A REVIEW ON NON-INVASIVE HYPERTENSION MONITORING SYSTEM BY USING PHOTOPLETHYSMOGRAPHY METHOD

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Abstract

Hypertension, the abnormal elevation of blood pressure, is one of the chronic diseases that usually comes with no symptom and signal. Hypertension is diagnosed if the systolic blood pressure (SBP) over 140 mm Hg or diastolic blood pressure (DBP) is over 90 mmHg. The purpose of this paper is to review methods of early diagnosis of hypertension by monitoring the SBP, DBP, and heart rate (HR) non-invasively. Although accurate measurement of BP and HR of a person can be obtained invasively, the measuring probe needs to place under patient's skin, which in turn would cause discomfort to the patients and not to mention the possibility of thrombosis to occur. External pressures are necessary to induce to the artery in order to measure BP and HR by using auscultatory and oscillometric methods, hence, a pressure cuff is used to measure BP. The pressure cuff will restrict the motion of the patient and it is rendered not suitable for continuous monitoring. On the other hand, pulse transit time (PTT) and photoplethysmography (PPG) methods are introduced to measure BP non-invasively without the use of a cuff. The limitation of PTT over PPG is PTT needs both PPG waveform and ECG waveform to estimate BP, and artificial phase lag might occur which will affect the reliability of the measured result. Therefore, for long-term hypertension monitoring, non-invasive mean using photoplethysmography method is preferred since it enables continuous monitoring without cuff and it requires only one waveform to estimate the BP as well as HR.

Keywords: Hypertension, non-invasive, systolic blood pressure, diastolic blood pressure, heart rate, photoplethysmography

Introduction

Hypertension is one of the chronic cardiovascular diseases that affects over one billion people in the world. When systolic blood pressure (SBP) is over 140 mm Hg or diastolic blood pressure (DBP) is over 90 mm Hg, it is defined as hypertension. Blood pressure (BP) is the pressure against the wall of arteries as the blood is circulating in arteries (BC Guidelines & Protocols Advisory Committee). The pressure acts as driving force to push the blood flow to the vessel and the entire body. It can be divided into two sections, namely, SBP and DBP. SBP is the pressure in the arteries when the blood is pump from the heart, whereas DBP is the pressure in the arteries when the heart is resting (Alton). Hypertension is also said as a silent killer since it might attack without any symptoms or signs. Therefore, daily monitoring of blood pressure is a good way to prevent hypertension (Gao et al., 2009).

Table 1: Classification of adolescent above 18 years old.

Blood Pressure Classification	Blood Pressure (mm Hg)	
	Systolic	*Diastolic*
Normal	< 120	And < 80
Prehypertension	120-139	Or 80-89
Stage 1 hypertension	140-159	Or 90-99
Stage 2 hypertension	≥ 160	Or ≥ 100

Source: (BC Guidelines & Protocols Advisory Committee)

Table 1 shows the classification of hypertension for adolescents above 18 years old. A BP for a normal adolescent is below 120 mm Hg and 80 mm Hg for SBP and DBP respectively. The SBP of between 140 and 159 mmHg or DBP of between 90 and 99 mmHg is defined as the first stage of hypertension while the second stage is when the SBP is higher than 159 mmHg or the DBP is greater than 99 mmHg (BC Guidelines & Protocols Advisory Committee).

Invasive and Non-invasive Monitoring Methods

From the definition of hypertension, BP is highlighted as the main parameter to detect hypertension. There are two approaches to measure BP, which are invasive and non-invasive. Invasive BP monitoring system uses a catheter, a thin flexible tube, inserted into the artery. A beat-to-beat BP wave is displayed and recorded for long-term monitoring purpose. This technique is commonly used in monitoring the BP of patients in the Intensive Care Unit (ICU) or operating theatre (Vadivelan).

An accurate BP reading can be obtained by invasive BP measurement. Therefore, this method is typically used in hospitals to monitor the BP of a patient from time to time (Zhang, 2010). However, it requires experts such as physicians and doctors to conduct the monitoring system. Therefore, it is not suitable for out-of-hospital hypertension monitoring (Vadivelan).

Table 2: Advantage and disadvantage of invasive BP monitoring

Advantage	Disadvantage
An accurate result can be obtained directly from the artery.	The measuring probe leads to thrombosis and causes occlusion.
Allow measurement for patient.	Specialist is needed to insert the catheter to the intra-arterial.
Trauma of repeated cuff inflation can be avoided.	The monitoring device is expensive.

Source: (Vadivelan) (Zhang, 2010)

Table 2 lists the advantages and disadvantages of the invasive BP monitoring system. By using the invasive method, an accurate and continuous BP value of the patient can be obtained. This approach also allows measurement of all kind of patient including morbidly obese patient whose BP cannot be measured by non-invasive method. Besides, invasive BP measuring method does not require patient to wear pressure cuff during measurement. Therefore, trauma of repeated cuff inflation can be avoided for patients who are required to have their BP measured from time to time for an extended period.

However, to measure the BP invasively, a catheter needs to be inserted under skin, which might results in thrombosis. The measuring probe will cause the formation of blood clot within the blood vessel and lead to occlusion. Moreover, the catheter needs to be placed in the intra-arterial to obtain an accurate BP measurement. Therefore, the setup of the measurement only can be conducted by a specialist such as a physician and doctor. Besides, the disadvantage of the invasive BP monitoring system requires expensive and cumbersome monitoring devices.

Besides of invasive method, BP can be measured by noninvasive methods. The measurement can be conducted by using a device equipped with a cuff or without a cuff. The common noninvasive BP device equipped with a pressure cuff. The pressure cuff is inflated to induce external pressure to the artery. When the external pressure is higher than the BP in the artery, the artery collapse, then the pressure start to deflate (Yamakoshi, Shimazu, Shibata, & Kamiya, 1982). When the external pressure is lower than SBP, the blood will start to spurt and cause the artery in the cuff region to expand, a unique sound, named Korotkoff, is produced with each heartbeat. This spouts of blood can be estimated by the auscultatory or oscillometric method.

Auscultatory Method

The auscultatory method is the gold standard clinical BP measurement that recognised by the Association for the Advancement of Medical Instrument (AAMI) as well as by British Hypertension Society (BHS). Through the auscultatory method, a sphygmomanometer and a stethoscope, as shown in Figure 1, are used to listen to the Korotkoff sound and estimate the BP while Figure 2 shows the phases when Korotkoff sound is detected.

Before the measurement, the subject is required to take a rest for at least five minutes in the sitting position, and the upper arm is placed at the same level with the heart. The pressure cuff is surrounded the brachial artery (upper arm), and the stethoscope is placed at the brachial artery as well to detect the pulse (Andersen).

Figure 1: Sphygmomanometer and stethoscope
Source: http://www.wzcare.com/data_qx/upload/product/20089251837058666.jpg

The pressure cuff is inflated until the artery is collapsed. At this moment, there will be no sound detected and the external pressure from the cuff is 30 to 40 mm Hg higher than the subject's BP value. Subsequently, the cuff is deflated at the speed of 2 to 3 mm Hg per second (Andersen). Once Korotkoff sound is heard, this indicates that the blood starts to flow into the previously collapsed artery. The pressure at that moment is estimated as SBP. Once the Korotkoff sound is gone, this indicates that blood flow has returned to its normal condition. The pressure at that moment is considered as DBP (Babbs, 2012).

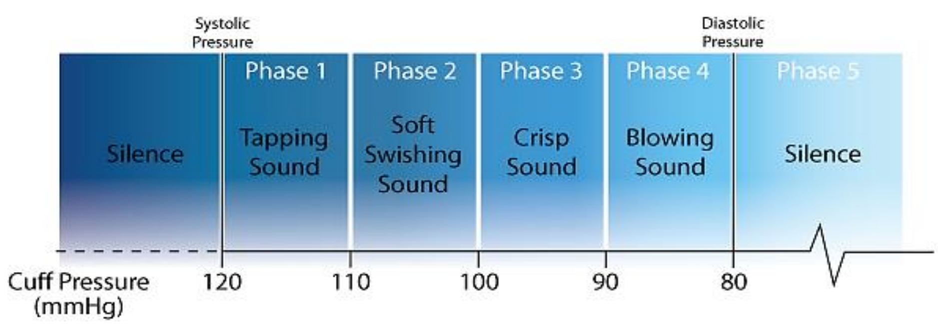


Figure 2: Phases when Korotkoff sound is detected
Source: http://adctoday.com/blog/intro-blood-pressure

According to AAMI and BHS, for every newly invented BP measurement device, it must be tested on 85 subjects, 3 trials each and the difference between SBP and DBP must not exceed 5 and 8 mm Hg, respectively, compared to the measurement taken using auscultatory method (Nitzan, 2009).

Oscillometric method

Oscillometric method is similar to auscultatory. A pressure sensor is attached to the pressure cuff to measure the oscillation of the blow flow through the artery (Babb, 2012). The pulsation in arterial cause oscillations in the cuff pressure. When the oscillation reaches the maximum, the mean cuff pressure equals to the mean arterial pressure. The measured mean arterial pressure and oscillation pattern are used to determine systolic and diastolic blood. However, the arm must be placed at the same level as the heart during the measurement (Zhang, 2010).

For cuff-less BP measuring device, pulse transit time (PTT) method and photoplethysmography (PPG) are the techniques that are widely used. Pulse transit time is the time interval for the arterial pulse pressure to travel from the aortic valve to a peripheral site. An algorithm is used to correlate PPT with pulse wave velocity (PWV) as well as with BP (Teng & Zhang, 2003). Photoplethysmography utilises a light source, usually from an infrared LED, and photodetector to estimate the blood flow in arteries. The body tissue and blood cell will absorb the light intensity from the light source. The remaining light source will either reflect or transmitted through the arteries, and this light residue is detected by photodetector. A blood flow wave is generated, and BP is estimated from the waveform (Jeong, Ko, Hwang, & Yoon, 2006). This two method will be further discussed in the following sections.

Pulse transit time

Pulse transit time (PTT) can be defined as the time taken for the arterial pulse pressure wave travel from aortic valve to periphery (Smith, Argod, Pépin, & Lévy, 1999). It is the index of arterial stiffness and cardiac output. It has been used to estimate BP indirectly (Ahlstrom, Johansson, Uhlin, Länne, & Ask, 2005). Two parameters are involved to obtain PPT, which are electrocardiogram (ECG) and photoplethysmography (PPG). Figure 3 shows the ECG waveform and PPG waveform. Skin electrodes are used to measure ECG, where ECG shows the electrical activity of the heart. Conversely, PPG measures the change of volume of blood in the organ. PPG can be detected using pulse oximeter by illuminating the skin and measuring the amount of light transmitted or reflected under the skin (Ma & Zhang, 2005). PTT is calculated by computing the time delay between R-peak from ECG and arrival of the pulse wave in the periphery which measured by PPG. Usually, the ECG is measured from the chest, and PPG is measured from index finger (Geshe, 2012). The relationship between PTT and BP can be analysed by using linear and nonlinear regression. There is a negative correlation between PTT and blood pressure, that is, when BP increases, arterial compliance decreases which reduce the pulse wave velocity and it causes PTT decreases (Zhang, 2010).

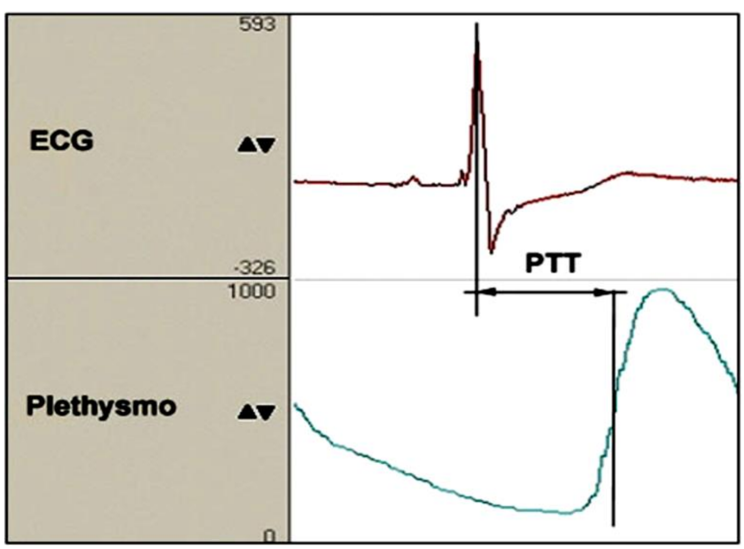


Figure 3: ECG waveform and PPG waveform
Source: (Gesche et al.)

Photoplethysmography

PPG is a volumetric measurement of an organ using a pulse oximeter. BP can be estimated by using PPG time domain and frequency domain (Zhang, 2010). PPG sensor is an optical sensor, which can be used to detect the blood volume changes in the arterial segment (Tamura, 2014). PPG sensor equipped with series connected light source and parallel connected photodetectors, photodiodes (Yamakoshi, 1982). The light source, normally from the infrared LED or green LED with wavelength from 500nm to 600nm, transmits through or reflects from tissue or blood cell under the skin. Part of the light intensity is absorbed by the tissue and red blood cell, the remaining will reflected and detected by a photodiode. Since the red blood cell absorbs more light intensity than body tissue, therefore, the red blood cell can be differentiated easily with the body tissues by observing the reflected light intensity. As shown in Figure 4, PPG waveform consists of two components, i.e. the alternative current (AC) component and direct current (DC) component. The AC is used to detect the change of cardiac synchronous in the blood volume for every heart beat, whilst the DC attributes to identify and transmit the optical signal from tissue and estimate the blood flow for every heartbeat (Tamura, 2014).

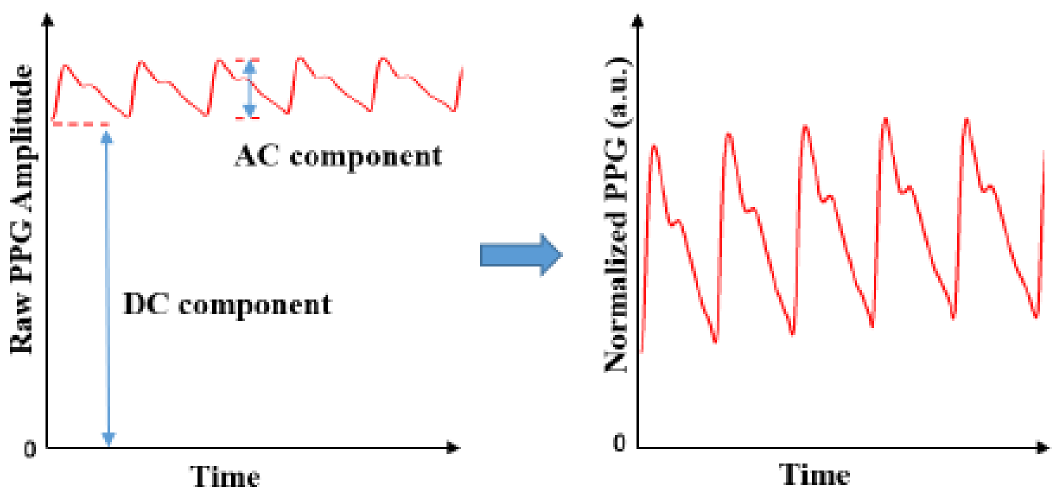
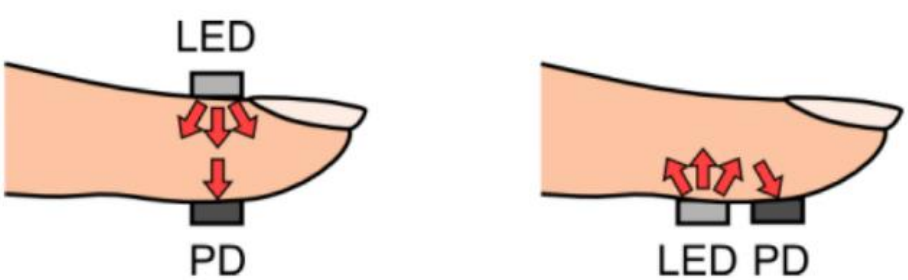


Figure 4: PPG waveform
Source: (Xing & Sun, 2016)

PPG measurement can be performed in two ways, which are transmittance PPG (TPPG) and reflectance PPG (RPPG) as shown in Figure 5. For transmittance PPG, the position of the light source is parallel to the photodetector. Light intensity is transmitted through the blood or body tissue and detected by the photodiodes (Agrò et al., 2014). For transmittance, the light source and photodetector are aligned. The light intensity is reflected by the blood or tissue and detected by the photodiodes (Geun et al., 2008).



(a) (b)

Figure 5: TPPG sensor; (b) RPPG sensor
Source: http://www.mdpi.com/electronics/electronics-03-

Heart Rate

Another parameter that used to monitoring hypertension is by measuring heartbeat. The range of heart rate for an adolescent is between 60 and 100 beats per minute (bpm). The heart rate depends on the fitness of the body. A slim person has a lower heart rate. If one's heart rate is higher than the normal range, he/she is considered as tachycardia. Otherwise, it is considered as bradycardia (Fontaine, 2013).

Heart Rate Measurement by PPG

According to Guyomard and Stortelder (2015), there is two methods to determine the heart rate from PPG waveform, which is peak to peak and spectral analysis. Peak to peak method analyses the peaks of the heartbeats and the time delay between two peaks and gives a period of the heartbeat signal from PPG waveform. Heart rate can be determined from the reciprocal of the period of the heart beat. The second method is spectral analysis. The large spike at the frequency is the raw data of heart rate; it is retrieved and undergone fast Fourier Transform to computing the heart rate.

However, PPG waveform is sensitive and easily disturbed by motion. The filtration of unwanted noise is difficult and ineffective. In most case, an algorithm is generated to eliminate the noise by reducing the sensitivity of PPG waveform (López, 2012).

Result

Table 3 is the summary of the review from four studies of measuring BP by PTT method. The parameter taken from subjects are ECG waveform and PPG waveform on the body of subjects. PTT is calculated based on the measured ECG and PPG. Correlation analysis is performed to estimate the SBP and DBP. The experimental results are compared with the commercial device such as cuff-based sphygmomanometric aneroid and cuff-oscillometric system.

Table 4 is the summary of the review from four studies of measuring BP by PPG method. Overall, the PPG is obtained from the index finger of subjects. The systolic upstroke time, diastolic time and time taken per cycle are retrieved from the PPG waveform. Correlation analysis is performed in order to estimate the SBP and DBP.

Based on the studies, the limitation of PTT over PPG includes, the PTT requires the ECG parameter in order to compute the pulse transit time. Besides, the filters used in PPG sensors and ECG sensors are different. Artificial phase lag is generated between ECG and PPG. It is hard to remove the phase lag, and it affects the accuracy of the reading. Moreover, to detect ECG, small electrodes need to attach to chest, arms and legs. The device will be cumbersome if it comes with both ECG and PPG sensors. Furthermore, assistance from others is needed in order to place the electrode correctly in order to get an accurate result by using ECG (Teja, 2012).

Table 5 lists the review of the measurement of heart rate by using PPG method. Similar to the method of estimating BP from PPG method, the PPG signal is obtained from the index finger of the subjects. The frequency of peak value of each cycle is retrieved by using fast Fourier Transform, where the frequency of the peak value is used to determine the heart rate.

Table 3: Review on other relevant research study on experimental setup of measuring BP by using PTT method

Author, Year	Reference Parameter	Method	Experiment Setup	Findings
Ding et al. (2015)	BP (Finapres sensors)	PTT	PTT was calculated from ECG to PPG and ECG to PPG readings in standing, sitting and lying position. Average SBP and DBP were computed by correlated SBP and DBP by linear and nonlinear regression.	To determine the effect of posture change to the value of PTT. To compare the accuracy of PTT that computed from ECG to PPG and from ECG to TAG (Tonoarteriography)
Gesche et al. (2012)	BP (cuff-based sphygmo-manometric aneroid)	PTT	Pulse wave velocity (PWV) is computed from PTT. A nonlinear function is generated by PWV to compute BP. Individual correlation coefficients for SBP measured by PTT and by cuff varied between r = 0.69 and r = 0.99.	To create a function between SBP and PWV. To test its reliability for the determination of absolute SBP using a non-linear algorithm and a one-point calibration.
Ye et al. (2010)	ECG, PPG, BP (Commercial device)	PTT	ECG and PPG were measured for 20 times from similar subject to obtain the average value, and this value is used to calculate PTT. The correlation analysis is performed to obtain SBP and DBP by linear regression	To generate algorithm that used to estimate the BP from measured PTT
Wibmer et al. (2014)	BP (cuff-oscillometric system)	PTT	The ECG and PPG are measured to calculate PTT. Analysis of the relation between PTT and BP by using linear and nonlinear regression. A Bland-Altman graph is plotted to assess the overall agreement between the BP measured by referenced device and the calculated BP.	To evaluate the feasibility of PTT measurement during routine maximal cardiopulmonary exercise testing by means of standard medical equipment. To analyse the relation between BP and PTT using both a linear and a non-linear approach.

Table 4: Review on other relevant research study on experimental setup of measuring BP by using PPG method

Author, Year	Reference Parameter	Method	Experiment Setup	Purpose
Teng & Zhang, (2003)	ECG PPG BP	RPPG	PPG signals are obtained from the index finger of 15 healthy male subjects that undergo rest-step climbing-recovery session. The 2/3 pulse amplitude width, ½ pulse amplitude wave width, systolic upstroke time and diastolic time are retrieved from PPG signal and used for further regression analysis respectively.	To study the relationship between arterial BP and PPG signal
Jeong et al. (2006)	Clinical tested invasive BP, ECG, blood volume and vessel resistance from animal and clinical tested noninvasive BP, PPG and ECG from patients	RPPG	PPG signal is obtained from the index finger of the subject. The measurement is taken after subject takes 5 minutes rest. The relationship between BP and PPG signal is determined by multi-regression method.	Trial of estimating arterial BP using PPG signal
Samria et al. (2014)	BP (digital BP monitoring machines)	TPPG	PPG signals are obtained from the finger of 22 subjects in two age group (18-25 years old & 26-50 years old). The systolic upstroke time, diastolic time and time taken between systolic and diastolic peak are retrieved for linear regression analysis in order to estimate BP.	Introduce new approach to measure BP with noninvasive, cuffless and painless technique by PPG
Nitzan et al. (2009)	SBP (Cuff-based Sphygmomanometer)	PPG Oscillom etric	SBP is estimated from cuff-based oscillometric-PPG on right arm and PPG signal from two index fingers. 62 male subjects without cardiovascular disease except hypertension involved in the examination. Measurement is taken for three times for each subject in sitting position, hand laid on the table and is made to rest for 10 minutes before the examination. The correlation coefficient is calculated for correlation between PPG and BP. Mean and standard deviation based on reference value is calculated.	Present a cuff-based technique for automatic measurement of SBP, based on PPG signal measured simultaneously in fingers of both hands.

Table 5: Review on other relevant research study on experimental setup of measuring heart rate by using PPG method.

Author, Year	Reference Parameter	Method	Experiment Setup	Purpose
López et al. (2012)	ECG	TPPG	A complete maximal exercise followed by active recovery is performed by two groups of athletes. PPG measurement is taken from the index finger. Linear Pearson's correlation analysis is used to correlate quantitative variables. Algorithm for computing heart rate is generated from FFT spectra.	To develop and validate an algorithm, which is based on heuristic analyses, for obtaining the heart rate from a PPG signal in the presence of severe motion artifacts
Venkatesh (2013)	-	RPPG	The measurement is sent to the computer via Zigbee. The analysed data are shown in GUI, and the previously recorded data is stored in the database.	To develop a wireless, wearable health monitoring device to detect pulse rate by reflectance pulse oximetry.
Guyomard, & Stortelder, (2015)	-	RPPG	The PPG is measured from the index finger without motion and from the earlobe during motion artifacts. The heart rate is computed from PPG signal by Fast Fourier Transform. The results are compared to observe the effects of motion to the heart beat.	To introduce a solution to detect PPG in motion artifacts.
Fontaine (2013)	Pulse rate, SpO_2 (commercial Pulse Oximeter)	RPPG	Average of pulse rate is taken on wrist and chest for every 10 seconds throughout a 6-minute timespan for 36 trials in sitting and standing position. The highest amplitude frequency between 0.75Hz and 2.25Hz from PPG waveform is retrieved for computing pulse rate. Linear regression is used to correlate PPG and pulse rate	To demonstrate the use of reflectance-based pulse oximetry to obtain measurements for pulse rate and SpO_2 from the chest and wrist

Conclusion

Hypertension can be diagnosed by monitoring BP and HR of a person. Although BP and HR obtained from the invasive method are reliable, a catheter is needed to be inserted into the artery of the patient. An alternative method to estimate the BP and HR is by means of non-invasive methods. Although pressure cuff can be used to measure BP and HR, it is only able to obtain one result at a time instead of continuous measurement. Besides, the cuff size must be proper to cater different individuals. Therefore, the cuffless non-invasive hypertension monitoring system is investigated, that i.e. PTT, and PPG method. Based on the review, the PPG is preferred compared to the PTT as PPG only requires one sensor instead of two. Furthermore, there is no artificial phase lag, and the device is less bulky as compared to PTT device.

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