Journal of the Optical Society of Korea, Vol. 10, No. 2, June 2006, pp. 91-95

Nonconstrained Blood Pressure Measurement by Photoplethysmography

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(Received June 13, 2006 : revised June 15, 2006)

Blood pressure was predicted from photoplethysmography (PPG). To obtain PPG, backscattered light from a fingertip was measured and its waveform was analyzed. Systolic upstroke time and diastolic time in the pulse waveform were used as parameters to predict blood pressure. The experiment was carried out with five subjects on five different days. The systolic upstroke time had a correlation coefficient of -0.605 with respect to systolic blood pressure and the diastolic time had a correlation coefficients of -0.764 for diastolic pressure. This PPG method does not require an air-cuff installation on the arm and can predict blood pressure continuously. This simple LED/photo detector setup can be a good candidate for nonconstrained monitoring of blood pressure variations.

OCIS codes : 170.1610, 170.3890, 170.4580, 170.5380

I. INTRODUCTION

Photoplethysmography (PPG) is an optical monitoring method of the volume variations due to blood circulation within the body. Around 1870, Mosso invented a PPG instrument, known in Italian as a "pletismografo", and first reported in Scientific American in July 1872 [1]. A measurement setup is simple. Light often from a LED preferably in the longer visible or near infrared wavelength which penetrates deeper into biological medium is irradiated into the body of interest such as finger or earlobe. Transmitted or backscattered is measured by a photo detector (Fig. 1). Since that invention, various medical or scientific applications of PPG have been studied. Heart beat was measured by PPG [2]. Oxygen saturation in an artery has been widely used as one of the important physiological parameters in the intensive care [3]. Other applications include jaundice diagnosis and hematocrit estimation [4,5] where PPGs at various wavelengths were analyzed. Clinical applications based on PPG have been also investigated for the estimation of arterial stiffness by analyzing PPG waveform and light propagation in the forearm [6,7].

Blood pressure (BP) is one of the four vital signs in health care along with body temperature and pulsatile and respiratory rates. For blood pressure monitoring, noninvasive measurement methods that can reduce medical expenses and offer comfort to patients are necessary. There are several noninvasive methods to measure BP such as cuff sphygmomanometry and arterial tonometry [8-10]. Cuff sphygmomanometry is not continuous beat-beat measurement of BP since it requires periodic cuff inflation and deflation. A subject in sleep is disturbed by pressure on the arm or noise

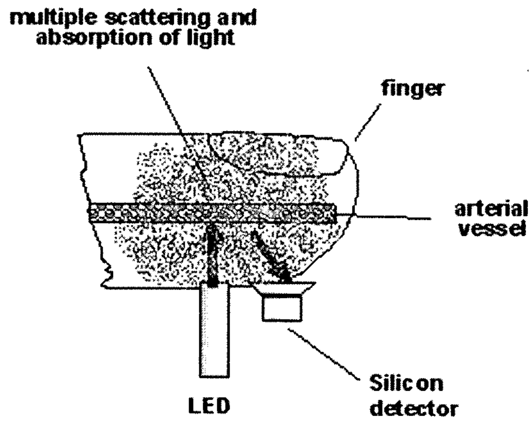

FIG. 1. PPG measurement on a finger tip. LED light shines into finger and multiple scattering and multiple weakly absorption occurs.

generated when the cuff is being handled. Arterial tonometry has the capability of monitoring blood pressure continuously. However, due to wrist motion and high sensitivity to sensor position, the arterial tonometry is not appropriate for use in daily activities [9]. It is reported that noninvasive, cuffless and continuous measurement of BP can be done using PPG [10-15]. This method is desirable for designing a 24-hour non-constrained blood pressure monitoring system. Because of simplicity and usefulness, it has been applied either for the purpose of physiological research or for clinical applications. However, most blood pressure predictions based on PPG require an additional measurement such as an electrocardiogram to compute pulse transit time. Pulse transit time is the time interval between the on-set time of systole and the arrival time of blood volume at a certain location. The R-wave of electrocardiogram is the systolic on-set time and the peak of PPG at the local position represents the arrival time of blood volume.

However, additional measurement such as electrocardiogram requires the attachment of the electrodes on the surface of human body. Another difficulty associated with pulse transit time is the difference between the onset time and the actual cardiac pumping. To accomplish a completely nonconstrained measurement, we investigated a method of predicting blood pressure from only one channel PPG waveform. This can be done with an extremely compact device. To check the performance of the proposed method, experiments were performed in terms of individual differences and day-to-day variations.

II. METHOD AND EXPERIMENT

A propagating pressure wave from the left ventricle follows the cardiovascular circulatory system and reaches the peripheral arteries. Propagation depends on cardiac output and vessel wall rigidity. A reflected wave was generated according to the position of vessel branches and also vessel wall rigidity. The pressure wave is the summation of propagation and reflection waves. Mathematical expression for the velocity of the front of the pulse wave traveling along an artery is given as a function of the elasticity coefficient, the thickness of the arterial wall and end-diastolic diameter of the lumen of the vessel.

$$C^2 = E\ a\ /\ p\ D \qquad (1)$$

where C: pulse wave velocity, E: elastic modulus, a: wall thickness, p: blood density, D: vessel diameter (a<<D). The stronger cardiac output is, the faster the pulse wave velocity is. There are several factors which determine C. For example, elasticity of the vessel wall is related to aging, and blood pressure to blood density. Pulse transit time has been used to predict blood pressure as a parameter that is inversely proportional to blood pressure. When calibrated to a particular person, pulse transit time can be used as a parameter to predict blood pressure.

There are several ways of measuring plethysmography. Most common sensors are pressure sensors such as strain gauges and photo sensors. Necessities of tight contact onto the body surface and sensor bulkiness are disadvantages of using the pressure sensor. Plethysmography using a photo sensor, on the other hand, is compact and inexpensive. For PPG signal, backscattered light from the right hand index finger was measured. Typical PPG signals are shown in Fig. 2. Each period in Fig. 2 corresponds to one heart beat. Alternating amplitude is only several percent of the signal detected by a photo detector. Direct component or baseline signal of PPG should be filtered out and a proper bandpass filtering is required to see the waveforms in Fig. 2. The systolic period of the cardiac cycle corresponds to the systolic upstroke time and the diastolic period to the diastolic time.

The experiment was performed with five healthy male volunteers (age: 25-30 years). PPG signals were recorded simultaneously for 60 seconds at a sampling rate of 227 Hz using a self-developed portable device. We used a 940 nm LED (Model EL-23G, Kodenshi Corp.) and a phototransistor as photo detector (Model ST-23G, Kodenshi Corp.). As for reference values, blood pressure was simultaneously measured by a digital oscillometric blood pressure meter (BP-1M, CASIO^{TM}) with the air cuff installed on the left upper arm. 18 seconds of PPG data in the middle of a 60-second measurement were analyzed in order to compare with the reference value. PPG and reference blood pressure values were measured at the same time. Measurements were done under two different conditions; one under the rest condition and the other just after exercise to induce the elevation of blood pressure. The rest condition was set by taking a rest for at least five minutes on the chair. Increase of blood pressure was induced by having 100 step-climbing

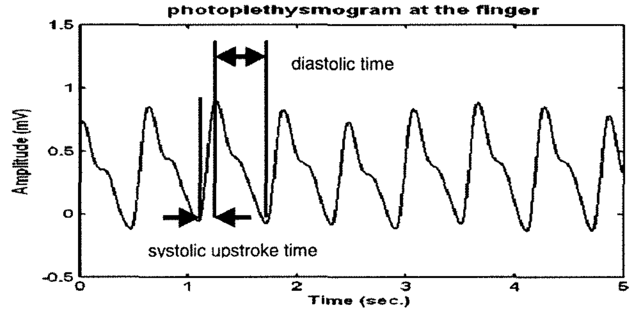

FIG. 2. PPG signal. Systolic upstroke time corresponds to the systolic period in cardiac cycles and the diastolic time to the diastolic period.

exercises (each step was 21 cm high). Just after the step-climbing exercise, measurements were recorded at the same seated position. This measurement protocol was repeated three times during the same day. At least 20 minutes time interval was maintained to secure a stable condition and to avoid the exhaustion of the subject. This whole protocol was repeated on five different dates for the same subject to investigate day-to-day variations.

Systolic upstroke time (Sys_t1) and diastolic time (Dia_t2) were computed from measured PPG waveform. Analysis was automatically performed with the aid of Labview^{TM} (National Instrument, USA). Linear regression analysis in the form of y=ax + b was set up for systolic blood pressure (SBP) and diastolic blood pressure (DBP) respectively. Regression analysis was made for the individual data set of each subject (Individual Calibration). The absolute mean errors were computed from measured and estimated blood pressure values. In the Individual Calibration, a regression line was obtained using the data of four days as leaving one day dataset. The remaining one day data set was predicted and errors were computed, which is the so called 'leave-one-out' method [16,17]. Estimation of blood pressure for each day was done in the same manner.

III. RESULTS AND DISCUSSION

Fig. 3 shows the mean correlation coefficients when SBP and DBP were predicted by the systolic upstroke time. All five persons and five days data were used in this computation. In the same manner, the diastolic time was used to compute SBP and DBP and the results were displayed in Fig. 4. The systolic upstroke time was correlated with SBP (-0.605) and DBP (-0.663) as summarized in Table 1. The diastolic time gave correlation coefficients of -0.605 and -0.764 with respect to SBP and DBP. SBP correlations with the systolic upstroke time and the diastolic time were the same up

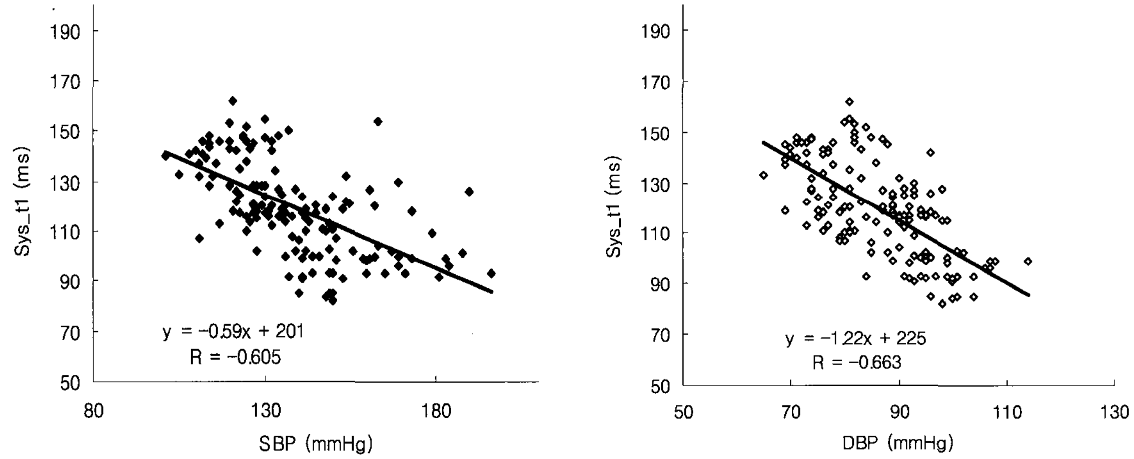

FIG. 3. Linear regression lines between the systolic upstroke time (sys_t1) and systolic blood pressure (SBP) and diastolic blood pressure (DSP).

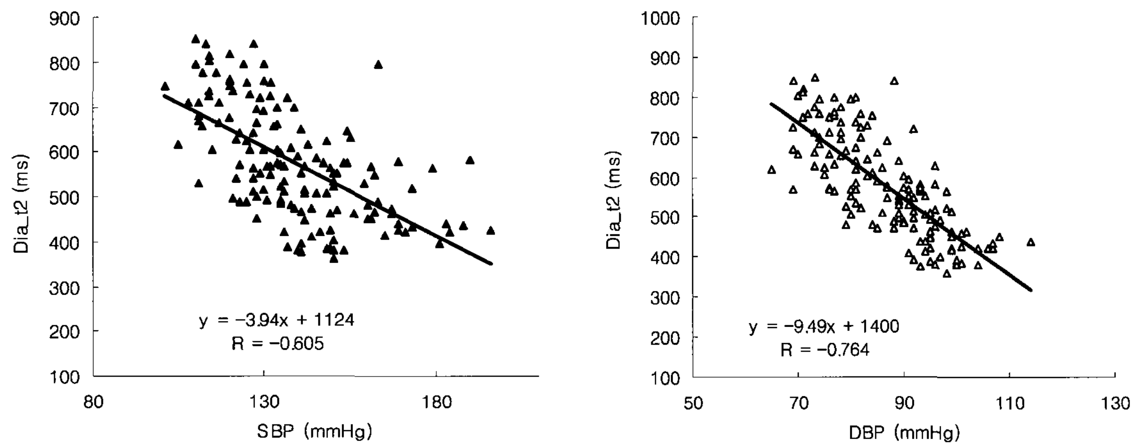

FIG. 4. Linear regression lines between the diastolic time (dia_t2) and systolic blood pressure (SBP) and diastolic blood pressure (DSP).

TABLE 1. The mean correlation coefficients were computed when systolic and diastolic blood pressures were predicted by the systolic upstroke time (sys_t1) and the diastolic time (dia_t2). All the data (five persons, five-day data) were utilized.

correlation parameter	systolic blood pressure	diastolic blood pressure
Sys_t1	-0.605	-0.663
Dia_t2	-0.605	-0.764

to three digits. They were different at the fourth digit where they were -0.6049 and -0.6046 respectively with a slightly better result by Sys_t1. For prediction of diastolic pressure, the diastolic time was a better parameter.

When we examined day-to-day variations in terms of the absolute mean-percent errors of prediction, a similar trend was observed. The diastolic time was a better choice for DBP prediction. For SBP, not significantly but slightly better results could be pointed out with the systolic upstroke time. For example, the mean percent errors by Sys_t2 were between 7 - 12% with standard deviations of 2.51-8.70% whereas Dia_t2 had mean percent errors with a range between 8 - 13% and the standard deviations of 2.71 - 10.27%. However, the difference was insignficant for SBP prediction by either Sys_t1 or Dia_t2. Theoretically, Sys_t2 is engaged with the systolic period. Therefore, our choice for the parameters of PPG waveform was Sys_t1 for SBP and Dia_t2 for DBP.

As expected, there were day-to-day variations in terms of the mean percent errors even for the same subject. Fig. 5 and Fig. 6 show day-to-day variations for five individuals. It was unexpected that SBP had higher errors than DBP, however. One subject had unusually high SBP percents errors compared with those others whose values were confined with a window of 5 - 10%. DBP values were mostly within 10% error. It has been known that prediction of DBP is more difficult than that of SBP.

Nonconstrained measurement is simple and useful since it can show blood pressure change on beat-to-beat base. Each person has different cardiac output, vascular structure and physical properties of blood. Aging also influences vessel rigidity. PPG waveform differs depending on all these parameters. Therefore, it is necessary to calibrate in advance using an existing accurate blood pressure meter. Once calibrated, blood pressure variations can be calculated from the regression equation.

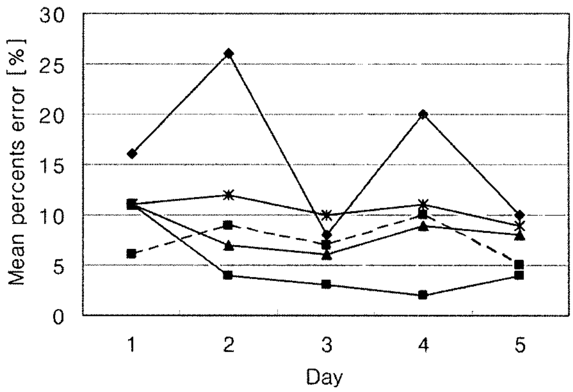

FIG. 5. Day-to-day variations of systolic blood pressure. Each subject had the individual calibration using Dia_t2.

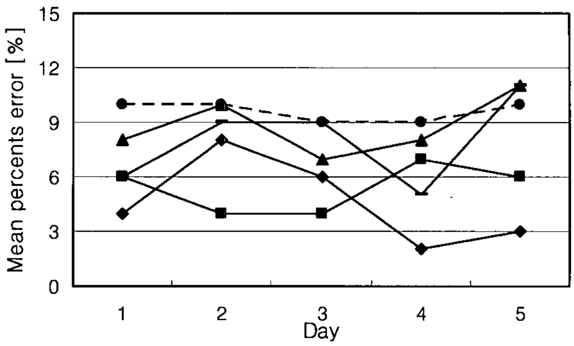

FIG. 6. Day-to-day variations of diastolic blood pressure. Each subject had the individual calibration using Dia_t2.

IV. CONCLUSIONS

This PPG measurement is extremely simple in instrumentation and can be an excellent candidate for continuous and nonconstrained monitoring of blood pressure variations. Our method of investigation in this paper requires only analysis of PPG waveform. With the pulse transit time method of obtaining blood pressure, additional electrocardiogram measurement is required to compute pulse transit time. We suggest that the systolic upstroke time is better for predicting systolic blood pressure and the diastolic time for diastolic pressure. Even though there is a slight sacrifice of accuracy, the proposed method can predict blood pressure on beat-to-beat base. Accuracy can be improved with further investigations on extracting more variables from PPG waveform and their correlations with blood pressure. Clinical studies with more extended populations will follow.

ACKNOWLEDGMENTS

This work was supported by grant No. R 01-2004-000-10965-0 from the Basic Research Program of the Korea Science & Engineering Foundation.

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