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Cuff less Continuous Non-Invasive Blood Pressure Measurement Using Pulse Transit Time Measurement

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***Abstract*— High Blood Pressure or Hypertension is the most common cause of heart disease and coronary artery disease. Hypertension is also a major risk factor for stroke, aneurysms of the arteries, peripheral arterial disease and is a cause of chronic kidney disease. And it is estimated that the number of patients in India with high blood pressure is likely to rise from about 140 million in 2008 to nearly 215 million by 2030. And it's not just an old age problem anymore. Hypertension is rarely accompanied by any symptom, and its identification is usually through screening of continuous monitoring of blood pressure. Blood pressure measurement is performed either invasively by an intra arterial catheter or noninvasively by cuff sphygmomanometery. The invasive method is continuous and accurate but has increased risk, the cuff is safe but less reliable and infrequent. A reliable continuous non-invasive blood pressure measurement is highly desirable. While the possibility of using Pulse Transit Time (PTT) and Pulse Wave Velocity (PWV) were shown to have co-relation with arterial blood pressure (BP) and have been reported to be suitable for indirect BP measurement. Arterial blood pressure (BP) was estimated from Electrocardiography (ECG) and PPG waveform. PTT is a time interval between an R-wave of electrocardiography (ECG) and a photoplethysmography (PPG) signal. This method does not require an air cuff and only a minimal inconvenience of attaching electrodes and LED/photo detector sensors on a subject.PTT computed between the ECG R-wave and the maximum first derivative PPG was strongly correlated with systolic blood pressure (SBP) (R=0.734) compared with other PTT values, and the diastolic time proved to be appropriate for estimation diastolic blood pressure (DBP) (R = 0.731). Our proposed method can be used for continuous BP monitoring for the purpose of personal healthcare.**

***Keywords*— Electrocardiography (ECG), Hypertension, Photoplethysmography (PPG), Pulse Transit Time(PTT), Pulse Wave Velocity(PWV).**

I. INTRODUCTION

High Blood Pressure or Hypertension is the most common cause of heart disease and coronary artery disease. Hypertension is also a major risk factor for stroke, aneurysms of the arteries, peripheral arterial disease and is a cause of chronic kidney disease.

And it is estimated that the number of patients in India with high blood pressure is likely to rise from about 140 million in 2008 to nearly 215 million by 2030. And it's not just an old age problem anymore. Hypertension is rarely accompanied by any symptom, and its identification is usually through screening of continuous monitoring of blood pressure. Hypertension affects every third person above the age of 18. Normally, the blood pressure varies throughout the day. Hence, a single reading of high blood pressure is not the basis for diagnosing hypertension. If you have a persistently high blood pressure reading, you will be diagnosed as having a hypertension with continuous monitoring of blood pressure.

Blood Pressure (BP) is considered to be a strong indicator of an individual's well being and one of the most important physiological parameters that reflect the functional status of the cardiovascular system of human beings. Therefore, the measurement of BP is helpful for a physician to understand and diagnose the integrity function of the cardiovascular system. The various indirect methods of measuring BP such as Riva-Rocci's, oscillometric, ultrasound, and tonometry method, etc. Different noninvasive methods utilizing occlusive air cuffs are frequently used by physicians and nurses in hospitals as well as by laypersons in home care. Such a simple measurement reveals the systolic and diastolic pressure in a specific instant of time. Traditional cuff based methods using Korotkoff sounds or oscillometric methods do not measure BP continuously. These methods require inflation and following deflation of the cuff, which is time consuming and prevents continuous measurement. Furthermore, for reliable measurements, the interval between measurements should be at least 2 min. Therefore, changes in BP, which are in the range of seconds to minutes, cannot be detected.

There are few methods that allow for continuous blood pressure measurement. The most precise results may be obtained using invasive measurement. In this case, a catheter is inserted into the patient's blood vessels, enabling measurement in various places in heart or arteries.

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Moreover, a precise pulse wave shape is provided. This measurement requires highly skilled personnel, special instrumentation and time consuming preparation of the patient. It is very uncomfortable, stressful and potentially dangerous due to its invasive catheter. Therefore, it is only used in cases of critically ill patients, when advanced diagnostics is necessary. Two methodically different methods of non-invasive and continuous BP measurement are available and work in practice, the method after Penaz using a finger cuff and the more recently introduced method using pulse transit time (PTT).

PTT is defined as the time it takes the pulse wave to travel between two arterial sites within the same cardiac cycle. This time is related to the propagation velocity of the pulse wave. The pulse wave travels along with the elastic arterial walls. The physiological reason for the elastic nature of the arterial wall is to buffer the pulsatile ejection of blood from the heart and to provide constant flow in the capillary beds. The pulse wave velocity (PWV) can describe the state of the artery. The speed at which the arterial pressure wave travels is directly proportional to blood pressure (BP) [1]. The pulse wave velocity is measured by measuring PTT, which refers to the time interval between two pulse waves propagating in the same cardiac cycle from separate arterial sites [2]. PTT can be measured by recording the time interval between passages of arterial pulse wave at any two consecutive arterial points or time interval between the dual mode PPG signals recording from earlobe and finger [4, 5]. The PTT is obtained by measuring the time between the R peak of ECG and systolic peak of the pulse [2]. The ECG signal provides health status of the heart and heart rate while PTT can be used as an index of arterial stiffness, which is recognized as a major determinant of cardiovascular diseases.

The aim of the present study was to develop a PWV–BP function on the basis of the physiological properties of arterial walls and to check if a one-point calibration of the PWV–BP relation offers an adequate measure of the Blood Pressure.

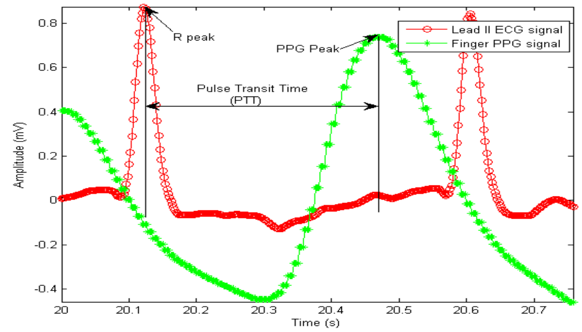

Figure 1. The Definition of PTT[8]

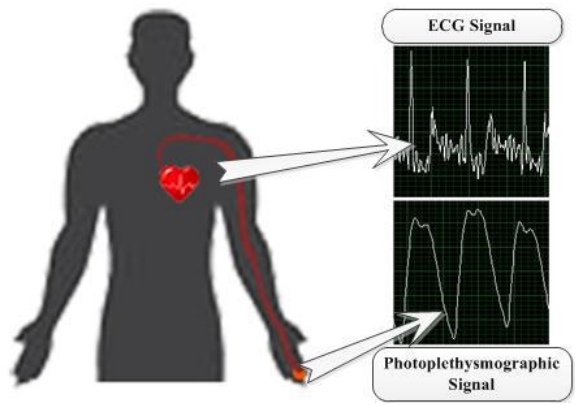

Figure 2. Measurement sites of the ECG and PPG signals[11]

II. Methods And Materials

A. Apparatus

Data is collected from the multipara recording system from RMS medical system POLYRITE-D. This is used to conduct the most widely studied responses on humans and animals in Physiology, Pharmacology labs & Educational Institutions and Research Centers. Analysis of the acquired data is possible online as well as offline. RMS system covers the Cardiovascular, Muscular, Neurophysiology and Autonomic Nervous System Studies.

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These having the advanced features like File compatibility with other applications like MS excel. Heart rate variability analysis, Pulse analysis, ECG analysis, Respiration analysis and Wave overlap facility and FFT function. For data transferring like Data archiving on CD, Data Comparison are available. For photoplethysmographic measurements a reflective type sensor unit has been used TIL78 (IR LED) and TIL32 (Photodiode) with peak spectral response at wavelength of 940 nm. Lead II ECG is selected for measuring and Electro Touch electrodes were used. The signal has been digitized and transmitted to PC using USB interface. Once the data have been acquired and received, offline processing was done using MATLAB. BP was measured for all the subjects by automatic Digital BP monitor (Model: Omron BP Monitor Upper Arm HEM-7201).

B. PTT Calculation

Once the data is collected, the below algorithm is used to analyze the data. PTT calculation since it is the time interval between adjacent peak points of ECG and PPG in the same cardiac cycle. To calculate true PTT, peak points for ECG & PPG are sequenced by occurrence time. Points with same sequence are paired to calculate time interval. Normally the healthy subjects' PTT value is within a certain range from 70 to 200 ms, thus it can be used to discriminate abnormal cases.

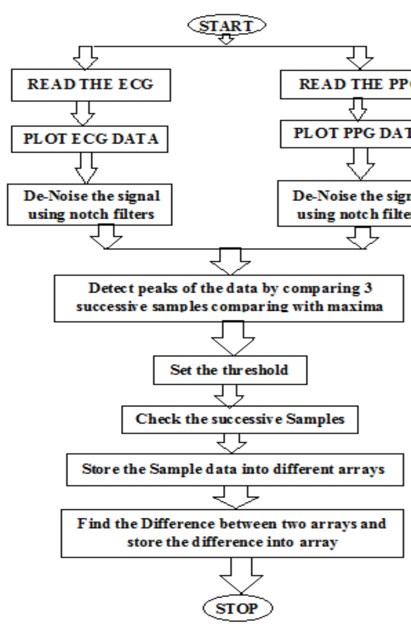

Figure 3. Peak finding Flow chart.

C. ECG R-Peak Detection

R-spike detection of electrocardiographic data can be accomplished through a variety of methodologies. Due to the distinct nature of the waveform, implementing filtering techniques (usually band-pass since the typical frequency components of a QRS complex range from about 10Hz to 25Hz) with relatively simple decision parameters (such as threshold and local peak determination) are often sufficient for detection. Low pass filtering of the ECG waveform is very helpful in the elimination of undesired high frequency noise components. Additional high-pass filtering of the ECG waveform (thus creating a band-pass filter) is helpful in attenuating such signal components as motion artifact, P-waves, T-waves, and baseline drift. This technique appears to be the most commonly used for R-spike detection in the continuous and noninvasive measurement of blood pressure through PTT.

The 'R peak' detection routine first looks for a change from positive to negative differences and then checks that the size of the change is larger than a set threshold. If these conditions are met the interval at which the change occurred is marked as an R peak. Once the R peaks are identified, the program can then go on to calculate the heart rate by checking the period between successive R peaks.

D. PPG Peak Detection

For PPG peak detection, the input to the program is PPG samples which were recorded using the acquisition circuit. We are first setting a threshold and then searching for peaks above the set threshold. The program first looks for a change from positive to negative differences and then checks that the size of the change is larger than the set threshold. Whenever these conditions are met a PPG peak is thus detected, the program stores the interval at which it was detected. Once the PPG peaks are thus detected the pulse rate is calculated using the interval between two successive PPG peaks.

III. BLOOD PRESSURE ESTIMATION

Due to the effectiveness of the non-invasive applications PTT-based blood pressure estimation, it is employed to the data from collected from subjects. The collected database includes signals and periodic measurements obtained from the Polyrite D multipara monitor. The data are recorded continuously, and the information of the patients can also be provided, such as gender and age. Continuous ECG, PPG are available, and blood pressure is recorded by the Non-invasive way.

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The algorithm is applied on the data collected from subjects to obtain the filtered ECG and PPG. Then, R wave peaks of ECG and characteristic points of PPG are detected. Different PTTs are calculated and used to estimate Pulse wave velocity (PWV). Since PTT & PWV is highly related to blood pressure, the model for each individual is linearised as:

$$BP = a * PWV + b.$$

A. Coefficient Calibration

When the PTT values are detected, the Pulse wave velocity is calculated and using this parameters original calibration is performed firstly when the method is used for blood pressure estimation. About 20 values of PTT are required for the original calibration for acceptable outcome. Least Square algorithm is a prevalent statistical method that has been widely employed in many applications. It minimizes the sum of the squares of the errors to achieve the proximal values. The original calibration in our work is accomplished through Least Square method. The procedure is stated as follows.

The unknown coefficients *a* and *b* are gathered into the matrix

$$\beta = \begin{bmatrix} a \\ b \end{bmatrix}$$

For SBP and DBP respectively. We collect the blood pressure and PWV into matrices

$$Yn = \begin{bmatrix} BP1 \\ . \\ . \\ . \\ . \\ BPn \end{bmatrix}, \quad Xn = \begin{bmatrix} PWV1 \\ . \\ . \\ . \\ . \\ PWV2 \end{bmatrix}$$

Where *n* denotes the *n*th measurement.

Least Square algorithm is employed to determine the unknown coefficients *a* and *b*, which is considered as the calibration process. As the blood pressure values are available along the collected data, the estimated blood pressure results by the PTT & PWV-based method can be compared with the actual blood pressure values.

IV. Results And Discussions

A software code was written in Matlab. Turning point method was used for ECG QRS detection and threshold method was used for PPG peak detection.

This program takes the ECG and PPG signals as input and finds Pulse transit time based on which blood pressure is calculated for each heart beat. Data from patients were acquired using this device and its working was validated. The device was found to be working within the set limits and acceptable accuracy levels. The data for analysis was taken from 11 different subjects. These subjects are of age group between 22-45 years, and in the Height range of 152-172cms and weight range of 41-89Kgs. All the individuals are healthy in all aspects of physiological parameters. All the results were taken when the subjects were in rest condition.

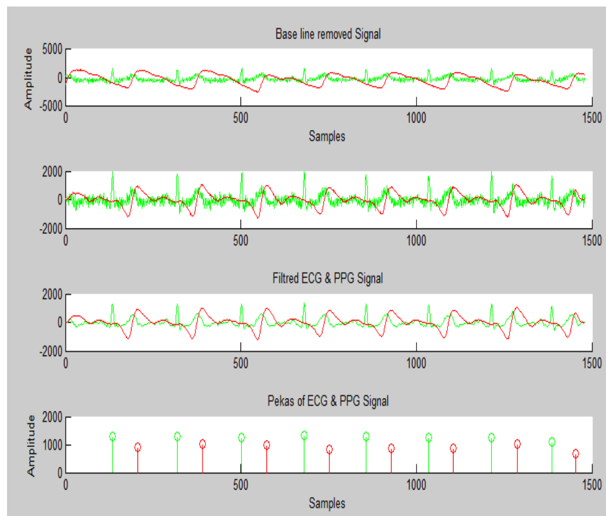

Figure 4. Snapshot from MATLAB with ECG and PPG signal as input and its peaks detected

The following table gives us the information regarding the data collected from various subjects for the calculation of PWV from the resultant PTT values obtained from the code developed.

Table I
Tabulated results for measured PWV using PTT.

Subject	Age/Gender	Height (cm)	PTT (msec)	PWV (cm/sec)
Subject 1	45/M	165	78	1057.692
Subject 2	32/F	157	81	969.136
Subject 3	32/F	155	73	1061.644
Subject 4	32/F	152	67	1134.328
Subject 5	28/F	164	85	964.706
Subject 6	26/F	149	73	1020.548
Subject 7	22/F	158	84	940.476
Subject 8	22/F	152	74	1027.027
Subject 9	22/M	165	79	1044.304
Subject 10	23/F	172	78	1102.564
Subject 11	25/M	168	69	1217.391

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Least Square algorithm is employed to determine the unknown coefficients *a* and *b*, which is considered as the calibration process. As the blood pressure values are available along the collected data, the estimated blood pressure results by the PTT & PWV-based method can be compared with the actual blood pressure values. The error mean, error standard deviation and correlation coefficient are presented.

For Systolic Blood Pressure the linear regression coefficients a and b are

a = 0.05089855
b = 62.5590972

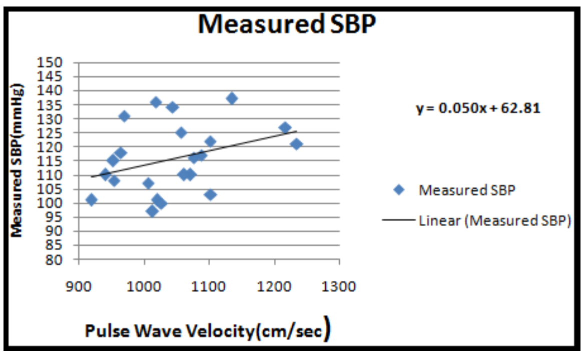

Figure 5. Linear Regression Curve between Measured SBP and Pulse wave velocity

Linear Equation for Finding SBP is
Systolic Blood Pressure (Y) = 0.05089855 X + 62.5590972

Table II
Results for the Measured SBP and Estimated SBP and error.

Subject	PWV (cm/sec)	Measured SBP (mmHg)	Estimated SBP (mmHg)	Diff b/w M-SBP & E-SBP (mmHg)
Subject 1	1057.692	125	116.394	-8.605
Subject 2	957.317	115	111.285	-3.714
Subject 3	1061.644	110	116.595	6.595
Subject 4	1101.449	122	118.621	-3.378
Subject 5	964.706	118	111.661	-6.338
Subject 6	1006.757	107	113.801	6.801
Subject 7	940.476	110	110.427	0.4279
Subject 8	1027.027	100	114.833	14.833
Subject 9	1044.304	134	115.712	-18.287
Subject 10	1088.608	117	117.967	0.967
Subject 11	1217.391	127	124.522	-2.477

For Diastolic Blood Pressure the linear regression coefficients a and b are

a = 0.04940772
b = 17.4800472

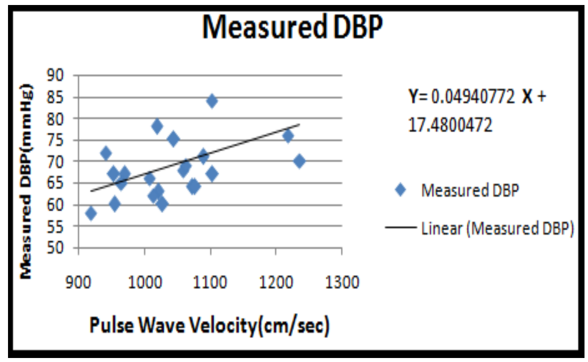

Figure 5: Linear Regression Curve between Measured DBP and Pulse wave velocity

Linear Equation for Finding DBP is
Diastolic Blood Pressure Y = 0.04940772 X + 17.4800472

Table III
Results for the Measured DBP and Estimated DBP and error.

Subject	PWV (cm/sec)	Measured DBP (mmHg)	Estimated BP (mmHg)	Diff b/w M-DBP & E-DBP (mmHg)
Subject 1	1057.692	68	69.738	1.738
Subject 2	957.317	67	64.778	-2.221
Subject 3	1061.644	69	69.933	0.933
Subject 4	1101.449	84	71.900	-12.099
Subject 5	964.706	65	68.612	3.612
Subject 6	1006.757	66	67.221	1.221
Subject 7	940.476	72	63.946	-8.053
Subject 8	1027.027	60	68.223	8.223
Subject 9	1044.304	75	69.076	-5.923
Subject 10	1088.608	71	71.265	0.265
Subject 11	1217.391	76	77.628	1.628

In principle, The Pulse Wave velocity method can be used by placing the electrodes to the Extremities of the patient or otherwise can place to chest to record the ECG and PPG sensor is placed as per subject connivance. By placing these both sensors we can get the ECG and PPG. By computing these two signals we can get the Pulse Transit Time (PTT), Pulse wave velocity (PWV), which enables noninvasive, pulse-by-pulse monitoring of blood pressure.

The mean errors obtained with the PWV method in the subjects are all are normal and healthy patients. The calculated SBP Errors in the range from 14.833 to -18.287 and the DBP Errors in the range from 8.223 to -12.099.

The actual continuous values of blood pressure are obtained, the estimated blood pressure based on the data collected by the mutiparamonitor. The results show the application of the method to our data. It is commonly accepted that the blood pressure variation estimation is measured to the daily health monitor by using the compact devices to measure continues blood pressure.

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