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Research Article

# FAST AND ACCURATE METHOD FOR CONTINUOUS BP MEASUREMENT

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**Abstract**

Blood Pressure (BP) measurement becomes a vital parameter now days due to 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. 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. The work shows how the use of wavelet de-noised PPGs can replaces the existing ECG based techniques to decrease the complexity of overall devices and also increases precision level.

**Keywords**: Wavelet de-noised; Non-invasive; Photoplethysmograph; Electrocardiography; Chronic heart diseases.

## I. Introduction

Blood Pressure (BP) is a widely measured physiological parameter which indicates the status of cardiovascular health in human beings. The BP is defined as the pressure exerted by the blood on the walls of the blood vessels (arteries). BP varies from a minimum called Diastolic Blood Pressure (DBP) to a maximum called Systolic Blood Pressure (SBP) in a complete cardiac cycle. Systolic Blood Pressure is the maximum pressure exerted on the walls of the arteries during the pumping phase of heart or systole. It occurs at the onset of the cardiac cycle. Diastolic Blood Pressure (DBP) is the minimum pressure exerted by the blood on the walls during the relax phase of heart or diastole [1]. The typical value of SBP over DBP for a healthy person is measured as 120/80 mmHg [2].

The main cause of most of the heart diseases and coronary artery diseases is High Blood Pressure. High Blood Pressure commonly called Hypertension is a disease in which blood flows through the blood vessels (arteries) at a rate higher than the normal rate. It is a common factor for diseases like heart stroke which leads to death in most of the cases worldwide, aneurysms of the arteries, peripheral arterial diseases and chronic kidney diseases [3]. In the meanwhile, Low BP, known as Hypotension, is also threatening as it shows few ailments like nerve or endocrine disorders, severe bleeding and dehydration [4]. Hence Blood Pressure measurement has become a vital parameter for the diagnosis of such diseases. Introduction of catheter into the blood vessel to measure the Blood Pressure is an accurate, continuous and invasive technique. But still it leads to many side effects including pain and contamination into the patient's blood vessel. Numerous non-invasive methods including Riva-Rocci's, oscillometric, ultrasound and tonometry method, etc. were developed for the measurement of BP solving the above problems [5]-[6], but still there is inconvenience in attaching the cuff to the patient's arm for indirect BP measurement and also the main limitation is in measuring BP continuously. Hence the most useful and convenient non-invasive parameter used recently is Pulse transient time (PTT).

PTT is defined as the time taken by the blood or pulse wave to travel between any two consecutive arterial sites with in the same cardiac cycle [7]. PTT is also obtained by using ECG and finger photoplethysmograph (PPG) by calculating the time lag between R peak of the ECG and the arrival of pulse wave in periphery (finger) [8]. This is a continuous and non-invasive method in which simultaneous recording of electrocardiogram (ECG) and photoplethysmograph (PPG) is required. Photoplethysmograph (PPG) sensors are optical sensors available for the measurement of blood volumetric changes occurs in various parts of the body. PPG signal comprises a huge knowledge of the cardio-pulmonary system. Motion artifact is the major problem associated with this signal, which causes corruption in actual PPG signal. Wavelet transform is most widely used in signal processing applications. A wavelet de-noising method can be used for the removal of AWGN from the PPG signals [9].

Invasive methods were previously used for continuous measurement of BP which includes the insertion of catheter into the blood vessel [10]. These But due to a major disadvantage of pain and infection various non-invasive techniques have been developed. In 1876, oscillometric method was demonstrated which is based on recording of the oscillations present on the BP monitoring cuff [11]. The Korotkoff method [12] which used sphygmomanometer, mercury and a cuff is still broadly used today. But measurements from this method should be done under the supervision of a trained staff. Mercury sphygmomanometer is another device used for BP measurement and these devices are so accurate that these are extensively used nowadays [13]. Still use of cuff leads to discomfort for the patients and also it does not provide continuous readings of BP. Dependencies are present between blood pressure and pulse arrival time and pulse wave amplitude [14]. BP can be estimated using time interval between R-peak of ECG waveform and characteristic point of the PPG signal [15]-[16]. The velocity of blood with which it flows between the arteries also called pulse wave velocity is directly proportional to the BP [17]. Pulse wave velocity can be measured by measuring PTT which is the time interval between any two different points of arteries with in the same cardiac cycle [18]. PPG signal contains rich source of information related to cardio-pulmonary system. Motion artifacts of PPG signal can be reduced using various wavelet de-noising techniques [19].

This paper is arranged in five sections. Section I starts with the introduction and a brief literature review. Section II starts with the basic terms related to BP followed by detection of P-base point and ends with the estimation equation for BP calculation. Section III frames the proposed methodology with algorithm implemented in the work. Section IV is results and discussion section followed by section V which concludes the accuracy of proposed method and discussed the points for future work.

**II. Calculation of pulse transit time (ptt) and blood pressure estimation**

Pulse transit time or PTT is the time required by the pulse wave to leave the heart and reach the PPG measurement site or from one PPG measurement site to another. Pulse transit time can be derived from ECG and PPG signal or it can be derived from two PPG signals. The principle of PTT is shown in Fig.1.

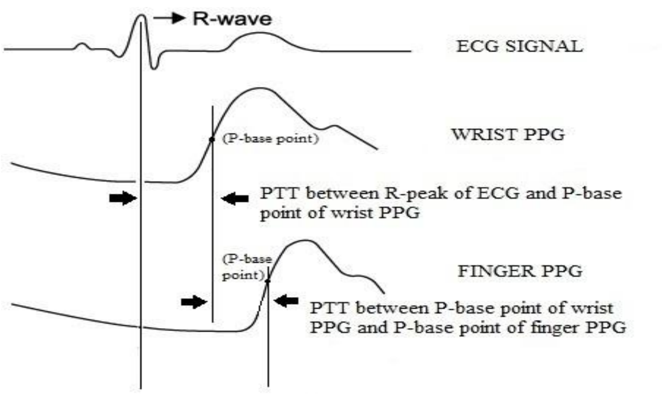


**Fig.1. Principle of pulse transit time measurement.**

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).

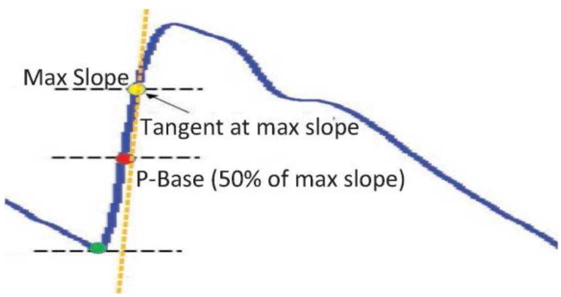


**Fig.2. P-base point or virtual base point.**

The main advantage of using P-base point is that it provides a better noise and artifact robustness [21]. Wide range of noise source is present which interferes with the PPG signal. Among all the sources present, motion artifact caused due to continuous movement of patient whose PPG is measured is very difficult to remove. Various mother wavelets can be used for de-noising of PPG signal. Haar wavelet is used in our work to remove AWGN from the noisy PPG signal [9].

**A. PPG P-base point detection**

Block diagram of steps included in calculation of P-base point is shown in Fig.3. Noisy PPG signal is filtered using wavelet transform. Local minima principle is used simply to find the minimum points of pulse signal. The filtered PPG is differentiated and local maxima obtained from the differentiated signal gives the maximum slope points. Mid-point of maximum slope point and local minima point is the P-base point which is the characteristic point of PPG signal used for the measurement of pulse transit time.

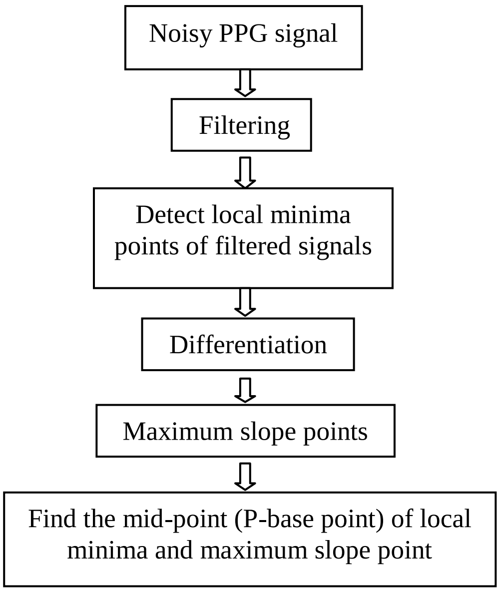


**Fig.3. P-base point calculation.**

**B. Blood pressure estimation**

BP is having an inverse relationship with PTT, as BP decreases with the increase in PTT and vice-versa [a]. Heart rate (HR) is simply the number of R-peaks in 1 minute. Also BP has a direct relationship with HR. With heart rate (HR) and pulse transit time (PTT) as inputs, a linear regression equation can be derived as given below:

$$BP = a*PTT + b*HR + c \qquad (1)$$

Non-linear curve fitting is done to calculate variables a, b and c using MATLAB to estimate the blood pressures of the collected data.

**III. Proposed Methodology**

Pulse transit time is the time taken by the blood when it travels between the two successive blood arterial sites within the same cardiac cycle. Previously, many researchers estimated BP using continuous recording of ECG and PPG signals. Even though this method formulated accurate results in many studies, there are still some limitations using ECG signals. Recording of ECG uses a number of electrodes and components which ultimately leads to the increased complexity of the system. Also synchronization of ECG and PPG signal is required correctly [22].

The proposed technique implemented a comparative study of BP measurement using ECG and PPG signals and two PPG signals. The use of two PPG signals for BP measurement leads to the reduction in error as compared to the former methods.

This work includes the estimation of BP 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**

Non-linear $2^{nd}$ order curve fitting technique is applied using MATLAB [R2013a (8.1.0.604)] on the databases collected. Input variables used for the curve are HR and PTT to get the $BP_{sys}$ (systolic blood pressure) and $BP_{dia}$ (diastolic blood pressure).

The estimated BP is then compared with the BP measurement taken from the standard biomedical instrument OMRON M2. The databases used in this work are provided by Mr. Niranjan Kumar author of the paper "Cuffless BP Measurement using a Correlation Study of Pulse Transient Time and Heart Rate" [23]. The Data collection was done on 8 Subjects in the age group of 18-23 years. Standard biomedical instrument OMRON M2 is used for BP measurement.

**C. BP measurement using ECG and wrist PPG:**

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

$$BP_{sys} = 929.5+(-9.456)*HR+(-5381)*PTT+0.03275*HR^2 + 27.4 *PTT*HR+9917*PTT^2 \quad (2)$$

$$BP_{dia}=348.6+(3.698)*HR+(1411)*PTT+0.01454*HR^2+7.182* PTT*HR+2702*PTT^2 \quad (3)$$

**Table I. Estimated BP using ECG and wrist PPG**

| **Subject** | **SBP** | **DBP** | **PTT** | **Estimated sbp** | **Estimated dbp** |
|---|---|---|---|---|---|
| S1 | 145 | 90 | 0.2150 | 146.5273 | 90.3696 |
| S2 | 145 | 87 | 0.1530 | 129.7170 | 84.7243 |
| S3 | 120 | 81 | 0.1608 | 127.1926 | 84.3094 |
| S4 | 149 | 84 | 0.1510 | 147.2939 | 84.4858 |
| S5 | 121 | 80 | 0.1748 | 125.7872 | 83.6918 |
| S6 | 149 | 83 | 0.1008 | 149.6120 | 83.4184 |
| S7 | 122 | 89 | 0.1720 | 130.6605 | 90.4262 |
| S8 | 123 | 84 | 0.1501 | 127.4000 | 81.4350 |
| S9 | 138 | 92 | 0.1890 | 127.1266 | 88.1965 |

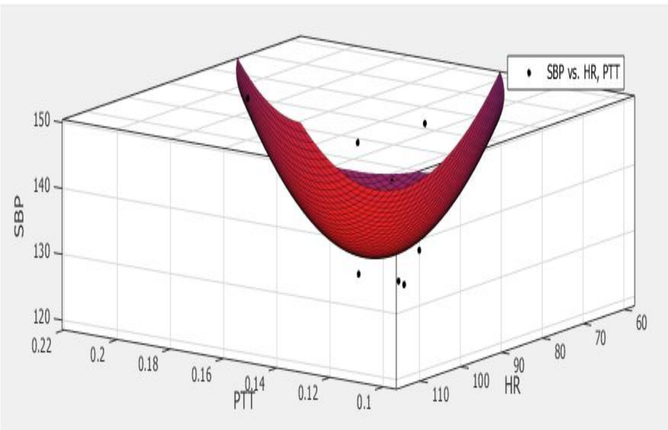


Fig.4.1. 2nd order non-linear SBP regression curve when PTT is taken between ECG and wrist PPG

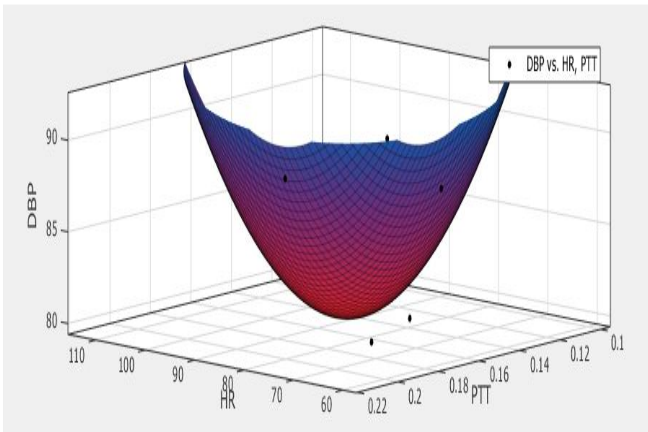


Fig.4.2. 2nd order non-linear DBP regression curve when PTT is taken between ECG and wrist PPG

Table I shows the estimated values of BP using equation (2) and (3). Estimated results are compared with the BP measurements taken using cuff based monitor which gives a maximum deviation of 10% shown in Table IV. Also the 2nd order non-linear regression curves for SBP and DBP are shown in Fig. 4.1 and Fig. 4.2.

***D. BP measurement using ECG and finger PPG:***

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

$$BP_{sys}=5119+(-55.46)*HR+(-0.0002645)*PTT+0.1518*HR^2+147.9*PTT*HR+0.0003491*PTT^2 \quad (4)$$

$$BP_{dia}=3970+(-41.21)*HR+(-0.0002051)*PTT+0.1076*HR^2+109.2*PTT*HR+0.0002704*PTT^2 \quad (5)$$

**Table II. Estimated BP using ECG and finger PPG**

| Subject | SBP | DBP | PTT | Estimated sbp | Estimated dbp |
|---|---|---|---|---|---|
| S1 | 145 | 90 | 0.2490 | 149.8271 | 91.3138 |
| S2 | 145 | 87 | 0.2444 | 133.8255 | 83.8757 |
| S3 | 120 | 81 | 0.2306 | 125.0881 | 82.6723 |
| S4 | 149 | 84 | 0.1846 | 146.8765 | 82.8159 |
| S5 | 121 | 80 | 0.2340 | 128.0220 | 81.6870 |
| S6 | 149 | 83 | 0.1734 | 151.5649 | 83.4939 |
| S7 | 122 | 89 | 0.2420 | 128.9572 | 90.4946 |
| S8 | 123 | 84 | 0.2082 | 124.0356 | 83.9687 |
| S9 | 138 | 92 | 0.2342 | 128.3873 | 89.7588 |

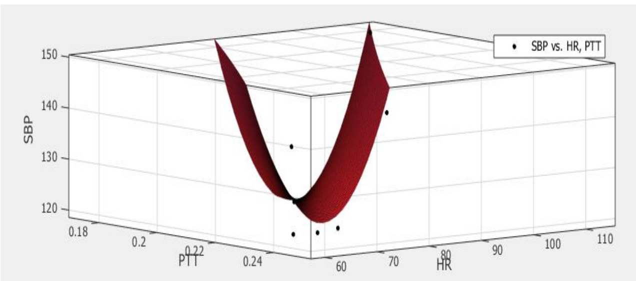


Fig.5.1. 2nd order non-linear SBP regression curve when PTT is taken between ECG and finger PPG

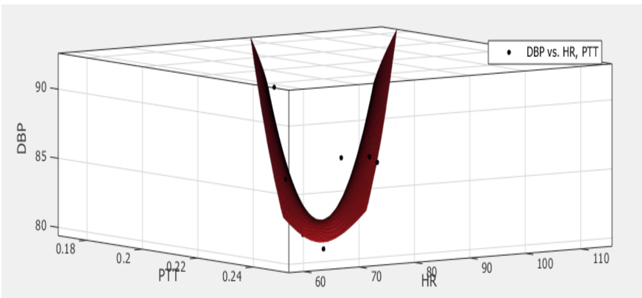


Fig.5.2. 2nd order non-linear DBP regression curve when PTT is taken between ECG and finger PPG

Table II shows the estimation of BP using equation (4) and (5). Estimated results are compared with the BP measurements taken using cuff which gives a maximum deviation of 7% shown in Table IV. The 2nd order non-linear regression curves for SBP and DBP are shown in Fig. 5.1 and 5.2.

**E. 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 the similar manner by using non-linear curve fitting. Formulated equations for SBP and DBP are shown below:

$$BP_{sys}=400.7+(-3.084)*HR+(-5203)*PTT+0.01413*HR^2+15.37*PTT*HR+0.0003194*PTT^2 \quad (6)$$

$$BP_{dia}=222.7+(-2.119)*HR+(-1445)*PTT+0.009643*HR^2+4.856*PTT*HR+7946*PTT^2 \quad (7)$$

**Table III. Estimated BP using ECG and finger PPG**

| Subject | SBP | DBP | PTT | Estimated sbp | Estimated dbp |
|---|---|---|---|---|---|
| S1 | 145 | 90 | 0.0346 | 147.4267 | 90.6480 |
| S2 | 145 | 87 | 0.0914 | 143.9787 | 86.6815 |
| S3 | 120 | 81 | 0.0698 | 121.5795 | 82.7790 |
| S4 | 149 | 84 | 0.0336 | 148.5407 | 84.1486 |
| S5 | 121 | 80 | 0.0592 | 121.2104 | 82.6901 |
| S6 | 149 | 83 | 0.0726 | 149.3367 | 83.1966 |
| S7 | 122 | 89 | 0.0700 | 123.3780 | 88.4554 |
| S8 | 123 | 84 | 0.0576 | 121.4654 | 80.7086 |
| S9 | 138 | 92 | 0.0458 | 134.9542 | 91.3025 |

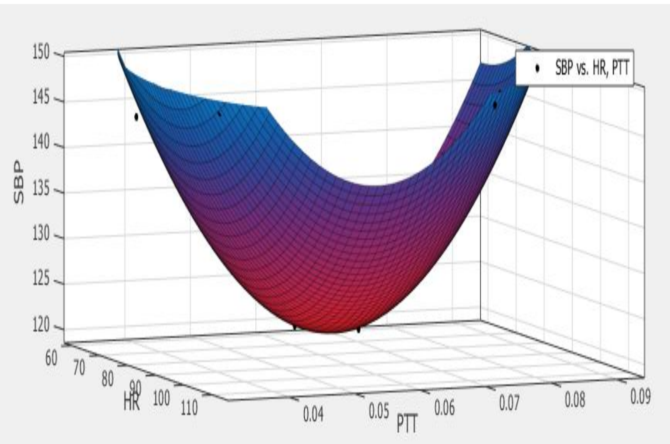


Fig.6.1. 2nd order non-linear SBP regression curve when PTT is taken between PPG wrist and finger PPG

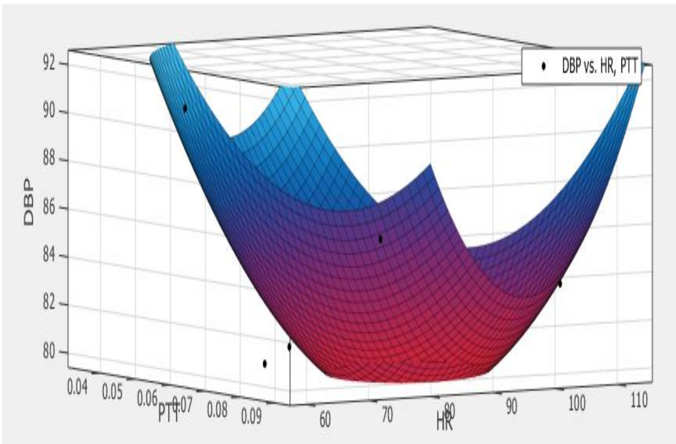


Fig.6.2. 2nd order non-linear DBP regression curve when PTT is taken between wrist PPG and finger PPG

Estimated SBP and DBP calculated using equation (6) and (7) are shown in Table III. Maximum error deviation in this method is decreased to 3% when compared to the BP measurements taken from the standard biomedical device. $2^{nd}$ order fitting curves are shown in Fig. 6.1 and 6.2

**Table IV Comparison among errors from the three techniques**

| | BP measurements taken from standard device | | PTT between ECG and wrist PPG is taken | | PTT between ECG and finger PPG is taken | | PTT between wrist PPG and finger PPG is taken | |
|---|---|---|---|---|---|---|---|---|
| **Subject** | **SBP** | **DBP** | **Error % in SBP** | **Error % in DBP** | **Error % in SBP** | **Error % in DBP** | **Error % in SBP** | **Error % in DBP** |
| S1 | 145 | 90 | -1.0530 | -0.4107 | -3.3290 | -1.4598 | -1.6736 | -0.7200 |
| S2 | 145 | 87 | **10.5400** | 2.6157 | **7.7066** | 3.5911 | 0.7043 | 0.3661 |
| S3 | 120 | 81 | -5.9938 | -4.0857 | -4.2401 | -2.0646 | -1.3162 | -2.1963 |
| S4 | 149 | 84 | 1.1450 | 0.6121 | 1.4252 | 1.4096 | 0.3083 | -0.1769 |
| S5 | 121 | 80 | -3.9564 | -4.6148 | -5.8033 | -2.1087 | -0.1739 | -3.3626 |
| S6 | 149 | 83 | -0.4107 | -0.5041 | -1.7214 | -0.5951 | -0.2260 | -0.2369 |
| S7 | 122 | 89 | -7.0988 | -1.6025 | -5.7026 | -1.6793 | -1.1295 | 0.6119 |
| S8 | 123 | 84 | -3.5772 | 3.0536 | -0.8420 | 0.0373 | 1.2476 | **3.9183** |
| S9 | 138 | 92 | 7.8793 | 4.1342 | 6.9657 | 2.4361 | 2.2071 | 0.7582 |

Table IV shows change in percentage of error in SBP and DBP. The error % reduced from 10% to 3% as we moved from first technique to third.

I. Conclusions and future work

The current study investigated blood pressure (BP) using signals taken from three different positions of body, heart wrist and finger. Results (Table 1, 2 and 3) show an inverse relationship of BP with pulse transit time (PTT) and a direct relation of BP with heart rate (HR). A $2^{nd}$ order curve fitting helps to estimate the regression equation to a higher precision level. It was observed that when BP was calculated between electrocardiogram (ECG) and Finger photoplethysmograph (PPG) the errors were reduced. Further errors were reduced to a high extent when two PPGs are taken from different arterial sites of body.

The results obtained are quite accurate and do not include typical sphygmomanometer which gives the readings of BP at particular instant of time. This method gives a continuous reading of BP, and also the use of two PPGs does not require ECG sensors on the body. This method shows how the use of two PPGs is more reliable than the cuff based BP measurement method and also gives the most accurate results than other non-invasive techniques used in this study. Being in the early stage of research, the study has been done on small sample of data and $2^{nd}$ order fitting technique is used to get the estimated equations. Same methods can be used on a large number of samples which include all the variations of BP to increase the precision level. Also another technique can be implied to estimate the BP equations. Different other inputs can be taken like age and model can be implemented using neural networks.

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