Estimation of Non-invasive Cuff-less Blood Pressure Using the Photoplethysmogram Signal

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Research

Keywords: PhotoPlethysmoGram, Pulse Transit Time, Pulse Arrival Time, Blood pressure, Pulse Wave Delay

Posted Date: April 20th, 2020

DOI: <https://doi.org/10.21203/rs.3.rs-22297/v1>

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ESTIMATION OF NON-INVASIVE CUFF-LESS BLOOD PRESSURE USING THE PHOTOPLETHYSMOGRAM SIGNAL

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ABSTRACT

BACKGROUND: This article presents a novel technique relating to the advancement of non-invasive cuff less blood pressure measurement using the PhotoPlethysmoGram (PPG) signals. The morphological characteristics of PPG signal have a strong correlation with the cardiovascular parameters and blood flow. The exact distinguishing feature of the PhotoPlethysmoGram signals is such as height as well as width of the pulse has considered into count for the measurement of blood pressure. In comparison to the existing measurement system like inflatable cuff and electrocardiogram units, this system only requires a pulse plethysmogram unit. The traditional blood pressure unit has many disadvantages such as expert personal, depends on the ability of the person to detect the korotkoff sounds, provides discomfort to the user and is not suitable for long time measurements. Moreover, this is very perceptive to artifacts owing to the existence of cuff. The PAT, PTT of the existing non-invasive techniques need many number of factors for estimation of blood pressure and are highly complex.

RESULTS: This method has intended for estimating the cardiovascular parameter of a non-invasive cuff-less blood pressure by utilizing the method of linear regression from PhotoPlethysmoGraphy signal. The real data has obtained using the GUI LabVIEW and further mathematical modelling of the obtained signal has performed by analysis using MATLAB tools. The obtained results had revealed that this technique is simple, non-invasive, cost-effective and consistent for estimating the arterial pulse signal in connection to variation in the amplitude of the waves. The exact distinguished feature of the PhotoPlethysmoGraphy signals like height and width of the pulse, which had considered into the count up for the measurement of blood pressure. The results obtained have been cross validating during the existing blood pressure monitors.

CONCLUSIONS: The simulated output reveals the height of the pulse (systolic height) is inversely proportional to the systolic blood pressure as well as it rises for increasing cardiac output, however it occurs in less span of time. The pulse width and area is directly proportional to the systolic blood pressure. Our simulation result shows the specific relation between PPG and blood pressure. Error percentages as per the calculation among the extracted features have been less for inflection height ranging from ± 10 to a min of ± 2 .

Key words: PhotoPlethysmoGram, Pulse Transit Time, Pulse Arrival Time, Blood pressure, Pulse Wave Delay

Background

Blood pressure is a very important constraint in the estimation of functioning of cardiovascular. Its regular monitoring can be indicative of the early diagnosis and prevention of cardiovascular diseases [1]. It has generally accepted that the resistance in the cardiac output and peripheral vessels, which corresponds to the controlling of blood pressure through diastole and systole, correspondingly [2], significantly affects blood

pressure control. The current conventional method of blood pressure monitoring includes the direct approach and the indirect approach. The methods employ auscultation and oscillometry techniques. The auscultation method measures the systolic and diastolic blood pressure.

These methods usually suffer from signal distortion, complex measurement, requires expert personal and the subject stability causing significant discomfort to the users leading to the erroneous results. Moreover, in case of severe or critical treatments, the patients have to undergo numerous monitoring units at the intensive care leading to a burden to them. Thus, the importance of using a non-invasive cuff less is rapid and easy to use system is need of the hour.

PhotoPlethysmoGram (PPG) signals is a non-intrusive optical technology, which will detect the variation in the volume of vascular blood system. In the year 1938, Hertzman introduce the PhotoPlethysmoGram (PPG) signals that reflect the changes in the volume of the blood of the finger arterioles [1]. This has been recognizing as non-intrusive, consistent, cost-effective, and simple method for estimating the arterial pulse waves also with the variation in the amplitude of waves [2]. The PPG wave exhibit different morphology because of the variations in vascular capacity and blood volume and consist of numerous cardiovascular information. Many studies have shown the use of PPG for evaluating blood pressure estimation, heart rate, vascular ageing and cardiac output. The PPG wave is generally collected using a pulse oximeter. The PPG waveform consist of two peaks, first is the onset of the systolic wave, systolic peak followed by dicrotic notch and a diastolic peak. The exact distinguishing feature of the PhotoPlethysmoGram (PPG) wave such as height and width of pulse had considered into account to correlate with the blood pressure estimation. These variations in turn signify the cardiovascular changes and blood flow. This work proposes an efficient method for estimation of blood pressure based on linear regression in order to reduce the gap between the continuous monitoring systems. Further, the use of Neural Network logic leads to accurate and effective monitoring of blood pressure. Here we have utilized these features of PPG and estimated the blood pressure. The estimation had made by utilizing a mathematical tool like regression analysis in MATLAB and the real time data acquisition had done via LabVIEW. Based on this physiological establishment, variation in vessel status and blood pressure has estimated by observing the variation in the flow of blood.

LabVIEW based data acquisition with high-speed hardware platform has used to obtain the data [3]. A cuff-based method and PPG pulse sensor has utilized for regular computation of a systolic blood pressure and heart rate using the photoplethysmographic waveform calculated concurrently in fingers [4][5][7]. The combination of morphological features along with temporal variability aims to advance the accurateness of very important physiological characteristics [6]. The extraction from the combination of white noise and data has carried out using a pairs of ensemble IMFs with positive and negative white noises [8]. Motion and noise artifacts detection method has given a clean as well as degraded result on every PPG sections [9][10][21].

In the existing methods, it has found that the measuring device for blood depends on a general idea of an inflatable cuff to the arm, which depends on the principle of oscillometry or auscultatory method. This existing method for the measurement of blood pressure, based on the cuff are considered to be not convenient for every day observation, moreover these are extremely perceptive to artifacts owing to the occurrence of cuff [11]. Several research works have projected their explanation in this view along with other non-invasive techniques such as PWD (Pulse Wave Delay), PAT (Pulse Arrival Time) and PTT (Pulse Transit Time) which need other parameters such as PPG and ECG in order to measure the blood pressure. A more consistent simple available method has the significance of this investigation. In the later on literature survey, the estimation of blood pressure has measured from the PhotoPlethysmoGram signal by considering the ECG signal as a reference factor, calculating the relation among the blood pressure and transit time [4]. The registration of the automatic activities of the blood vessel's walls has detected by the speed of the pulse wave and calculating the time delay in various section of the human body by utilizing an ECG as a reference waveform [13]. Therefore, the signal that is of mainly significant is ECG [14] as it has obtained to calculate the Pressure. In another method, Pulse Wave Transit Time [15] (PWTT) of the nose, finger and toe has calculated, as well as the difference among every site's of PWTT was estimated [12]. To extend a non-invasive estimation technique of the circulatory factor by examining

the digital PPG signals, statistical modelling of input (monitored PPG signal) relations had executed. A novel technique by monitoring the cuff-less blood pressure was suggested, where waveforms from plethysmographic sensors were combined with a mathematical model to calculate the beat-to-beat blood pressure signal. In a recent study, Pulse Arrival Time (PAT) intervals in the medical information mart for intensive care database were calculated to authenticate the estimated of blood pressure measurements values. In another work, mean arterial pressure and systolic blood pressure estimation of appropriate or inappropriate signals had designed. This method has proven to estimate the BP values irrespective of feature extractions or morphology of the PPG signals. Although these many studies have already demonstrated the usefulness of PPG as blood pressure estimation index, however the gap between the commercialization with remarkable accuracy and repeatability is the point of concern. The work discussed in the current study is simple, user friendly and can be implement, if tested for large set of database.

Plethysmograph (PG) is a blending of the extremely old Greek words ‘plethysmos’, implies increase, along with ‘grapho’ is the word refers to write, and is device typically utilized to estimate as well as record the changes in blood flow or blood volume in the human body that take place with every heartbeat.¹ Photoplethysmograph is one of the traditional techniques for calculating the blood flow in the extremity. In 1938, Hertzman establish a relationship among the strength of backscattered light as well as volume of the blood in the skin.

PhotoPlethysmoGraph (PPG) signal is an optical method that naturally works by utilizing the infrared light, permitting the transcutaneous registration of venous along with arterial blood volume varies in the skin vessels. Photoplethysmograph waveform has generated with the complex interaction among the connective vasculature along with the heart. The essential of this proposed method is the identification of the dynamic cardiovascular pulse wave produced by the heart as it moves all over the human body. In general, the enlightening PhotoPlethysmoGraph wavelength has selected to give a poor absorption in tissue; however, in the blood, a strong absorption will offer a more degree of optical contrast. Infrared radiations have repeatedly engaged as well as offer a suitable illumination source. It gives a waveform proportional to variation in the volume of blood in the skin. The pulsatile part has frequently known as the ‘Alternating Current’ component and of PhotoPlethysmoGraph signal having its elementary frequency as 1 Hz, depending on heart rate [16]. This Alternating Current component has applied onto a huge quasi-DC component, which relates to the average blood volume and to the tissues. This DC component changes gradually owing to vasoconstrictor waves, vasomotor activity and respiration.

Results

The individual’s age should be within the range of 40. The signals had acquired for a minute subsequent to the individual person totally gets relaxed. Furthermore, the reading of the pressure using a digital blood pressure monitor had obtained for further reference. The data, which has to analyzed, was achieved in LabVIEW, the corresponding signals had acquired and stored using the proposed algorithm. The front panel of the proposed work simulated in LabVIEW has shown in Fig. 1.

Fig. 1 Front Panel of the Proposed Work

The morphological characteristic for example, height and width of the Pulse, area under the curve has taken out as well as more investigation has carried out by utilizing a mathematical tool known as regression analysis. The area under the curve of PhotoPlethysmoGraphic signal has simulated in LabVIEW software as shown in Fig. 2. The equations attained have utilized to estimate the Systolic Blood Pressure values (SBP). The area under the curve (AUC) for each signal has computed, furthermore the Inflection point ratio has evaluated followed by regression analysis.

The general equation for the analysis of regression has specified below:

$$Y = \beta_0 + \beta_1 x_i + u_i \quad (1)$$

A correlation of the IPA Vs the estimated SB values were determined. Fig. 3 demonstrates that the IPA is linearly proportional to the measured SBP values with the regression coefficient of 0.98 and follows the Eq. (1).

$$y = [9.166 \times 10^{-4} \pm 3.9 \times 10^{-4} (\text{SBP})] + 0.901 \quad (2)$$

Fig. 2 Area under the curve of PPG signal

Fig. 3 Comparison of SBP vs IPA.

Fig. 4 Analysis of Pulse height through linear regression.

Fig. 5 Analysis of pulse width through linear regression.

Similarly, the regression analysis for the pulse width and pulse height had performed and SBP value was determined as shown in Fig. 4 and Fig. 5 respectively. The obtained results for the PH regression analysis indicate that the PW is inversely proportional to the measured SBP values.

The equations used for estimating the values of blood pressure from the height and width of the pulses were given in Eq. (3) and (4).

$$Y = (0.49 \pm 14.09) (\text{Pulse height}) + 45.24 \tag{3}$$

$$Y = (0.65 \pm 0.58) (\text{Pulse width}) + 66.20 \tag{4}$$

The SBP values estimated using the pulse height, pulse width and AUC had estimated and further feeded to the system to create a dataset for supervised learning module. This data set has used for evaluating the Blood pressure values for the unknown subjects as shown in table 1. The data had obtained in triplicates and further averaged before applying the regression.

TABLE 1
ESTIMATED SYSTOLIC BLOOD PRESSURE VALUES FROM PHOTOPLETHYSMOGRAPHIC SIGNAL

S.NO.	PULSE RATE (BPM)	Pulse height	SBP (estimated)	Pulse width	SBP (estimated)	SBP (Measured BP)
Patient1	63	53	1.06	128	79.41	121.12
Patient2	70	52	1.04	110	93.77	126.71
Patient3	72	51	1.02	140	98.4	126.91
Patient4	75	49	0.98	133	100.7	131.21
Patient5	80	47	0.94	137	105.2	134.65
Patient6	82	45	0.9	127.5	110.8	138.53
Patient7	93	42	0.84	129	116	141.6
Patient 8	95	40	0.8	129	122.1	143.49
Patient 9	101	35	0.7	137	122.4	146.41
Patient 10	104	33	0.66	130	130.5	156.29

Discussion

This proposed method intended to estimate the pressure of the blood from the various characteristics of PPG parameters. The PhotoPlethysmoGraph signal has separated into particular parts and the manipulation has carried out for each of the parts [17]. The corresponding morphology pulse height, pulse width and area under the curve have separated for the PPG signal. The systolic and the diastolic peak of a PhotoPlethysmoGraph signal have correlated by means of the blood pressure values. The number of characteristics related to the PhotoPlethysmoGraph signal has explained in the literature.

The local vascular distensibility is directly proportional to the systolic amplitude over an extraordinarily broad range of cardiac output has found by Dorlas and Nijboer. The various parameters disturbing the systolic amplitude has estimated and pointed out in table 2. The pulsatile variation in the blood volume that has produced by arterial blood flow in the region of the measurement site has indicated by the systolic amplitude [18] as shown in Fig. 6. It has also recommended that systolic amplitude is more appropriate factor than Pulse Arrival Time (PAT) in addition it has potentially utilized for calculating the measurement of continuous blood pressure [19]. The difference among the PhotoPlethysmoGraph values of the cardiac peak and the preceding valley has calculated as Pulse amplitude.

The systemic vascular resistance has much correlates with pulse width than by the Systolic amplitude. The pulse width has used as the half of the maximum height from the systolic peak [20]. The width of the pulse in the PhotoPlethysmoGraph signal is shown in Fig. 7. An additional approach to estimate the width of the pulse is by calculating the pulse inflection point (P_i) lying between the peak of the pulse (P_p) and the pulse valley (P_v) and then subtracting previous P_v from pulse inflection point (P_i).The expression can be given as :

$$\text{Width of the Pulse} = \text{Pulse inflection point} - \text{Pulse valley} \tag{5}$$

The total area under the curve (AUC) of the PhotoPlethysmoGraph (PPG) curve has measured as the area of the pulse. The DC area subtracted from the integral gives the total area under the curve. The PhotoPlethysmoGraph area reacts to the skin incision to differ between movers and non-movers has found by Seitsonen et al.

$$\text{AUC} = \text{Integral} - \text{DC area} \tag{6}$$

Fig. 6 The systolic component.

TABLE 2 DIFFERENT FACTORS OF SYSTOLIC PEAK

Peak of Systolic Amplitude	Parameters	Causes
Low	Comparative height of measurement site	Pulsations of blood volume has reduced and diminish the volume of venous blood
	Arterial pressure in blood raises due to greater resistance in peripheral	Pulsations of blood volume has reduced
	Serve hypovolaemia	Pulsations of blood volume has reduced
	(General) hypothermia	Vasoconstriction of the Peripheral
	Activation of sympathetic (e.g. strain, sneezing)	Vasoconstriction of the Peripheral
	Vasoconstrictors (e.g. Noradrenaline)	Vasoconstriction of the Peripheral

High	Raise in blood pressure of arterial owing to bigger cardiac output	Pulsations of blood volume has raised
	Mainly anesthetics	Vasoconstriction of the Peripheral
	Epidural anesthesia	Vasoconstriction of the Peripheral

Fig. 7 Depiction of amplitude, width of the pulse, and area under the curve extracted from the PhotoPlethysmoGram signal.

The area of the pulse waveform has split up into two regions at the dicrotic notch by Wang et al. They establish that the ratio of the two regions has utilized as an indicator of resistance of the total peripheral as shown in Fig. 8. This ratio has known as the Inflection Point Area (IPA) and has defined as:

$$IPA = A_2 / A_1 \quad (3)$$

In order to study the patterns although individual accounting for physiologic variability, the corresponding area, width and amplitude of the PhotoPlethysmoGraph waves has computed as well as further had standardize with respect to the values of baseline.

Fig. 8 Point of inflection P_i separated the area under the total PPG signal as A1 and A2.

Conclusion

In this article, calculating the Systolic Blood Pressure values by using PhotoPlethysmoGraphic signal values is proposed by utilizing the algorithm, in which the particular morphological characteristics were taken out in

LabVIEW simulation software and the data analysis has been performed in MATLAB and plotted using Origin 8. The proposed simulation output reveals that the height of the Pulse (systolic amplitude) is inversely proportional to the systolic blood pressure, as it rises for huge cardiac output but with reduced span of time. The width and area of the pulse are directly proportional to the systolic blood pressure. Our simulation results specifics the relation between PPG and Blood Pressure. Error percentage as per the calculation among the extracted features was less for Inflection height ranging from ± 10 to a min of ± 2 . Further efforts had to made to compare the designed algorithm with other such as SVR method, back propagation etc.

Methods

To decrease the impact of peripheral influences on measurements, a pre-test guideline has given to the participants. At least before an hour of data acquisition, consumption of tobacco and caffeine has strictly prohibited. Ten patients (8 males and 2 females) had recruited for the study. The temperatures of the room has measured and at both sessions keep the temperature at a bare minimum of 20 to 22°C to avoid vasoconstriction of digital arteries. The flowchart of signal acquisition and investigation of PPG waveform has shown in Fig.9.

Fig 9 Flowchart of Signal acquisition and analysis.

With the help of Photoplethysmography unit, PhotoPlethysmoGraphic signal has obtained from the particular persons through a sampling rate of 4000 samples per second. The frequency response for PhotoPlethysmoGraphic signal is 0.05-15Hertz. It has acquired by utilizing a transmissive USB type PhotoPlethysmoGraphic sensor.

Fig. 10 Block diagram of the proposed method

The signal has obtained in LabVIEW simulation software (Signal processing toolbox) as well as more investigation had carried out by executing the proposed algorithm. The real time implementation has supported by LabVIEW simulation software. The procedure for acquiring the PhotoPlethysmoGraphic signal from normal as well as abnormal subjects has attained as shown in Fig. 10

The proposed algorithm has executed in LabVIEW simulation software and more regression had carried out using MATLAB tool.

- Step a: Acquire the PhotoPlethysmoGraphic signals.
- Step b: Filter the signal by utilizing the low pass filter, which is less than 15 Hz.
- Step c: Estimate the DC value
- Step d: Compute the corresponding parameters i.e. Valleys and Peaks P_v and P_p .
- Step e: Calculate the Inflection Points P_i .
- Step f: Calculate the height, width of the pulse, as well as area under the curve (PW, PH and AUC).
- Step g: Apply the regression tool to the attained values (P_v , P_p , P_i)
- Step h: Calculate the values of the pressure from the regression equations drawn.
- Step i: Correlate the values of pressure with the calculated values of blood pressure.

ABBREVIATIONS

PPG - PhotoPlethysmoGraphm, PTT - Pulse Transit Time, PAT - Pulse Arrival Time, PWD - Pulse Wave Delay, PW- Pulse Width, PH – Pulse height, AUC- Area Under the Curve, SBP - Systolic Blood Pressure

ETHICS APPROVAL AND CONSENT TO PARTICIPATE

Not applicable.

CONSENT FOR PUBLICATION

Not applicable.

COMPETING INTERESTS

The authors declare no competing interests.

FUNDING

None.

AUTHORS' CONTRIBUTIONS

All the authors involved in writing the manuscript, simulating the experiments, analyzing the signal, read and approved the final manuscript.

ACKNOWLEDGEMENTS

Declared none.

AVAILABILITY OF DATA AND MATERIALS

Not applicable.

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Figures

Figure 1

Front Panel of the Proposed Work

PPG WAVE

Plot 0

Figure 2

Area under the curve of PPG signal

Figure 3

Comparison of SBP vs IPA.

Figure 4

Analysis of Pulse height through linear regression.

Figure 5

Analysis of pulse width through linear regression.

Figure 6

The systolic component.

Figure 7

Depiction of amplitude, width of the pulse, and area under the curve extracted from the PhotoPlethysmoGram signal.

Figure 8

Point of inflection P_i separated the area under the total PPG signal as A_1 and A_2 .

Figure 9

Flowchart of Signal acquisition and analysis.

Figure 10

Block diagram of the proposed method

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