimate ABP using PPG signal was discussed.

We used multi-regression methods for analysis of correlation between PPG signal and BP with a program which is SPSS 12.0 for Windows XP. The correlations between PPG signal and T and between PPG signal and P were also analyzed with the same method. In the analysis we set a dependent variable invasive BP (IBP) signal and independent variables BV signal and VR signal. Dependent variables were BV signal and VR signal and independent variables were T and P for the analysis of the correlations about physiological factors.

A. Animal tests

We used two dogs 20kg and 22kg for animal tests, did anesthesia with IM injections which are 25 mg/kg Ketamine sulfate and maintained anesthesia with Enflurance. During the anesthesia we did endotracheal intubations and used ventilators.

Fig. 3 shows the acquisition sites of sensors that are ECG, PPG and Invasive Aortic Pressure sensor. We used needle electrodes and set them to measure ECG in both sides of fore legs and the right hind leg. After shaving the dog, we set the PPG sensor on the dog's tail. In case of BP sensor we inserted a microtipped catheter in Femoral artery, set a pressure transducer (SPC-350, Millar, USA) and measured the invasive BP. After all of these processes, animals had stayed in quiet for 15 minutes.

To see the change of PPG according to the change of BP, we set the rise of BP with a subanesthetic concentration or an injection of Dopamine or Epinephine and set the fall of BP with a superanesthetic concentration or an injection of Heparin.

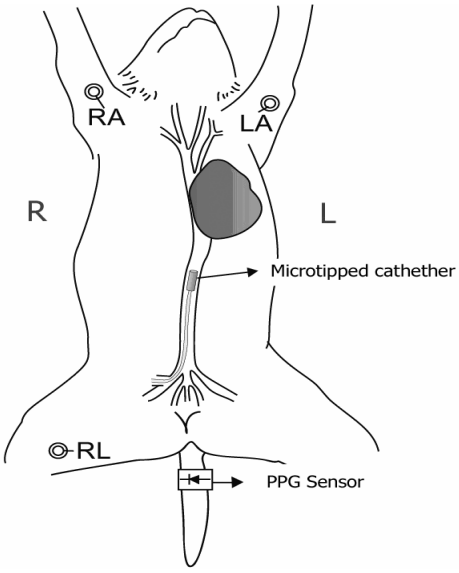


Fig. 3. Acquisition site of sensors for animal tests

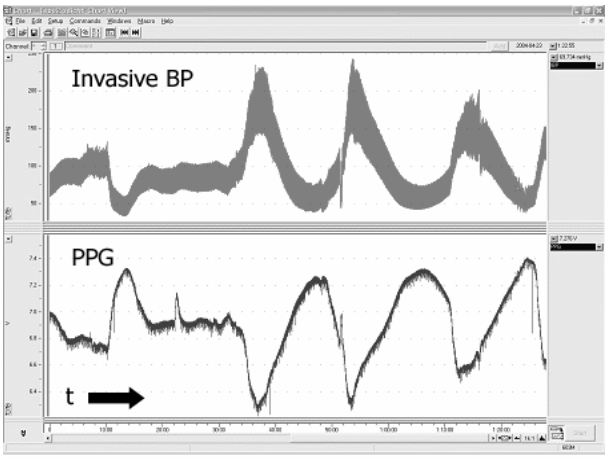


Fig. 4. IBP signal and PPG signal for one hour and half

Fig. 4 indicates invasive BP signals and PPG signals by time. The graph shows a linear relationship. This result was gotten by the maximum PPG signal which is the reflected infra-red PPG signal and IBP.

In multi-regression analysis, results were individually analyzed because each animal has own physiological differences. Correlation coefficients between BP and two signals (BV and VR) were 0.920 ± 0.060 for systolic BP (SBP) and 0.931 ± 0.460 for diastolic BP (DBP) ($p < 0.01$). Standard errors of the estimate were 4.149 ± 0.775 for SBP and 3.179 ± 0.655 for DBP. Results refer to the propriety for using dependent and independent variables in these tests.

B. Clinical tests

The clinical tests were processed with patients who were 9 to 83 years and were using an IBP instrument in Wonju Christian Hospital. In the tests we used non-invasive sensors however we measured data with specialists' supervision and help. The patients were selected by a significant situation that we could observe changes of IBP with patients' stability.

Fig. 5 shows the acquisition site of sensors that are ECG, PPG, and IBP. We used the BP transducer and set additionally on the BP catheter in a patient monitor. ECG electrodes used in a normal way and the PPG sensor was set on the index fingertip. During the tests we never artificially changed patients' BP.

Each of tests was advanced in a condition that we didn't give harm to patients for their priority medical treatment. As animal tests, clinical results were gotten by the maximum PPG signal which is the reflected infra-red PPG signal and the IBP.

In multi-regression analysis, correlation coefficients were 0.722 ± 0.090 for SBP and 0.831 ± 0.113 for DBP ($p < 0.01$). Standard errors of the estimate were 1.938 ± 2.280 for SBP and 1.647 ± 2.390 for DBP. Results refer to the propriety for using dependent and independent variables in these tests.

C. External factors' tests

External factors' tests were preceded for investigating the reproducibility because PPG signal would be changed by T and P effects. Subjects took a rest for 15 minutes, and then PPG signal was measured for recovery time after the rapid T drop. Next, when T is normal, the slow T rise process was performed. These processes were performed 3 times. While T was changed, PPG signals were measured for 15 seconds in 16 stages that had different step ladder appearance pressures.

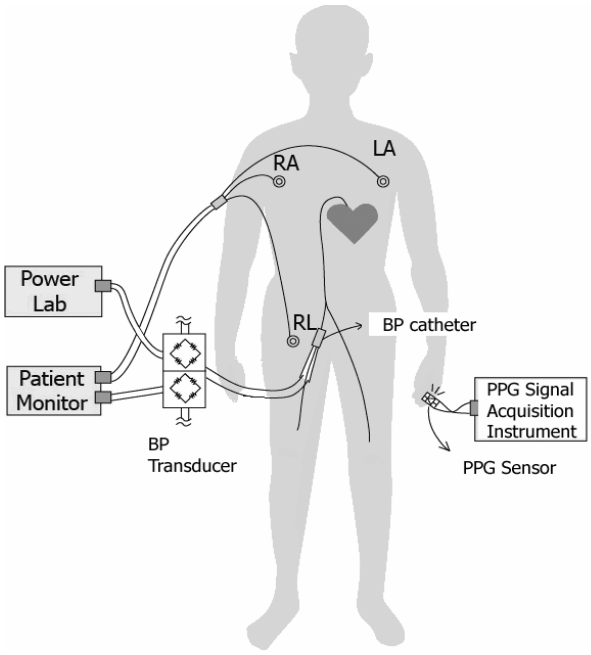


Fig. 5. Acquisition sites of sensors for clinical tests.

In multi-regression analysis, results were individually analyzed because each patient has own physiological difference. Correlation coefficients between BV and two signals (T and P) were 0.835 ± 0.155 for systolic BV and 0.844 ± 0.145 for diastolic BV ($p < 0.01$). The correlation coefficient between VR signal and two signals (T and P) was 0.767 ± 0.120 for VR signal ($p < 0.01$). The results refer to the propriety for using dependent and independent variables in these tests.

D. BP estimation

According to animal, clinical and external factors' tests, we are able to lead followed equations.

$$BP_{SYS} = a_{SYS} BV_{SYS} + b_{SYS} VR + c_{SYS} \quad (1)$$

$$BP_{DIA} = a_{DIA} BV_{DIA} + b_{DIA} VR + c_{DIA} \quad (2)$$

$$BV_{SYS} = \alpha_{SYS} T_{SYS} + \beta_{SYS} P_{SYS} + \gamma_{SYS} \quad (3)$$

$$BV_{DIA} = \alpha_{DIA} T_{DIA} + \beta_{DIA} P_{DIA} + \gamma_{DIA} \quad (4)$$

$$VR = A_{SYS\ or\ DIA} T_{SYS\ or\ DIA} + B_{SYS\ or\ DIA} P_{SYS\ or\ DIA} + C_{SYS\ or\ DIA} \quad (5)$$

where BP_{SYS} indicates SBP, BP_{DIA} indicates DBP, BV_{SYS} indicates systolic BV, BV_{DIA} indicates diastolic BV, T_{SYS} indicates systolic T, T_{DIA} indicates diastolic T, P_{SYS} indicates systolic P and P_{DIA} indicates diastolic P.

The reason why we establish multi-regression equations, PPG signals are individual to each model when we estimate BP. This condition comes from physical differences of patients. Therefore we concentrate on signs of correlation coefficients as Table Ⅰ.

TABLE I
CORRELATION COEFFICIENT AND SIGN

CORRELATION COEFFICIENT	SIGN
a	Negative
b	Negative
c	Positive
α	Negative
β	Positive
γ	Positive
A	Positive
B	Positive
C	Negative

IV. CONCLUSION

This study proposes a new method that can estimate BP from PPG signal with optical sensors. BV is proportioned to T and inverse-proportioned to P. VR is proportioned to T and P. Therefore, when PPG signal which is normalized by measured T and P is acquired, SBP and DBP are proportioned to BV and inverse-proportioned to VR without constant terms. Therefore PPG signal from the artery is proposed a basis to detect BP. We are also able to get transitions BV and VR when PPG signal is acquired during long term. These processes can predict the change of BP. From the experimental results, we discovered the possibility that we can develop the system which complements the weak points of existent cuff BP measurement by offering both accuracy and convenience.

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