Regression Based Comparative Study for Continuous BP Measurement Using Pulse Transit Time

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Abstract

Context: Blood Pressure (BP) measurement becomes a vital parameter now days due to the continuous increase in chronic heart diseases worldwide. Existing devices for BP measurement are less portable and also does not support continuous BP measurement. Many studies have been done on non-invasive BP measurement using electrocardiography (ECG) and photoplethysmograph (PPG) waveforms. These methods also clarify accurate results.**Calculation of PTT and BP:**This study relates BP measured using two PPGs with the existing methods which uses the ECG signals. The cuff and ECG signal can be replaced by PPG sensors as the results acquired using PPG signals gives high accuracy.Basic terms can be defined to relate BP followed by detection of P-base point and ends with the estimation for BP calculations.**Proposed Methodology:** The algorithm for the proposed technology can be defined and the work shows how the use of wavelet de-noised PPGs can replace the existing ECG based techniques to decrease the complexity of overall devices and also increases the precision level.**Results and Discussion:** Analysis of all the type of combinations can show the results that minimum error and maximum accuracy can be found when BP is estimated. **Conclusion:** PTT based on two PPG's are best among all other methods including the utilization of second order non-linear regression technique.

Key words: *wavelet de-noising, non-invasive, photoplethysmograph, electrocardiogram, chronic heart diseases.*

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I. INTRODUCTION

The most widely used parameter for the clinical assessment of the patients is Blood pressure (BP). The pressure applied by the blood on the arterial walls is the pressure of the blood pumped from the heart. The blood pressure is a continuously varying quantity and in a complete one cycle it, ranges from a minimum value called as the Diastolic Blood Pressure (DBP) to a maximum called as Systolic Blood Pressure (SBP). At the beginning of the cardiac cycle the maximum pressure exerted by the blood on the arterial walls is called as Systolic Blood Pressure (SBP). This phase of heart is also called as heart systole. During the relaxing state of heart, blood exerts a minimum pressure called as Diastolic Blood Pressure. This phase of heart is also called as heart diastole [1]. The typical value of SBP over DBP of the blood pressure of a healthy person is 120/80 mmHg [2].

The major reason for most of the coronary cardiac diseases is the raised pressure value of blood. This raise value of pressure of blood is called as Hypertension or High Blood Pressure[3]. In this condition the blood flows at a rate higher than the normal rate inside the blood vessels (arteries). This situation may lead to a condition of heart stroke which ultimately leads to aneurysm of the arteries, chronic kidney diseases and peripheral arterial diseases [4]. Also, a situation of Low BP is also quite important for consideration as it may lead to the ailments like dehydration, severe bleeding and endocrine or nerve disorders. This condition of low BP is also called as Hypotensionand is equally threatening [5]. Hence BP estimation has become an important diagnostic parameter. Previously, catheter introduced in the artery to diagnose continuous blood pressure. This technique is quite accurate but it is an invasive technique hence may lead to huge pain, infection and high supervision under trained staff. Thereafter many non-invasive techniques have been developed for the continuous blood pressure measurement including oscillometric, Riva-Rocci's, tonometry and ultrasound etc.[6]-[10]. Still, there are a lot of disadvantages associated with these techniques including the use of cuff to the patient's arm and discontinuous BP measurement.Hence Pulse Transit Time based technique is the most convenient and continuous technique now days[11]-[15]. PTT is defined as the time lapse between the blood flowing from one arterial site to the another in one cardiac cycle [16]. It can also be defined by calculating the time of blood flowing from the heart to the peripheral site like ear lobe or finger [17]. This method is associated with the advantage that it is continuous and non-invasive technique which requires the recording of Electrocardiogram (ECG) and PPG signal.

PPG sensors are optical sensors and are associated with the motion artefact. These artefacts cause corruption in the PPG and ECG signals. The most widely used method for these artefacts removal is the Wavelet Transform. For AWGN

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removal of the PPG signals, wavelet de-noising can be implemented [18].

II. CALCULATION OF PULSE TRANSIT TIME (PTT) AND BLOOD PRESSURE ESTIMATION

Pulse transit time is the time required by the pulse wave to travel from on arterial site to the other or the time required to reach an arterial site from the heart. Hence it can be easily derived from the ECG PPG combination or two PPG signal combinations. The PTT Principle is shown in Fig1.

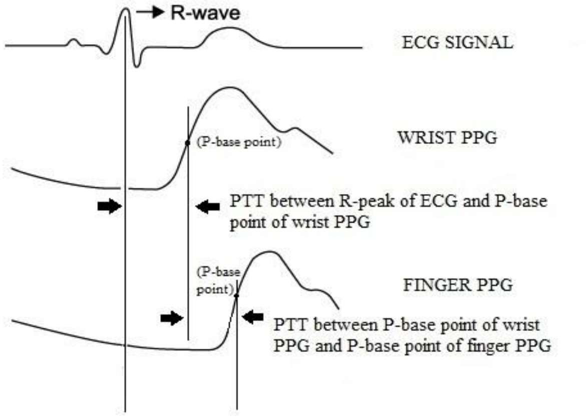

Figure 1: Pulse Transit Time estimation [19]

The virtual base point also known as P-base point is the 50% of maximum slope point. During the systolic rise of the pulse, it is defined as the mid-point of maximum slope point and absolute minimum point [20]. Fig 2 shows the P-base point calculations.The P-base point also known as virtual base point (50% of maximum slope point) is the midpoint of absolute minimum point and the maximum slope point of the pulse during systolic rise [20] (see Fig.2).

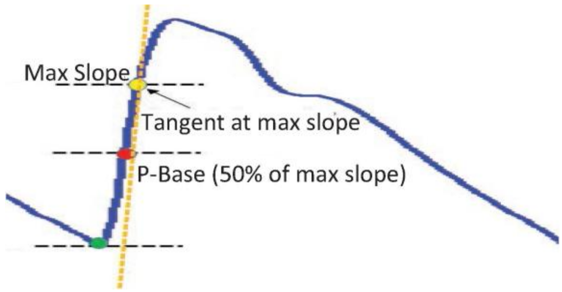

Figure 2: P-base or virtual base point[21]

Different work has been done to estimate the best position on PPG waveform for PTT calculations and the advantage of a better noise artefact robustness could be availed using a P-base point [21]. A signal can interfere from a wide range of noise sources. PPG sensors are most prone to the motion artefacts which occur because of the movement of patients. These artefacts are very difficult to remove from the PPG waveform. De-noising of PPG can be done by using various wavelets. In this work, theHaar wavelet is used to remove the AWGN noise from the ECG and mainly from the PPG signals [9].Beside one dimensional signal, there is two dimensional signals scan also which can be used to diagnose many ailments[22,31].

A. P- base point calculation

The noisy PPG waveform can be filtered out by using a wavelet transform. To detect the minimum points of the PPG pulse, local minima principle is used. Differentiation of filtered PPG is done and then to find the local maxima points. The P-base point is the mid-point of maximum slope point and local minima. This characteristic of the PPG signal is utilized as it gives maximum accuracy in the estimation of Blood Pressure.

B. Blood Pressure estimation

There is an inverse relation of BP with that of PTT because as BP increases the Pulse Transit Time decreases and vice versa [32]. Heart Rate (HR) is defined as the number of R-pulses in one minute. The Blood Pressure has a direct relationship with that of Heart rate. Hence as Blood Pressure of the body increases the Heart Rate also increases. As BP has relations with the PTT and HR, hence linear or non-linear regression equations can be derived from PTT and HR to get the estimated BP. A linear regression equation showing the relation between HR and PTT is shown below

$$BP = A * PTT + B * HR + C \qquad (1)$$

Linear curve fitting can be done to get the variables A,B and C using MATLAB to estimate the blood pressure from the collected data

III. PROPOSED METHODOLOGY

In one cardiac cycle when blood flows from one arterial site to other, then the time elapsed to reach the blood is called as Pulse Transit Time. Manykind of researches have been done on continuous BP measurement techniques using ECG and PPG signals. Even though these techniques gives precise results in many studies but still consist of few limitations when we involve ECG signal in the measurements. A number of electrodes are used when ECG signals are introduced in PPG measurements. This leads to increased complexity of the system. Also, great synchronization is required when we use such bio-signals.

The technique proposed a comparative study of BP measurement using two PPG signals and ECG and PPG signal with the help of linear and non-linear regression techniques. Two PPG signal technique with non-linear regression leads to the maximum accuracy in the measurement of estimated BP when compared with all other techniques.

This work includes the estimation of BP using linear and non-linear regression by calculating:

- PTT between R-peak of ECG and P-base point of PPG wrist.
- PTT between R-peak of ECG and P-base point of PPG finger.
- PTT between P-base point of wrist PPG and P-base point of finger PPG.

Algorithm for the calculation of pulse transit time measurement works as follows:

- Initially, de-noise the noised PPG signals using wavelets (Haar wavelet used in this work).
- Detect the peaks of ECG signal and store them in an array.
- Store the respective P-base points of wrist and finger PPGs in different arrays.
- Find the difference between the various peak points and respective wrist P-base points which gives the pulse transit time and take the average of all the PTTs in one frame. This will give the pulse transit time of ECG and wrist PPG signal.
- Repeat the above steps for ECG and finger PPG and also for wrist and finger PPGs.

IV. RESULTS AND DISCUSSION

On the collected databases, linear and non-linear curve fitting techniques are applied using the Matrix Laboratory version [R2013a (8.1.0.604)]. Pulse transit time (PTT) and Heart Rate (HR) are used as inputs for the fitting tool to get the desired curve for Systolic BP (BP_{sys}) and Diastolic BP (BP_{dia}). Linear and non-linear equations are developed to estimate the Blood Pressure and this calculated BP is compared with standard biomedical device OMRON M2. Mr Niranjan Kumar author of the paper “Cuffless BP Measurement using a Correlation Study of Pulse Transient Time and Heart Rate” provided the Databases for this work[33]. 9 subjects of age group 18-23 years were used for the collection of data.

1. BP measurement using ECG and wrist PPG

The equation (1) formulated for BP with inputs HR and PTT using linear curve is given below:

$$BP_{sys,l}=52.78+(0.6516)*HR+(186.6)*PTT \quad (2)$$
$$BP_{dia,l}=76.93+(-0.01982)*HR+(62.57)*PTT \quad (3)$$

The equation (1) formulated for BP with inputs HR and PTT using non-linear curve is given below:

$$BP_{sys,nl}=923.2+(9.404)*HR+(5333)*PTT+(0.0326)*HR^2+27.16*PTT*HR+9837*PTT^2 \quad (4)$$

$$BP_{dia,nl}=353.1+(3.745)*HR+(1441)*PTT+(0.0146)*HR^2+7.335*PTT*HR+2751*PTT^2 \quad (5)$$

The estimated equations of BP are shown in equation (2), (3), (4), (5). Estimated results are compared with the BP measurements taken using cuff based monitor which gives a maximum deviation of 11% for 1st order linear equations and 10% for 2nd order non-linear equations as shown in Table 1 and Table 2 and.

Analysis of data measured from ECG and wrist PPG

The readings taken from PPG sensors increases with the increase in the distance of the sensor from the heart. Also readings are more accurate at the peripheries of the body. Hence the data contains maximum error when wrist PPG is taken as compared to the next two techniques. Hence error comes out here is maximum as compared to the next two techniques, and that is 11% error deviation from the standard value of blood pressure.

2. BP measurement using ECG and finger PPG

The equation (1) for BP estimation with inputs HR and finger PPG using linear curve fitting can be formulated as:

$$BP_{sys,l}=(-92.24)+(1.232)*HR+(583.1)*PTT \quad (6)$$
$$BP_{dia,l}=75.68+(-0.02306)*HR+(52.62)*PTT \quad (7)$$

The equation (1) for BP estimation with inputs HR and finger PPG using non-linear curve fitting can be formulated as:

$$BP_{sys,nl}=5119+(55.46)*HR+(26450)*PTT+0.1518*HR^2+147.9*PTT*HR+34910*PTT^2 \quad (8)$$

$$BP_{dia,nl}=3970+(41.21)*HR+(20510)*PTT+0.1076*HR^2+109.2*PTT*HR+27040*PTT^2 \quad (9)$$

The estimated equations of BP are shown in equation (6), (7), (8), and (9). Estimated results are compared with the BP measurements taken using cuff which gives a maximum deviation of 9% with linear and 8% with non-linear regression equations shown in Table 1 and Table 2.

Analysis of readings taken from ECG and finger PPG

Since PPG taken from finger is a periphery PPG hence it will give better results as compared to the PPG taken from wrist. Results also show the same with elaborated readings and reduced errors when taken from finger. These are reduced to a value of 9% of maximum error deviation from the standard Blood Pressure.

3. BP measurement using PPG wrist and PPG finger

Using wrist PPG and finger PPG for BP estimation the equation (1) can be formulated again in a similar manner by using linear curve fitting. Formulated equations for SBP and DBP are shown below:

$$BP_{sys,l}=(106.8)+0.4113*HR+(-78.17)*PTT \quad (10)$$

$$BP_{dia,nl}=98.23+(-0.1079)*HR+(69.87)*PTT \quad (11)$$

Using wrist PPG and finger PPG for BP estimation the equation (1) can be formulated again in the similar manner by using non-linear curve fitting. Formulated equations for SBP and DBP are shown below:

$$BP_{sys,nl}=400.7+(3.084)*HR+(5203)*PTT+0.0141*HR^2+15.37*PTT*HR+31940*PTT^2 \quad (12)$$

$$BP_{dia,nl}=222.7+(2.119)*HR+(1445)*PTT+0.00964*HR^2+4.856*PTT*HR+7946*PTT^2 \quad (13)$$

Estimated SBP and DBP calculated using equation (10), (11), (12) and (13). Maximum error deviation in this method is decreased to 3% with 2nd order non-linear equation when compared to the BP measurements taken from the standard biomedical device. 2nd order fitting curves are shown in Fig. 3, 4, 5 and 6.

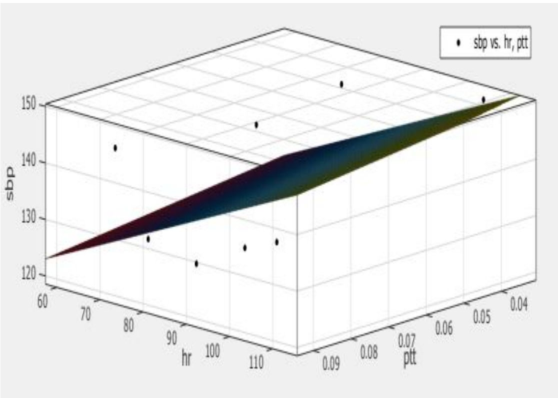

Figure 3: 1st order linear SBP regression curve when PTT is taken between PPG wrist and finger PPG

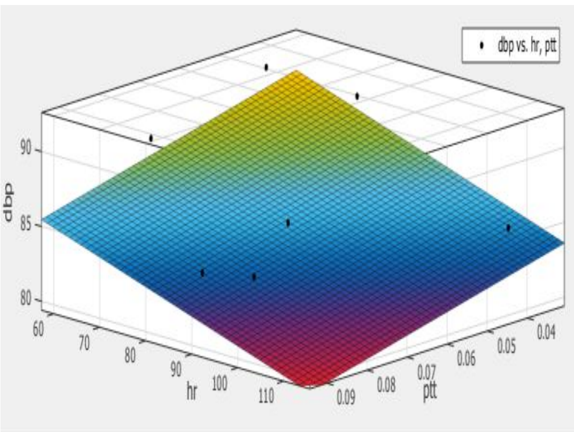

Figure 4: 1st order linear DBP regression curve when PTT is taken between PPG wrist and finger PPG

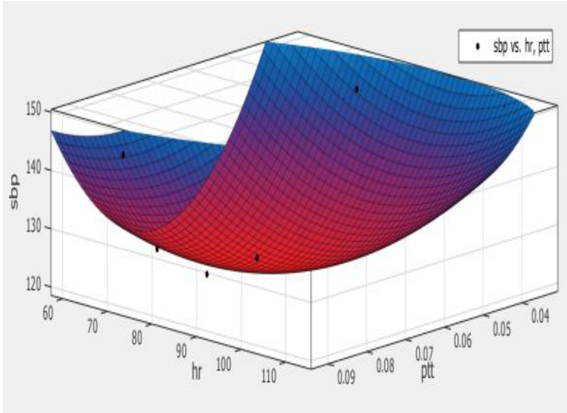

Figure 5: 2nd order non-linear SBP regression curve when PTT is taken between PPG wrist and finger PPG

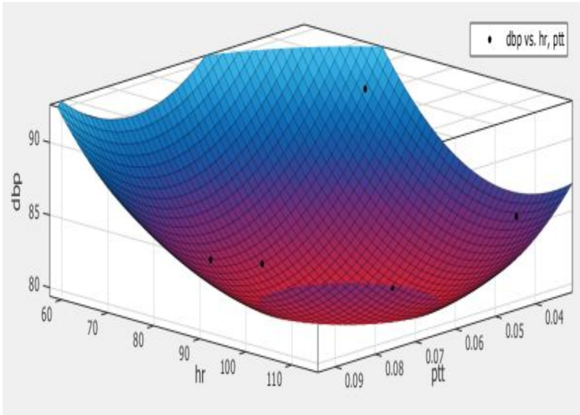

Figure 6: 2nd order non-linear DBP regression curve when PTT is taken between PPG wrist and finger PPG

Analysis of the measurements taken from wrist and finger PPG

When two PPGs are taken it reduces the errors due to non-synchronized ECG and PPG sensors and also due to the PEP (pre ejection period) of the ECG waveform. Hence the technique so implemented reduces the maximum error deviation up to 3%. This technique also eliminates the use

Table 1 Comparison among errors from the three techniques using 1st order linear regression.

BP measurements taken from standard device			PTT between ECG and wrist PPG		PTT between ECG and finger PPG		PTT between wrist PPG and finger PPG	
Subject	**SBP**	**DBP**	**Error % in SBPl**	**Error % in DBPl**	**Error % in SBPl**	**Error % in DBPl**	**Error % in SBPl**	**Error % in DBPl**
S1	145	90	2.6057	1.1784	0.5906	3.1783	7.0258	2.3609
S2	145	87	**11.6822**	2.0695	4.8713	0.1053	**9.8334**	3.0619
S3	120	81	-6.0730	-4.9826	-6.5066	-5.6270	-7.0778	-5.1001
S4	149	84	-0.6887	-0.3012	2.0186	1.1420	0.8246	-0.4836
S5	121	80	-8.0298	-6.9786	-8.8197	-6.8583	-7.5149	-6.7576
S6	149	83	2.5368	2.1767	0.6137	0.8711	0.9384	2.2122
S7	122	89	-1.3229	2.7143	-0.5303	2.1408	-2.6886	2.3205
S8	123	84	-6.2181	-0.8217	-2.3418	-0.8845	-7.9128	-1.8275
S9	138	92	5.5370	4.9051	**9.9530**	5.9480	5.6758	4.2126

of complex ECG sensors and replaces them with simple optical sensors.

Description showing comparison of the derived technique with the previous methods

Table 1 and Table 2 shows change in percentage of error in SBP and DBP. The error % reduced from 11% to 3% as we moved from first technique to third using 2nd order non-linear equations. Also 2nd order non-linear equations give more accuracy as compared to 1st order linear equations because as the degree on polynomial increases the probability of error reduces. This ultimately shows the effectiveness of the new technique implemented which is more reliable in terms of hardware and also in terms of accuracy. Reduced hardware complexity and reduced error in the estimation gives a better option for the medical staff to implement this technique instead of the previous ones.

Table 2 Comparison among errors from the three techniques using 2nd order non-linear regression.

BP measurements taken from standard device			PTT between ECG and wrist PPG		PTT between ECG and finger PPG		PTT between wrist PPG and finger PPG	
Subject	**SBP**	**DBP**	**Error % in SBPnl**	**Error % in DBPnl**	**Error % in SBPnl**	**Error % in DBPnl**	**Error % in SBPnl**	**Error % in DBPnl**
S1	145	90	-1.0037	-0.3834	-3.2396	-4.3623	-1.6286	-0.7043
S2	145	87	**10.3219**	2.4328	7.4996	-4.7574	0.6854	0.3462

S3	120	81	-4.7929	-3.6059	-3.4148	-5.4815	-1.0600	-1.9335
S4	149	84	1.1396	0.54273	1.4251	-8.9436	0.3082	-0.1615
S5	121	80	-3.2172	-3.9772	-4.7127	**-8.0735**	-0.1411	-2.9240
S6	149	83	-0.3932	-0.5260	-1.7214	-11.7458	-0.2259	-0.2136
S7	122	89	-5.7993	-1.5682	-4.6692	-12.0693	-0.9248	0.5919
S8	123	84	-2.9831	2.7563	-0.6950	-5.0838	1.0299	**3.5775**
S9	138	92	7.2621	4.1826	6.4515	-5.2829	2.0441	0.7581

V. CONCLUSION AND FUTURE SCOPE

The current work estimated the BP using three bio-signals acquired from three different body parts (heart, finger and wrist). Results are shown in table 1 and 2 which shows a direct relation of BP with heart rate (HR) and inverse relation with the PTT. 1st order and 2nd order curve fitting techniques are used to estimate the linear and non-linear regression equations. It mainly draws the following two conclusions:

- Higher order regression equation leads a better result when compared with the linear regression equation
- The PTT taken from the peripheries instead of including ECG signal also results in the more precise result as the errors due to PEP (Pre-Ejection Period) are eliminated.

The results do not include the typical sphygmomanometer and are quite accurate that these can be included in the current investigation procedures of BP. Also this procedure does not include ECG sensors on the body.

Being in the initial stage of research, the work has been done on a small sample of data. 1st and 2nd order fitting technique is used to get the estimated equations. Same technique can be implemented on large number of samples to increase the precision level. Different inputs like BCG (Ballistocardiogram) can be used to increase the variables to increase the accuracy further.

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