LabVIEW Based Measurement of Blood Pressure using Pulse Transit Time

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***Abstract*—Blood Pressure is the pressure exerted by blood on the walls of arteries. Normal blood pressure is considered to be a systolic blood pressure of 120 millimetres of mercury and diastolic pressure of 80 millimetres of mercury (stated as "120 over 80"). If an individual were to have a consistent blood pressure reading of 140 over 90, he would be evaluated for having high blood pressure. If left untreated, high blood pressure can damage important organs, such as the brain and kidneys, as well as lead to a stroke. Thus it becomes important to measure blood pressure as it can lead to early diagnosis of diseases that may be linked to high or low blood pressure. PTT is the time taken by the arterial pulse propagating from the heart to a peripheral site. This can be calculated from ECG signals and PlethysmoGram signals. Since, PTT has been found to be correlated to Blood Pressure, it is imperative to calculate PTT accurately. In this paper, a relation has been developed between PTT and Blood Pressure using regresssion analysis. Another indicator, known as the Photoplethysmogram Intensity Ratio, henceforth known as the PIR has also been used in estimation of the Blood Pressure. The coding has been done in LabVIEW which is has a graphical programming syntax that makes it simple to visualize, create, and code engineering systems.**

***Index Terms*—Blood Pressure, ECG, PTT, PPG, LabVIEW, Regression Analysis**

I. INTRODUCTION

A. Blood Pressure is the pressure exerted by blood on the walls of arteries. There are two values of blood pressure for a person at a particular instant, the Systolic blood pressure and the Diastolic blood pressure. The cardiac cycle consists of the steps from the beginning of one heart beat to the end and the beginning of the next heartbeat. It consists of Systole, Diastole and a gap in between. The heart consists of 4 chambers, the left and right Atria and the left and right Ventricles. Systole is when blood in the ventricles are pumped out to the body, the impure blood going from the right ventricle to the lungs and the pure blood to the body through the aorta. Following Systole, Diastole takes place when blood from the atria is moved into the ventricles. Ventricles having a larger volume, cause the blood to pushed out with a large amount of force as it has to travel all over the body through the arteries. Thus Systolic blood pressure has a higher value than Diastolic blood pressure. Thus, blood pressure is measured both as the heart contracts, i.e. systole, and as it relaxes, i.e. diastole. Normal blood pressure is considered to be a systolic blood pressure of millimetres of mercury and diastolic pressure of 80 millimetres of mercury (stated as "120 over 80"). Consistent Blood Pressure readings above the maximum value and below the minimum value is known as High Blood Pressure and Low Blood Pressure respectively. Both are damaging to the health of an individual especially high blood pressure in the long run, even though they may go undetected in the early stages. Regular checks of blood pressure is important and this leads to resarch in different ways to effectively calculate blood pressure which does not need the patient to visit the doctor frequently. The method using PlethysmoGram to indirectly calculate blood pressure is interesting in this respect.

B. Pulse Transit Time (PTT) is the time taken taken by the arterial pulse pressure wave to propagate from the point of origin which is the aortic valve to a peripheral site. The point of origin is the aortic valve from where the blood is pumped out via the left ventricle. Thus PTT can also be said to be the interval between ventricular electrical activity and the peak of pulse wave taken at a peripheral site. Calculation of PTT will be further enumerated in section II B. Pulse Transit Time is a useful marker which can be used to indicate arterial stiffness as well as cardiac output amongst other cardiovascular indices. It can also be used to estimate blood pressure. Pulse Wave Velocity (PWV) is the speed of a pressure pulse propagating along the arterial wall [2]. Since speed is inversely proportional to time, the Pulse Wave Velocity for the pressure pulse propagating along the arterial wall from the heart till a peripheral point can be calculated from the Pulse Transit Time which is the time taken by the same pressure pulse to move from the aorta to the peripheral site. Pulse Wave Velocity is related to blood pressure as a result of which the Pulse Transit Time can be used to estimate Blood Pressure given other parameters like elastic modulus of vessel wall, blood density, arterial dimensions among other parameters[1].

Pulse Transit Time has been used for a variety of applications. Pulse Transit Time has been used by Kounalakis et al. and has been shown to be related to cardiac output [3]. One of the earliest research in this area was done by Phillip Hallock where he related Pulse Wave Velocity to arterial elasticity in 1934[4].Smith et al. used the Pulse Transit Time for calculation of parameters needed for patients with sleep disorders [5]. Ochiai et al. used the Pulse Transit Time to predict blood pressure changes in canines in 1999 [6]. Ahlstrom et al. in 2005 used the Pulse Transit Time with patients undergoing Hemodialysis. Blood Pressure changes are not uncommon in patients undergoing hemodialysis and it is necessary to measure them so that the patient is not at a risk of injury due to a drop in blood pressure. He used the Pulse Transit Time to find changes in the Systolic Blood Pressure and showed that it is correlated to it for a trend-indicating system[7]. Alty et al. used the Pulse Wave Velocity technique which is derived from the photoplethysmogram to detect arterial stiffness which is indirectly related to hypertension or high blood pressure in 2007 [8]. Fechir et al. used the Pulse Transit Time to detect Sympathetic Nervous System (SNS) arousal in 2008. He used the PTT along with other cardiovascular parameters for comparison of SNS patterns during stress tasks undertaken by patients [9]. Schmalgemier et al. used the Pulse Transit Time and showed its correlation to the blood pressure under conditions of CPAP i.e. Continuous Positive Airway Pressure which is a type of ventilator [10]. Contal et al. compared Pulse Transit Time to respiratory ratio and concluded that it is promising for noninvasive assessment of inspiratory muscle effort under NIV (NonInvasive Ventilation) conditions [11]. Kortekaas et al. showed that the Pulse Transit Time is a reliable factor to assess if the axillary bracial plexus block is successful or not [12].

C. Plethysmogram Intensity Ratio (PIR) is the difference between the amplitude of the PPG peak (I_H) and the amplitude of the PPG Valley (I_L). Studies by Ding et al. study show that PIR can theoretically reflect the arterial diameter change during one cardiac cycle from systole to diastole, and PIR is exponentially linked with the diameter change [1]. PIR varies with the blood pressure and hence is used as an indicator to estimate the blood pressure.

Chapter II describes the technique of Pulse Transit Time calculation. Chapter III the data collection and procedure of signal processing involved. Results and discussion are in chapter IV followed by the conclusion in chapter V.

II. TECHNIQUE

A. *Current Technique*

Light is made to reflect off the skin or go through it using an infrared LED. The reflected light or the transmitted light is collected by a photodiode. The waveform produced depends on the amount of blood flowing through the capillaries in the volume through which the light has passed. There are two types of plethysmography depending on whether the reflected light or the transmitted light is used. Transmittance mode plethysmography uses the transmitted light. Reflectance mode plethysmography uses the reflected light.

Change in the flow of blood which depends on the heart rate causes a change in the intensity of the light which is reflected or transmitted. Thus the amplitude of the waveform depends on the volume of blood at that particular instant in time.

There are 2 components in a plethysmogram signal. They are the AC component and the DC component. The DC component does not vary much and is dependent on the material that does not vary through which the light passes. This material is skin, cartilage, venous blood, etc. The AC component on the other hand, varies and depends on the volume of the blood at that time instant. During Systole, the volume of blood increases and due to that, the light absorbed is more resulting in less light at the receiver. During Diastole, the volume of blood is less, resulting in more light at the receiver.

Now, PTT is the time taken by the arterial pulse propagating from the heart to a peripheral site, and can be calculated as the time interval between the R wave peak of electrocardiogram (ECG) and a characteristic point of photoplethysmogram (PPG). The characteristic point can vary and a number of points on the PPG waveform can be chosen as a characteristic point.H Ma et al. used the peak of the PPG signal as the characteristic point [13]. G Zhang et al. used the diastolic foot of the PPG as the characteristic point [14]. M Gomez Garcia et al. used the halfway point between the diastolic foot and the systolic peak as the characteristic point [15]. X Ding et al. used the peak upslope i.e. the maximum of the first derivative of the plethysmogram as the characteristic point which will be used in this paper [16].

We will be using the peak of the first derivative of the plethysmogram signal as our characteristic point.

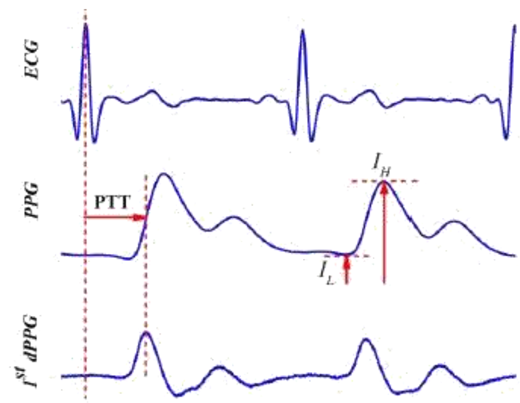

Fig 2.1 Calculation of PTT (reproduced from [1])

III. DATA COLLECTION AND PROCEDURE

Signals of ECG and Plethysmogram are taken from the mimicdb database provided by Physionet.org. 3 signals (ECG, PPG and BP) have been taken from 10 patients. Each set of signals have a duration of 2 minutes from which 80% of the data is used for regression analysis and 20% of the data is used for testing the relation between PTT and/or PIR with Blood Pressure.

The data was processed using LabVIEW. First the R-Peak detection of the ECG signal was done. Then the detection of the peaks of the first difference signal of the PPG signal. These two gave the values of Pulse Transit Time for each heart beat. Also, the PIR was calculated from the PPG signal for each heart beat. Next, the blood pressure peak value i.e.

the Systolic Blood Pressure and the valley value i.e. the Diastolic Blood Pressure were extracted from the Blood Pressure signal. So, the data after processing included sets of PTT values, PIR values and SBP and DBP values for each heart beat. 80% of the data was used for regression analysis and 20% of the data was used for testing the relation between PTT and/or PIR with Blood Pressure and the accuracy of the estimated relation got by regression analysis.

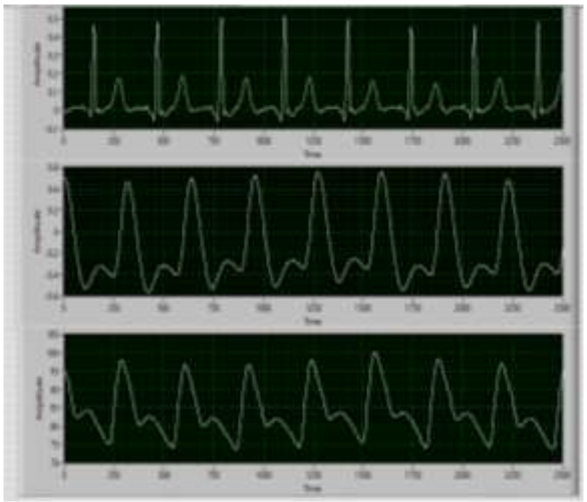

Fig 3.1 Signals ECG, PPG and Blood Pressure from mimicdb database

IV. RESULTS AND DISCUSSION

Using regression analysis on the calculated values of the SBP, DBP and PTT & PIR, coefficients for the relationships between SBP, DBP and various combinations of PTT and PIR were found using LabVIEW. The analysis was done for different equations between SBP, DBB and PTT and PIR. For SBP, Wibmer et al. used a linear relationship as well as a non-linear relationship wherein the SBP depends on the reciprocal of the square of the Pulse Transit Time [17]. Ding et al. used a relationship wherein the SBP depends on the inverse of the square of the Pulse Transit Time and the inverse of the Plethysmogram Intensity Ratio [1]. Table 4.1 lists the number of equations used. The values of the coefficients a, b and c for each equation was found using regression analysis. Similar equations were also used for analyzing the relationship between DBP and PTT and/or PIR.

Equation -
SBP = a*PTT + b…………….…….I
SBP = $a*e^{b*PTT}$ + c………………...II
SBP = a*(1/PTT^2) + b…………….…..III
SBP = a(1/PIR) + b………….……..IV
SBP = a(1/PIR) + b(1/PTT^2) + c…...V

Table 4.1 Equations used in regression analysis for SBP

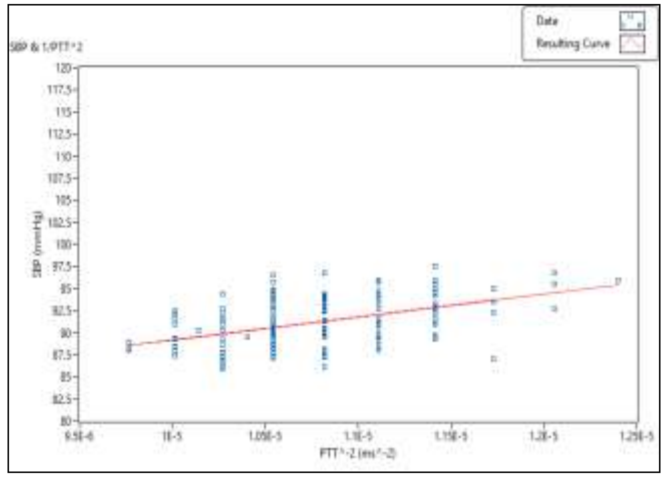

Fig. 4.1 SBP values plotted for corresponding values of PTT^{-2} (in blue). Also shows the resulting equation between SBP and PTT^{-2} (in red).

The calculated SBP and PTT values were plotted and regression analysis was done for each of the equations shown in table 4.1. A representative plot of SBP versus 1/PTT^2 for one of the subjects is shown in fig 4.1. It shows as the inverse of the Pulse Transit Time increases the SBP increases. That is, the SBP is higher for lower PTT values. The output of the regression analysis is the curve shown in red, which is of the form of equation III from table 4.1.

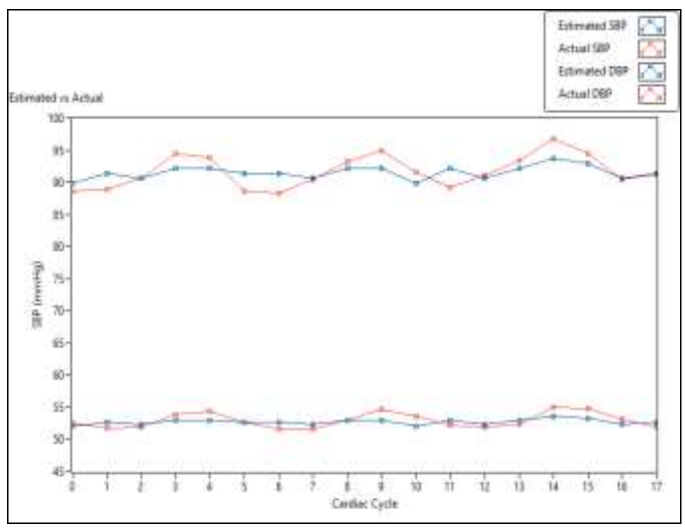

Fig. 4.2 Estimated Blood Pressure values versus Actual Blood Pressure Values for a single patient over 17 cardiac cycles.

Using the resulting equation, values of PTT were used then to calculate the corresponding blood pressure values. These values were then compared with the actual blood pressure values which were measured by invasive arterial blood pressure measurement technique. Fig 4.2 shows the actual SBP values (in red) compared to the ones estimated by using the equation calculated by regression analysis (in blue). Also shown are the actual DBP values (in red) along with the calculated DBP values (in blue).

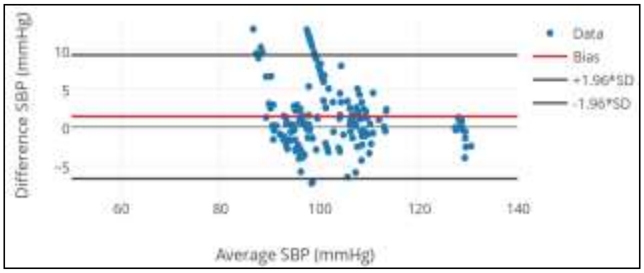

Fig 4.3 Bland Altman plot of Estimated SBP with Actual SBP

Bland and Altman plots are extensively used to evaluate the agreement among two different instruments or two measurements techniques. For the Bland-Altman plot, the x-axis of the plot represents the average of the estimated blood pressure with the actual blood pressure, while the y-axis shows the difference between the two values i.e. (estimated BP – actual BP). The bias (mean of the average of the differences between the two values) and the limits of agreement (bias±1.96×SD) are in red solid line and black solid lines, respectively. Majority of the data values in figures 4.3 and 4.4 lie within the limits of agreement. This indicates that the estimated BP with the proposed method are in close agreement with the actual BP calculated invasively.

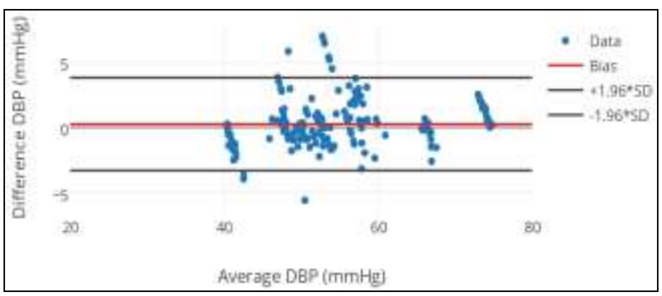

Fig 4.4 Bland Altman plot of Estimated DBP with Actual DBP

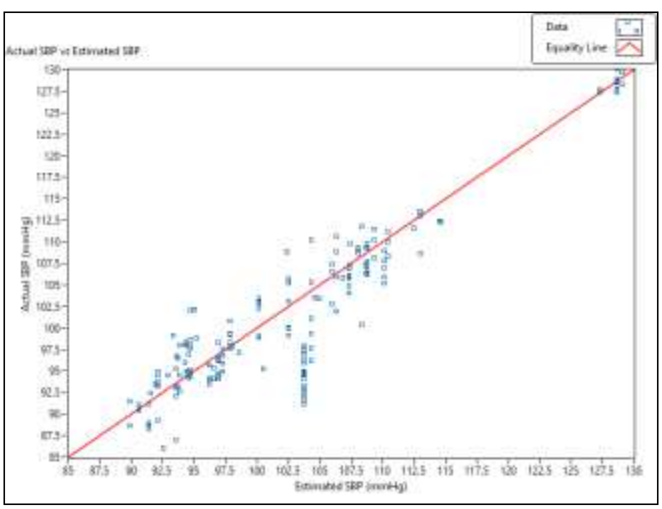

Fig. 4.5 Actual SBP versus Estimated SBP (in blue) with the equality line (in red) for the equation II

The values of the actual blood pressure were plotted along with their corresponding estimated values and is shown in figure 4.5 for SBP and in figure 4.6 for DBP. The plotted data points are shown in blue and the equality line is shown in red.

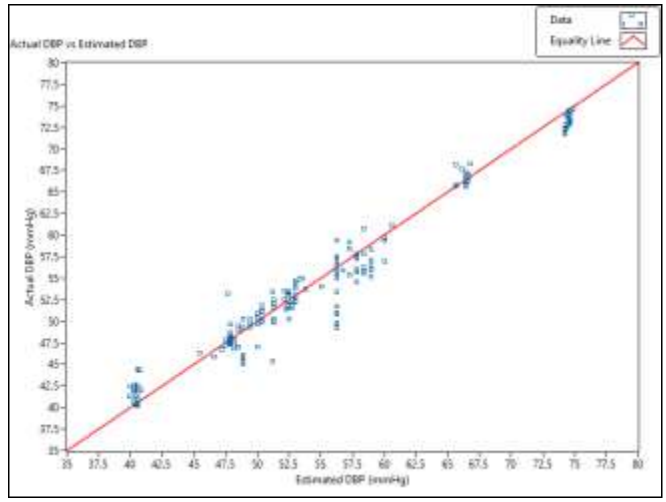

Fig. 4.6 Actual DBP versus Estimated DBP (in blue) with the equality line (in red) for the equation II

The value of the Pearson's Correlation Coefficient calculated for the values of actual SBP and their corresponding estimated values calculated by using equation II is 0.92 whereas the corresponding Correlation Coefficient for DBP is 0.98.

Eqn	SBP			DBP		
	r	Mean	SD	r	Mean	SD
I	0.87	1.51	5.26	0.98	0.26	1.82
II	0.92	1.33	4.10	0.98	0.26	1.81
III	0.87	1.51	5.23	0.97	0.22	2.39
IV	0.90	1.79	4.62	0.97	0.42	2.15
V	0.88	1.72	5.04	0.97	0.39	2.27

Table 4.2 Comparison of Correlation Coefficient, Mean of Error and SD of Error for different equations used

Finally, table 4.2 shows the results for all the different equation used in the regression analysis. The first column is the type of equation used which is shown in table 4.1. 'r' refers to the Pearson's Correlation Coefficient. The average of the difference between estimated blood pressure and actual blood pressure is shown in the 'Mean' column. The standard deviation of the difference between estimated blood pressure and actual blood pressure is shown in the 'SD' column. For SBP estimation, the exponential equation provide the best results, with highest *r* and lowest Mean and SD respectively. For DBP estimation, both the linear and exponential equations have the best correlation coefficient values, but the non-linear regression analysis in which the blood pressure varies as the reciprocal of the square of the PTT has the lowest error mean value.

V. CONCLUSION

PTT was calculated from the ECG and PPG signals and compared with the calculated values of Blood Pressure. Using Regression analysis, the data points of the blood pressure were fitted to a various combination of equations involving Pulse Transit Time values and Photoplethysmogram values resulting in either linear or non-linear curves depending on the equation used. The Systolic Blood Pressure and Diastolic Blood Pressure was found to increase with decrease in Pulse Transit Time as expected. From all the equations used, equation II i.e. exponential relationship between SBP and PTT had the lowest mean error value. For DBP, equation III, i.e. an inverse relationship between DBP and PTT^2 had the lowest mean error value. However, for DBP and for SBP the equation involving PIR did show promising results even though the mean error was higher than compared to equations that used PTT. However, since calculation of PIR requires only the PPG signal whereas the PTT requires both the ECG and the PPG signal, the loss in accuracy makes up for the advantage gained in reduction of complexity. This shows promising scope for future research in estimation of Blood Pressure completely based on PPG signals or similar signals which can easily be determined as compared as other signals like ECG.

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