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Pressure Sensor Based Estimation of Pulse Transit Time

Saransh Khandelwal[1], Simrat Sahni[2], Sanjeev Kumar[3], Amod Kumar[4]

[1, 2, 3, 4]Biomedical Instrumentation Unit,
CSIR-Central Scientific Instruments Organisation,
Sector 30-C, Chandigarh-160030

Abstract

With advancement in technology for acquiring and analysing the pulses with standardization and quantification of performance and widespread availability of high technology, multi-coloured display monitors has renewed interest in analysing pulse signal waveforms which should be expanded to clinical diagnosing capabilities. Pulse Transit Time is cardiovascular parameters of emerging interest suitable for estimation of cuff-less non-invasive blood pressure. It is a well-known demographic fact that as the population ages, the prevalence of hypertension increases even with the implementation of broad and effective preventive measures. In this paper, an automatic technique for continuous non-invasive Pulse Transit Time estimation has been explained which can be further applied to relate with systolic and diastolic blood pressure. The continuous pulse data of 25 healthy subjects (age 22 ± 5years) from the brachial artery, radial artery and digital artery has been recorded under normal lying down condition. Simultaneous peak from different pulse signals; inter peak to peak transit time and intra peak to peak transit time has been calculated for the estimation of the Blood Pressure.

Keywords: Diastolic Blood Pressure, Non-Invasive, Photoplethysmography, Pulse Transit Time, Pulse Wave Velocity, Systolic Blood Pressure.

Introduction

Blood pressure is the pressure exerted by circulating blood on the walls of blood vessels. It is measured in millimetres of mercury (mm Hg) and is recorded as two numbers usually written one above the other. The upper number is the systolic blood pressure, the highest pressure in blood vessels and happens when the heart contracts, or beats [1]. The lower number is the diastolic blood pressure the lowest pressure in blood vessels in between heartbeats when the heart muscle relaxes. Normal adult blood pressure is defined as a systolic blood pressure of 120 mm Hg and a diastolic blood pressure of 80 mm Hg. The existing method in monitoring blood pressure continuously in the intensive care unit (ICU) or Operation Theatre involved an invasive method such as inserting a catheter into the patient’s artery. The Non-Invasive techniques available for continuous monitoring of blood pressure are Doppler Ultrasound, Arterial Tonometry and Pulse transit Time.

In recent studies, the estimation of non-invasive blood pressure has been correlated with Pulse Transit Time derived from ECG and PPG signals [2, 3]. Pulse Transit Time (PTT) is the time interval that the arterial pulse pressure wave takes to travel from the aortic valve to the periphery and is usually recorded as the time between the opening of the aortic valve (‘R wave’ on the electrocardiogram) and the arrival of the corresponding pulse wave at a finger [4]. The basic principle involved in generating ECG and PPG signals are different resulting in a complex approach to calculate transit time whether peak to peak or peak to foot [5]. This paper proposes a highly economical and simple approach for non-invasive measurement of pulse transit time.

This study deals with the development of pressure based sensor, which picks up the blood flow pulse signals. Pulse represents the tactile arterial palpation. The blood flow in the artery gives a fluctuating voltage signals at each heartbeat which is amplified and filtered by the pulse sensor circuit developed in-house for measuring Pulse Transit Time. Non-Invasive pulse signals are recorded from different arterial sites such as brachial artery, radial artery, and digital artery. PTT is calculated from peak to peak distance acquired by the pulse sensor placed at three different positions of the subject. In parallel of recording data for pulse transit time calculation, blood pressure and heart rate was also recorded using automatic blood pressure monitoring system for further analysis of pulse transit time and its relation to blood pressure.

Methodology

Subjects

Twenty-five normal male volunteers without any cardiovascular disease background were included in this study with the mean age of 22 ± 5 years. In parallel to Pulse Transit Time measurement the reference Non-Invasive Blood Pressure and Heart Rate values were noted by Meditec M-901 Patient Monitor, Allied Medical Limited device, system. The subject was asked to take rest and lie on patient bed, where his left arm was subjected to cuff for automatic blood pressure monitoring with the Photoplethysmography finger clip placed on his index finger.

Hardware Implementation

The signals are sensed with the help of condenser microphone based sensors, amplified by using LM741 operational amplifier and filtered by using RC based low pass filter followed by signal visualisation using DSO and further acquisition by PC for processing and analysis. Following is the block diagram of the circuit as shown in the Figure 1.

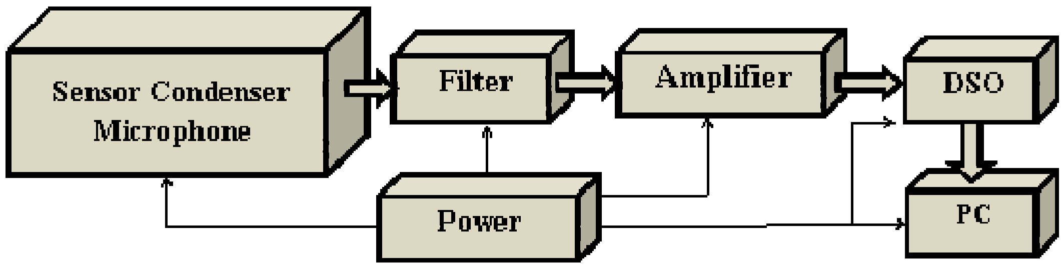


Figure 1: Block diagram of the Pulse Sensor Circuit

Pressure Based Pulse Sensor

The pulse wave sensor that is condenser microphone mainly used to amplify voice. The operation of condenser microphone sensor is caused by accumulation of voltages that means capacitance. So, the indirect measurement of the capacity of the microphone sensor using time-constant is achieved. The condenser microphone is also called a capacitor microphone or electrostatic microphone. Here, the diaphragm acts as one plate of a capacitor, and the vibrations produce changes in the distance between the plates. In this DC-biased microphone, the plates are biased with a fixed charge (Q). The voltage maintained across the capacitor plates changes with the vibrations in the air, according to the capacitance Equation 1:

$$C = Q/V. \qquad (1)$$

Where, Q = charge in coulombs, C = capacitance in farads and V = potential difference in volts. The capacitance of the plates is inversely proportional to the distance between them for a parallel-plate capacitor. The assembly of fixed and movable plates is called an "element" or "capsule". A nearly constant charge is maintained on the capacitor. As the capacitance changes, the charge across

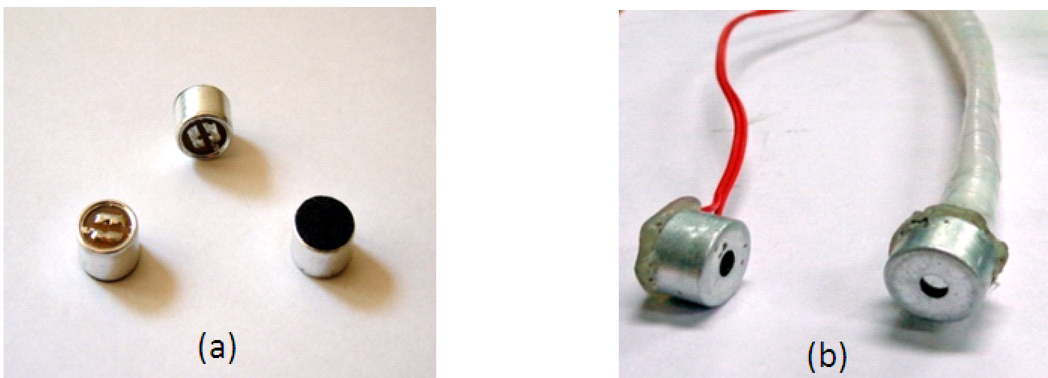


Figure 2: (a) A snap shot of Condenser Microphones, (b) Condenser Microphone with wire attached for further connection to pulse sensor circuit.

the capacitor does change very slightly, but at audible frequencies it is sensibly constant. The capacitance of the capsule (around 5 to 100 pF) and the value of the bias resistor (100 MΩ to tens of GΩ) form a filter that is high-pass for the audio signal, and low-pass for the bias voltage.

Mechanical Design

The second part consists of the mechanical design done by FORTUS 250mc 3D Production System, CSIR-CSIO, Chandigarh, which consists of two flat rectangular shaped housing for microphone sensor to fit at brachial and radial artery region and a U-shaped clipper like structure in order to acquire the pulse signals from digital artery that is finger region. It also consists of a design in which whole circuit and battery is embedded.

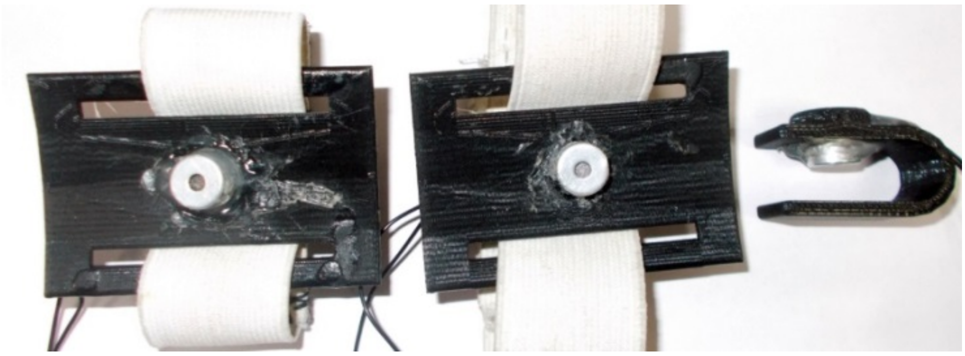


Figure 3: Condenser Microphone placed in plastic housing rectangular shaped for Brachial, Radial artery region and u-shaped for Digital artery region

Pulse Sensor Circuit

The pressure signal generated due to blood movement is feeble i. e. in the range of few millivolts. The two stage amplifier is used to amplify the signal using UA 741C which amplifies the signal to hundreds of millivolt. The arrangement is shown according to which the PCB layout is developed for the PCB fabrication. The following figure 4 is the PCB layout and in-house developed circuit.

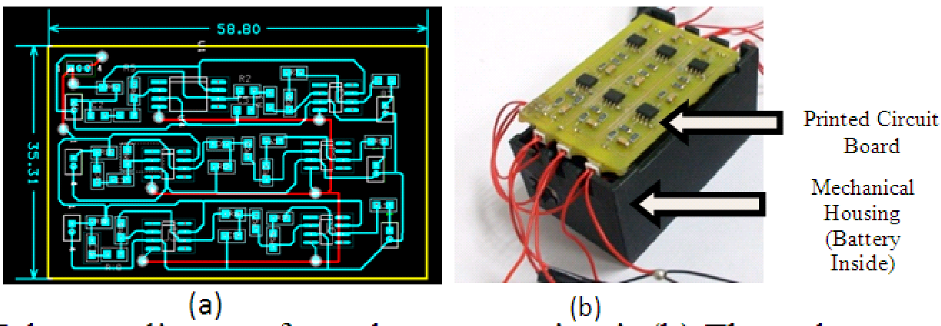


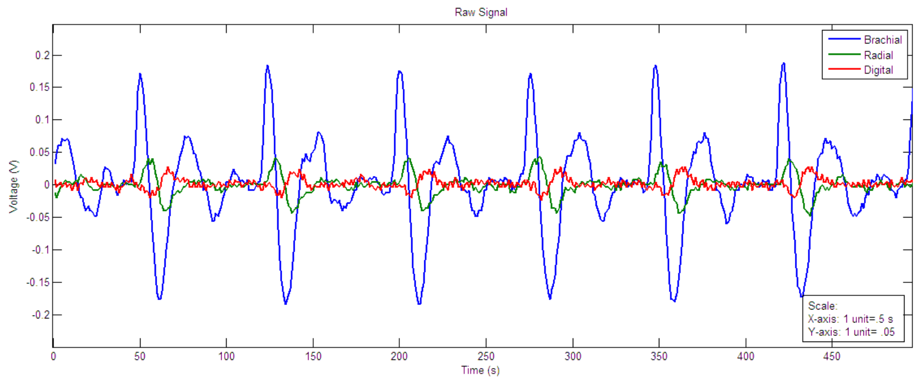
Figure 4: (a) OrCAD PCB layout diagram for pulse sensor circuit (b) The pulse sensor circuit with battery connected inside the mechanical housing

Data Acquisition

The condenser microphone based sensors, each for specified region that is brachial artery, radial artery and digital artery were placed on the right arm of the 25 subjects. The pulse signals were observed on the oscilloscope concurrently for all three channels, suitable adjustment of sensor placement for best signal strength was done, if required. Finally, after adjusting the sensor correctly, the pulse signals were acquired digitally to the computer by LabVIEW SignalExpress. Simultaneous blood pressure and heart rate readings were consecutively noted down for five times during record and averaged value is further implied for analysis.

Signal Analysis

In order to calculate the transit time in between the pulses acquired, following steps were required. First, the signal noise was removed followed by the detection of peaks and finally detection of intra and inter-peak to peak distance between pulses for Heart Rate and PTT calculation respectively.



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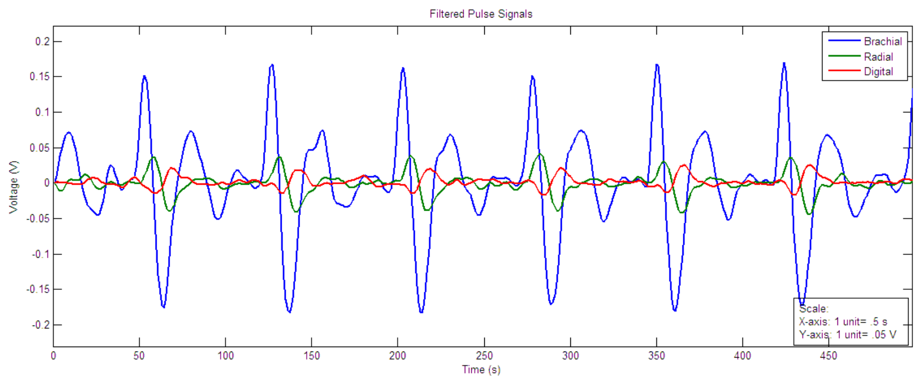

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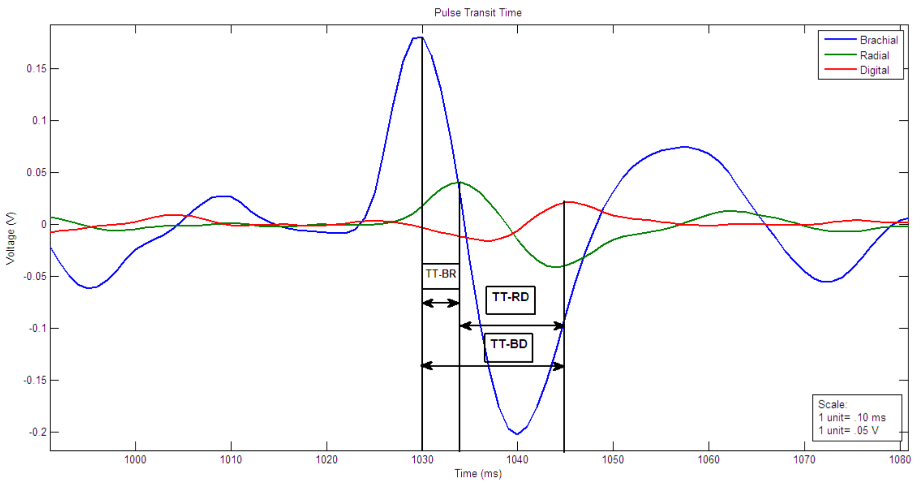

c

Figure 5: (a) Raw Signal acquired from the random subject (b) Signal output after Low Pass Filtering (c) Peak to Peak Transit Time shown for an instance of time.

The signals plotted are raw signals which were further filtered by using digital filter in MATLAB. The Low pass, Infinite Impulse Response, Butterworth filter of second order with F_c, Cutoff Frequency of 10 Hz and F_s, Sampling frequency of 100 Hz is used. The pulse signal consists of a pattern having peaks at a certain time interval which are beat to beat time interval due to pumping action of heart. An algorithm is developed for determination of peaks in MATLAB. The intra peak to peak time in between the signal is the heart beat which was further calculated and averaged from each signal. The beat to beat analysis of each signal peak to peak distance from three consecutive signals, gives pulse transit time value for each heartbeat. The time calculated is averaged and displayed for each recording for further analysis with simultaneous blood pressure and heart rate data acquired automatically by standard blood pressure monitoring system.

Results

The Pulse Transit Time and Heart Rate measured from the pulse signals recorded by 25 subjects from three different locations of sensor placement i. e. brachial, radial and digital artery is shown in the following table. The difference in the heart rate values calculated and observed is plotted, depicting the frequency of subjects corresponding to % error of heart rate.

Table 1: Recorded data from random five subjects showing PTT calculated from different sites. Here, B, R and D stand for Brachial, Radial and Digital arterial site.

Subject	Sex	Age (y)	SBP (mmHg)	HR* (bpm)	HR**(bpm)	% Error	PTT-BR (s)	PTT-RD (s)	PTT-BD (s)
3	M	24	116. 75	85	83. 53	1. 74	0. 079	0. 071	0. 150
7	M	27	113. 20	85	81. 35	3. 85	0. 025	0. 126	0. 150
14	M	27	130. 75	61	59. 22	2. 93	0. 032	0. 096	0. 128
19	M	23	131. 40	88	84. 51	3. 69	0. 036	0. 100	0. 136
23	M	24	130. 00	91	86. 96	4. 18	0. 010	0. 127	0. 137

The Heart Rate measured by the automatic blood pressure monitoring system and the pulse sensor circuit are analysed and the percentage error between the values obtained from both techniques is calculated, as shown in the table 1. A histogram of % error and frequency of cases falling into the range is plotted for the recorded data as shown in figure 6. The maximum and minimum % Error values are 7. 396 and-6. 134 respectively. The linear regression for pulse transit time data with respect to systolic blood pressure is analysed. Significant results are observed; P value 0. 0012, F value 13. 62 and R^2 value. 3719 for particular sensor placement site i. e. at brachial and digital artery pulse sensor site. The line equation for SBP vs. PTT-BD is Y =-0. 002199*X + 0. 5776.

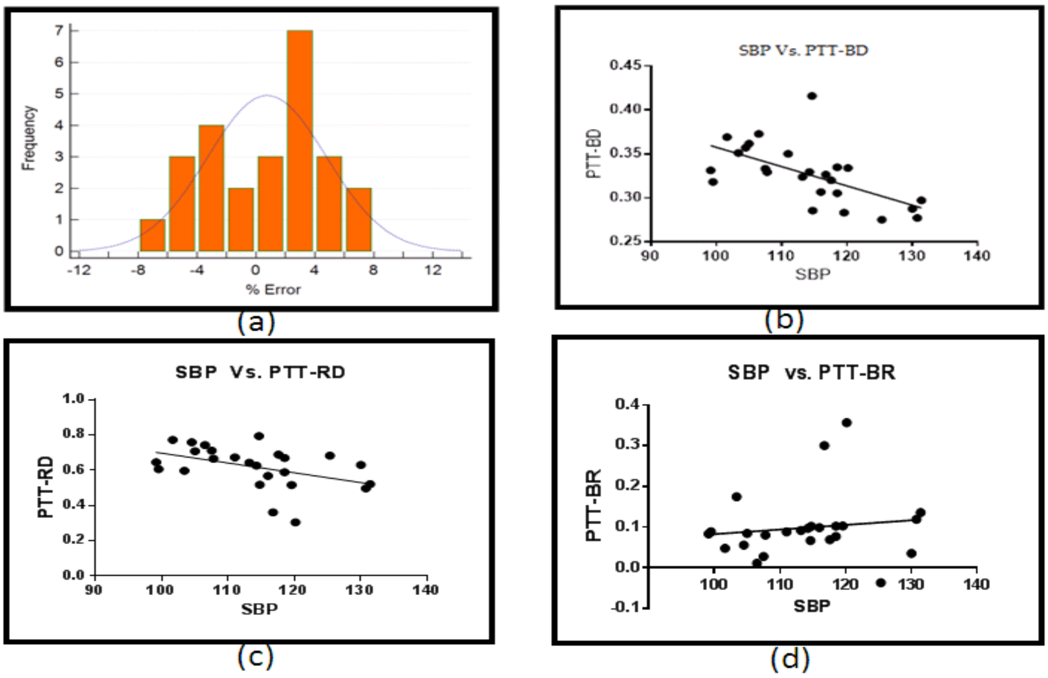

Figure 6: (a) Histogram plot showing the frequency of cases falling in a given % error range. (b, c and d) The Linear Regression line plotted between Systolic Blood Pressure and PTT

The results as shown in Figure 6 give a linear relationship between PTT-BD and Systolic Blood Pressure. The relationship found in the other sensor placement sites is given as P value 0. 0278 and 0. 5315, F value 5. 513 and 0. 4036and R^2 value 0. 1933 and 0. 01724 for radial-digital and brachial-radial artery pulse sensor site. The line equation Y =-0. 005557*X + 1. 253 and Y = 0. 001133*X-0. 03075 for SBP vs. PTT-RD and for SBP vs. PTT-BR respectively.

Conclusion

The proposed setup involves condenser microphone as a sensor, highly economical, to detect the peak generated due to the blood flow at each heart beat and other basic electronic passive components for filtering and amplification of signals. In this work the signal analysis and calculation of PTT is done in offline mode using different software's. The calculation and analysis of PTT with respect to blood pressure is done and the best sensor positioning site is achieved by analysing linear regression results found for each sensor placement. The linear relation is practically demonstrated in results and graphs plotted between PWV and PTT with respect to systolic and diastolic blood pressure.

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