East West University

Continuous Blood Pressure Estimation using Photoplethysmography

by

Md.Razanul-Islam

Siful Islam Tushar

In partial fulfillment of the requirements for the degree of

Bachelor of Science in Electrical and Electronic Engineering

Spring, 2018

Submitted to

Department of Electrical and Electronic Engineering

Faculty of Science and Engineering

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Sharmin R. Ara, PhD	Dr. Mohammad Mojammal Al Hakim

Abstract

Blood pressure is one of the major important parameters to monitor cardiovascular health. Sphygmomanometer and stethoscope are the most widely used noninvasive method to measure blood pressure. In this work a novel method to estimate blood pressure using photoplethysmogram (PPG) is proposed. The PPG signal data was collected from an online patient database, Multiparameter Intelligent Monitoring in Intensive Care (MIMIC), developed by MIT lab. The estimated BP using the proposed method is then compared with the reference BP acquired from the same database. The estimated results are in good agreement with the reference blood pressure values.

Acknowledgement

First of all, we are very grateful to the Almighty Allah for the opportunity to complete this work.

We would like to thank, our thesis supervisor, Sharmin R. Ara, PhD, Assistant professor, Department of Electrical and Electronic Engineering (EEE), East West University (EWU), for her continuous support, guidance and suggestions during this research.

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Authorization Page

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Chapter 1

1.1 Introduction

Blood pressure is an important hemodynamic parameter. It is measured in each beat of cardiac cycle and expressed in terms of systolic blood pressure (SBP) and diastolic blood pressure (DBP). These SBP and DBP give us the information about the cardiovascular health. High blood pressure is known as hypertension which is a major risk for health. Estimation of BP using photoplethysmogram (PPG) and electrocardiogram (ECG) signal is being researched in the recent years to develop a reliable technique for continuous assessment of BP. PPG is the most widely used clinical waveforms in critical care sections in hospital. It uses infrared LED and a detector to track the blood volume change in either reflection or transmission mode. It provides information about oxygen saturation in blood, as well as, information regarding heartbeat.

The objective of this work is to find a method to estimate blood pressure (both SBP and DBP) using only PPG.

1.2 Physiological background

Before we find a way to measure blood pressure we need to know some important physiological phenomenon which create, affect and can control blood pressure. In order to do so, this section will address physiological background of blood pressure.

1.2.1 Structure of heart

Heart is positioned inside the thoracic cavity close to the center of the chest. It is a hollow, cone shaped muscular organ. The size of heart may vary from person to person. The wall of the heart consists of three layers. Outer layer is pericardium, middle layer is myocardium, and inner layer is endocardium.

The inside of the heart is divided into four chambers. Two are on the left side and two are on the right side. The upper chambers with thin walls are called atria (left atria, right atria) and the lower chambers with thick walls are called ventricles (left ventricle, right ventricle). Ventricles receive blood from atria.

Right atrium: Right atrium receives blood from the veins called superior vena cava, coronary sinus, inferior vena cava. Blood passes from the right atrium to the right ventricle through the atrioventricular valve. This valve which prevents the backflow of the blood is called tricuspid valve.

Right ventricle: Blood passes through a semilunar valve into the pulmonary trunk from the right ventricle. This valve is called pulmonary semilunar valve. The pulmonary trunk is divided into the left and right pulmonary arteries.

Left atrium: Left atrium receives oxygen rich blood through four pulmonary veins. These come from the two lungs. Blood passes from the left to the right ventricle through an atrioventricular valve is called bicuspid valve.

Left ventricle: Blood passes from the left to the right ventricle into the aorta through the aortic semilunar valve. This valve's cusps are larger and thicker than the pulmonary semilunar valve [1].

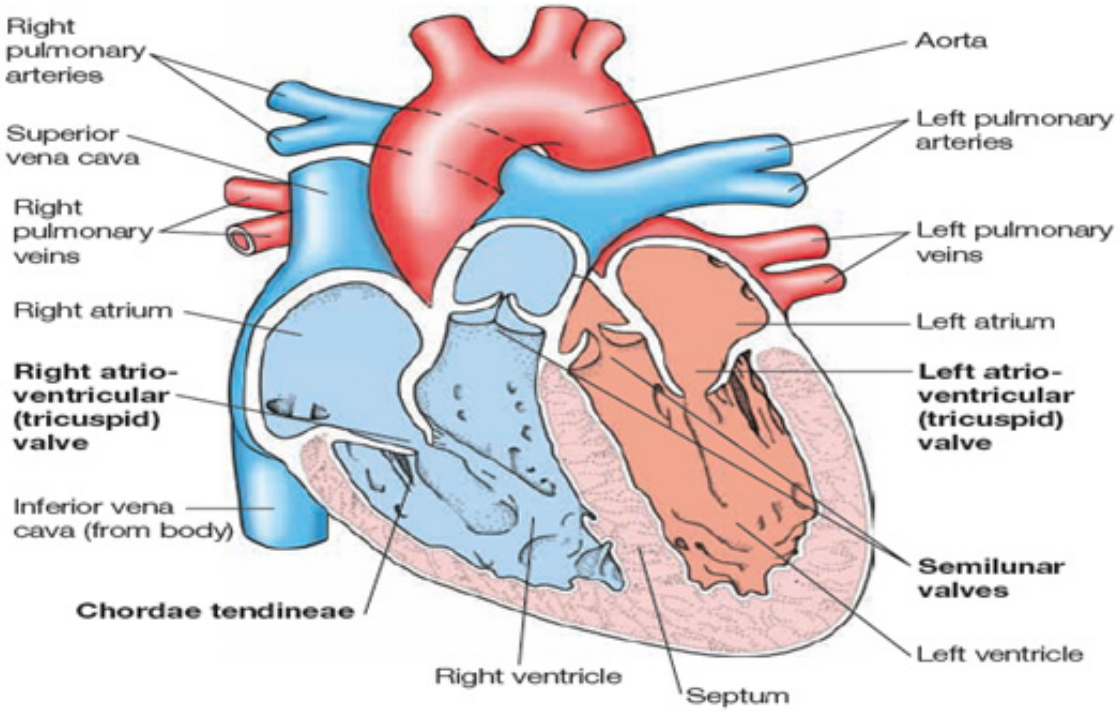

Fig.1.1. Structure of heart [2].

1.2.2 Cardiac Cycle

Cardiac cycle is the combination of all cardiac activities occurs in each heartbeat. Each cycle consists of relaxation and contraction of heart. This relaxation is called diastole and the contraction is called systole. During diastole blood fills heart and during systole blood leaves heart. Systole occurs after Diastole. Phases of the cardiac cycle are discussed below.

Atrial Systole: During this time right and left atrium contract, blood pressure rises and force blood to enter the ventricles through atrioventricular valves. During this time, semilunar valve remains closed and ventricle relaxed. Time required for this phase is 0.15s.

Ventricular Systole: Both ventricles contract in this phase, blood pressure rises and forces blood to enter into the pulmonary trunk through semilunar valves. This time atrioventricular valves remains closed. This phase require 0.30s.

Atrial and Ventricular Diastole: In this phase, atria and ventricles are relaxed. Blood return to the right atrium from the superior and inferior vena cava and to the left atrium from the left and right pulmonary veins and flows to the ventricles. During this time both atrioventricular valves are open and semilunar valves are closed. Time for this phase is 0.40s [1].

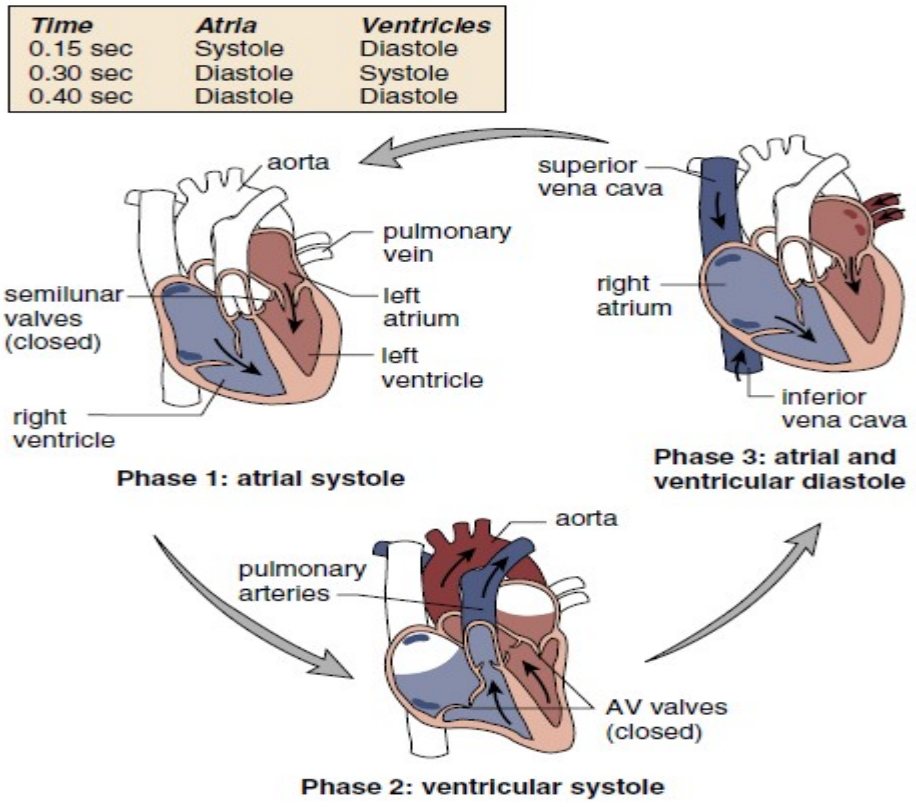

Fig. 1.2. Phases of Cardiac Cycle [1].

1.2.3 Blood Vessel

Blood vessels are classified into five types. These are; arteries, arterioles, capillaries, venules and veins.

Arteries: These vessels are elastic. They can expand under high pressure and recoil when relaxed. They can carry blood under high pressure. The walls of the arteries are thick, strong and composed of three layers (tunica interna, tunica media, tunica externa).

Arterioles: The subdivision of arteries into thinner tube is called arterioles. These vessels have some elastic tissue. Arterioles are encircled by smooth muscle fibers. The contraction of these muscle fibers decreases the cavity of the arterioles and the relaxation enlarges the cavity of the arterioles. This affects blood distribution and blood pressure.

Capillaries: These are microscopic blood vessels branched out from arterioles. The wall is composed of endothelial cells. Capillaries exist in all the region of the body by creating a network. The network of capillaries is called capillary beds. According to the demand of the cells, blood distribution in capillaries is controlled by precapillary sphincters. When capillary bed is closed, precapillary sphincters prevent blood to enter capillary by constriction. Opposite happens when capillary bed is open. By opening or closing the number of capillary beds, blood pressure can be regulated.

Venules: Venules are also small vessels like capillaries. They link the veins and capillaries.

Vein: These vessels carry blood from venules to heart. They have thin wall and the walls are less elastic. Some veins have valves which prevent backflow of blood. Blood veins act as a blood reservoir. They contain more than half of total blood volume found combined in veins and venules. In a condition of arterial hemorrhage, venous constriction help to maintain blood pressure [2].

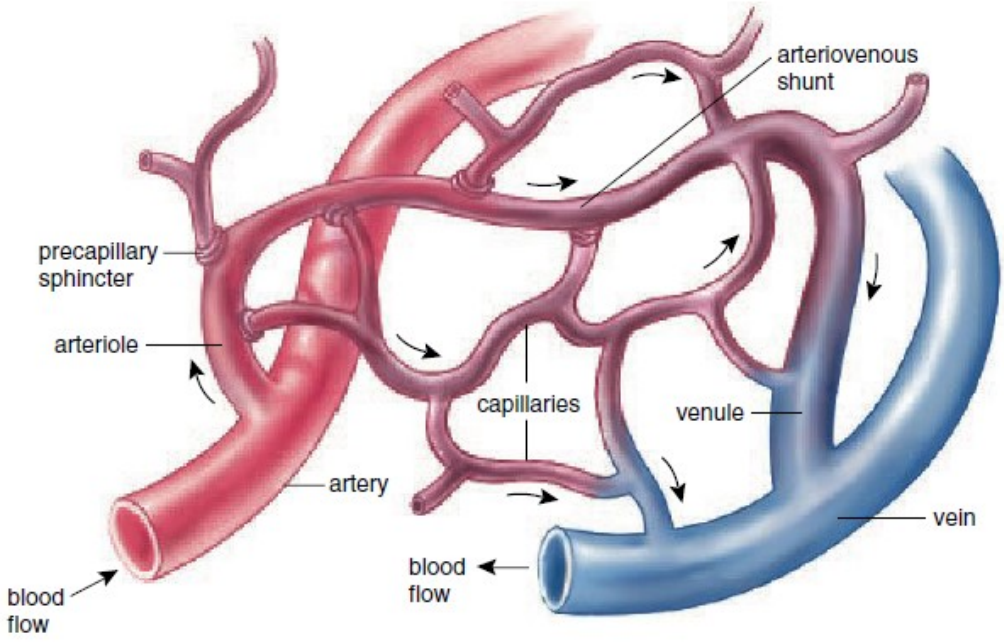

Fig. 1.3. Blood Vessel [1].

1.2.4 Blood Velocity

The velocity of blood leaving the heart is more than the velocity of blood returning to the heart. Aorta branches into arteries, arteries branches into the arterioles and arterioles branches into capillaries. Velocity of blood flow is higher in arteries and lowest in capillaries. This low velocity is important to exchange nutrients and gases for wastes. Blood flow again increases in veins as the blood from capillaries reach venules then vein and finally vena cava. The cross sectional area of vena cava is more than 2 times greater than the aorta. So the velocity of blood returning to the heart is low. Blood always flows from high pressure to low pressure and this pressure causes the blood to flow from aorta to vena cava [1].

1.2.5 Dependencies of Arterial Blood Pressure

Arterial blood pressure depends on some important factors and these are, heart rate, stroke volume, blood volume, peripheral resistance, and blood viscosity.

Heart rate: In medulla oblongata of the brain there is a cardio regulatory center which can change the heart rate by autonomic nervous system. Autonomic nervous system is a division of peripheral nervous system which is divided into sympathetic nervous system and parasympathetic nervous system. To slow the heart rate, vagus nerve conducts a

parasympathetic motor impulse and to increase heart rate, sympathetic motor fiber conduct a sympathetic motor impulse. There are receptors within the cardiovascular system. These receptors send sensory information to the cardio regulatory center. Baroreceptor is a such kind of receptor which is in the blood vessel and sense the blood pressure. If blood pressure falls the baroreceptor signal the cardio regulatory center and then the sympathetic motor sends impulse to the heart which increases the heart rate, similarly if the blood pressure begins to increase above normal parasympathetic motor impulse from the cardio regulatory center decreases the heart rate.

Stroke volume: Stroke volume is the quantity of blood leaves a ventricle. It depends on the strength of contraction. Two factors influence the strength of heart contraction - **venous return** and **blood pressure difference**. *Venous return* is the amount of blood entering the heart by vena cava or pulmonary veins. If the heart rate is slow it will take more time to fill the ventricles and this will increase the strength of contraction. If blood loss happens then there is low venous return and this will decrease the strength of heart contraction. According to Starling's law, the strength of contraction will be affected by any event that decreases or increases the volume or speed of blood entering the heart. *Blood pressure difference* is ventricular contraction strength which needs to be strong to oppose the blood pressure of attached arteries [1]

Cardiac output is the total amount of blood pumped out from the heart in one minute. An average human's cardiac output is 5.25L per minute. Cardiac output is defined as the product of heart rate and stroke volume, i. e. ,

$$\text{Cardiac Output} = \text{HR} \times \text{Stroke Volume}$$

Blood volume: Blood volume is the total formed element and plasma volumes in the vascular system. It may vary according to age, body size, and gender. Most adults have 5liters of blood approximately. Volume and blood pressure is directly proportional. Changes in blood volume changes pressure.

Viscosity: Viscosity is the resistance of blood flow. It is caused by the molecular or cell attraction of one another. If the viscosity is higher the resistance of blood flow is greater. Thus the increase of resistance or increase of blood viscosity causes the blood pressure to rise.

Peripheral resistance: It is defined as the resistance to blood flow through the arteries. It is determined by the blood vessel diameter and the contraction force applied by the vascular smooth muscle. It is an important factor for blood pressure [2].

1.3 Methods to measure Blood Pressure

Blood pressure is the force, which blood applies against the blood vessels. It generally refers the pressure in the arteries. Blood pressure in aorta is the highest which is the largest artery in the body. Aorta starts at the top of the left ventricle. Heart pumps out blood from the left ventricle to aorta. As heart forces blood into the aorta, blood pressure is high on the aorta. Blood pressure is lowest in the vena cava as they are the farthest from the left ventricle. The rise and fall of the arterial blood pressure occur according to the cardiac cycle phases which are described in sec. 1.2. There are two phase of blood pressure.

a. Systolic blood pressure (SBP): It is the pressure during the ventricular contraction. During the phase of the ventricular systole heart pumps out blood and exert a force to the aorta. This pressure is called systolic blood pressure.
b. Diastolic blood pressure (DBP): It is the lowest pressure in arteries before next ventricular contraction [1].

Fig. 1.4 shows that the variation of SBP and DBP from aorta to vena cava. BP value is highest in the aorta than the large arteries.

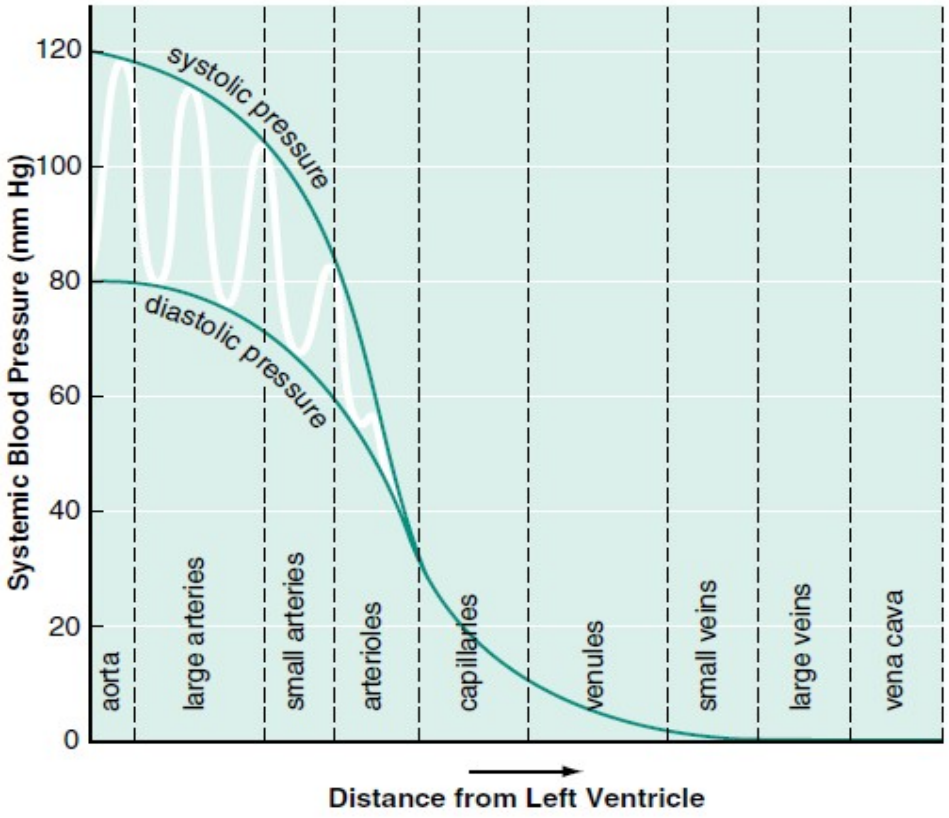

Fig. 1.4. Change of blood pressure throughout the circulatory system [1].

There are two ways to measure blood pressure. One is invasive and the other is noninvasive. One of the way to measure blood pressure invasively is cardiac catheter. In this process a catheter is inserted into a large blood vessel which leads to the heart, then a pressure transducer is used to measure the blood pressure in aorta [3]. Detail discussion of this process is beyond the scope of this work. On the other hand, there are several ways to measure blood pressure non-invasively. The most widely used method is measuring blood pressure using sphygmomanometer. The process to measure blood pressure non-invasively using sphygmomanometer is given below.

Blood pressure measurement using sphygmomanometer: Sphygmomanometer and stethoscope are used together to measure blood pressure from brachial artery. It shows the blood pressure in mmHg (millimeter mercury). This technique was first discovered by Russian surgeon Nikolai Korotkoff in 1905 [4]. He first identified the blood flow sound using stethoscope which is now known as “Korotkoff sound”. At first an inflatable rubber cuff is

wrapped around the patient's arm and the stethoscope is placed over brachial artery. The cuff is inflated using squeezable bulb until no blood flows through the brachial artery. During this time, no sound can be heard through the stethoscope. Then the cuff pressure is released gradually by opening the air valve of the squeezable bulb. When the cuff pressure goes below the systolic pressure blood flows through the brachial artery for the every time of ventricular contraction. This flow of blood produces vibration in the blood and in the surrounding tissues. This vibration can be heard using the stethoscope. The pressure at which the korotkoff sound is first heard, is called the systolic pressure. As the pressure in the cuff decreases due to the air valve opening in the squeezable bulb the korotkoff sound changes loudness and tone. After certain time, no sound is heard due to unconstrict cuff pressure. The pressure of the cuff at which the sounds disappear is called diastolic pressure. For a young adult the normal blood pressure is 120/80 mmHg. The higher number indicates the systolic pressure or the pressure at which left ventricle contracts and the lower number indicate the diastolic pressure or the pressure at which left ventricle relaxes [1].

From Fig. 1.5 this can be seen that, when blood pressure is more than BP 120mmHg, the brachial artery stops blood flowing. From BP 120mmHg, blood starts to flow and korotokoff sound is heard through the stethoscope and finally for pressure less than 80mmHg blood flows normally and no sound is heard.

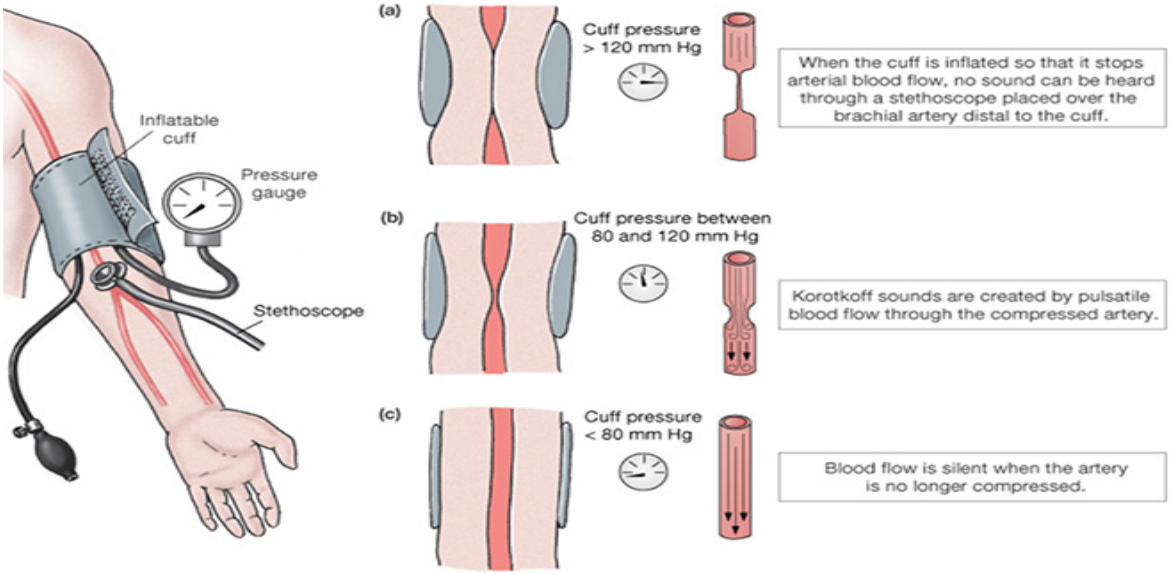

Fig. 1.5. Blood pressure measurement using sphygmomanometer and stethoscope [9].

Reported non-invasive techniques to measure BP: PPG along with ECG is considered as a potential noninvasive approach to measure blood pressure. Most of the PPG based BP estimation techniques employ pulse transit time (PTT) which requires ECG signal, as well as PPG. The PTT based methods use pulse wave velocity, which is the propagation of pressure pulse from the heart to a peripheral site and can be calculated from the time difference of ECG '*R*' wave and PPG. One of the problems of these techniques is that, to attain a satisfactory performance, ECG and PPG need to be synchronized. To overcome this problem, researchers have been proposing BP measurement technique only from the PPG signal. A method proposed in [5] extracts features, such as, width of 2/3 pulse amplitude and width of 1/2 pulse amplitude, systolic upstroke time, and diastolic time to measure BP. However, this

method did not perform well in measuring SBP. A machine learning approach to estimate BP is proposed in [6]. The SBP estimation using higher frequency component of PTT and lower frequency component from intermittently acquired SBP by auscultatory or oscillometric system is developed in [7]. A method proposed in [8] uses the key features of PPG signal, such as, amplitude and cardiac components and finally BP is estimated employing artificial neural network (ANN).

1.4 Classification of Blood Pressure

According to the range of systolic and diastolic pressure, blood pressure is classified into three types.

1. **Ideal blood pressure:** In this stage the value of systolic pressure range is 120-90mmHg and diastolic pressure range is 80-60mmHg [9]
2. **High blood pressure or hypertension:** According to the American college of Cardiology (ACC) and American Heart Association (AHA), the categories of high blood pressure is given below [10].
   i. Normal: Less than 120/80mmHg
   ii. Elevated: Systolic between 120-129mmHg and diastolic less than 80mmHg.
   iii. Stage 1: Systolic between 130-139mmHg or diastolic between 80-89mmHg
   iv. Stage 2: Systolic at least 140or diastolic at least 90mmHg.
   v. Hypertensive Crisis: Systolic over 180mmHg and diastolic over 120mmHg.
3. **Low blood pressure:** Systolic Pressure is less than 90mmHg and diastolic pressure is less than 60mmHg [9].

Table 1.1: Classification of blood Pressure

Blood Pressure	Sub category	SBP (mmHg)	DBP (mmHg)
Ideal Blood Pressure	NA	120-90	80-60
High Blood Pressure	i. Normal	120	80
	ii. Elevated	120-129	<80
	iii. Stage 1	130-139	80-89
	iv. Stage 2	>140	>90
	v.Hypertensive Crisis	>180	>120
Low Blood Pressure	NA	<90	<60

1.5 Clinical importance of blood pressure

High blood pressure or hypertension is one of the number one killer which is also known as 'silent killer'. One may have high blood pressure without symptoms. High blood pressure put extra force to the blood vessel, heart, brain, kidneys and other organs. Continuous high blood pressure may cause heart disease, heart attack, heart failure, strokes, kidney disease, vascular dementia etc [11]. The only way to diagnose high blood pressure is to measure BP regularly. Known case of hypertension is manageable with proper medication. Low blood pressure or hypotension may not show symptoms always. It is not a problem but significant low blood pressure causes symptoms like dizziness, chest pain, fainting, blurred vision, fatigue etc. Extreme low blood pressure manifested with shock which can be life threatening [12].

Chapter 2

2.1 Photoplethysmography (PPG)

PPG is the most commonly displayed waveform which shows the volumetric change of an organ [13]. It is a simple low cost technique to measure the changes of blood volume in the microvascular tissue [14]. PPG can be obtained by pulse oximeter. Information regarding cardiovascular system, blood pressure, oxygen saturation can be derived from PPG.

In PPG, invisible infrared light (wavelength of around 900nm) is sent into the tissue and the backscattered light represents the variation of the blood volume. PPG was first discovered in 1937 by Alrick Hertzman. Hertzman named it photoelectric plethysmograph as he believed that it was connected to blood volume changes. He uses the word 'plethysmos' which means fullness in Greek [15].Fig. 2.1shows raw PPG signal and corresponding filtered PPG signal.

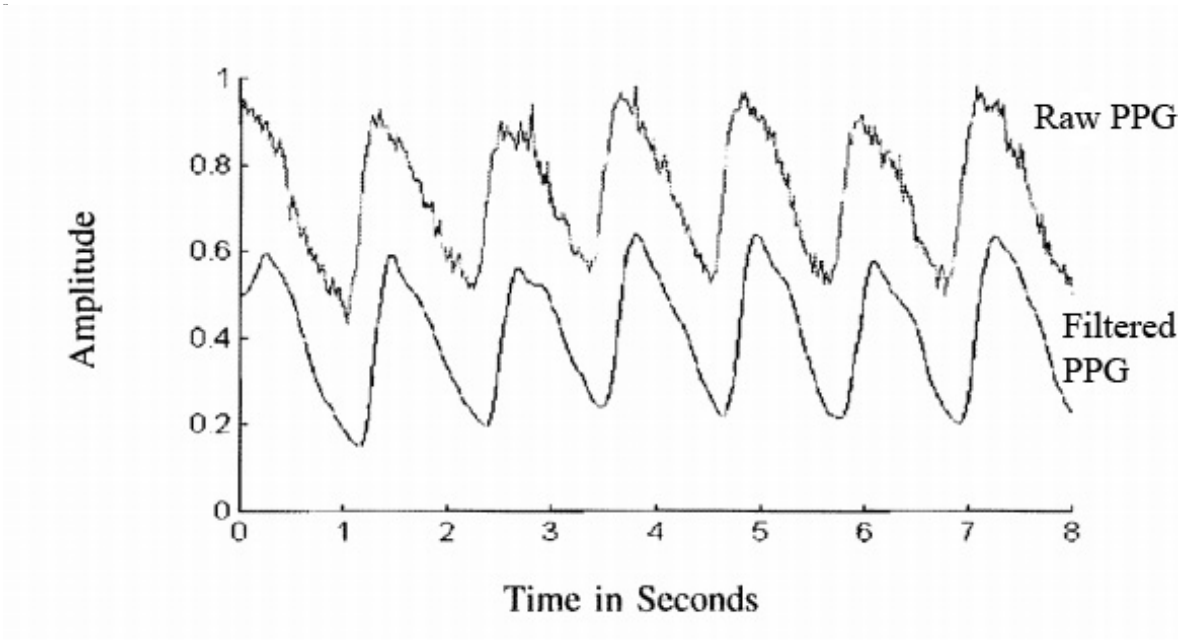

Fig. 2.1. Raw PPG signal and filtered PPG signal [16].

2.2 Components of PPG

This volumetric measurement of change in blood volume depends on the principle that the blood absorbs infrared light more than the surrounding tissue. Low level infrared light is used to detect small changes in blood volume. The quantity of blood cannot be measured by PPG rather it gives a relative measurement [16]. The PPG signal has two components, these are, pulsatile component and DC component. The pulsatile component is called the AC component. The AC component represents the variations in blood volume and it is synchronized with heart beat and caused by the pulsation of blood pressure over cardiac cycle [17]. The AC component is superimposed on the DC baseline. The DC component is the unchanging part and it is determined by the tissue structure, venous and arterial blood volumes. This DC part is generated from the reflection and transmission of the optical signal by the tissues.

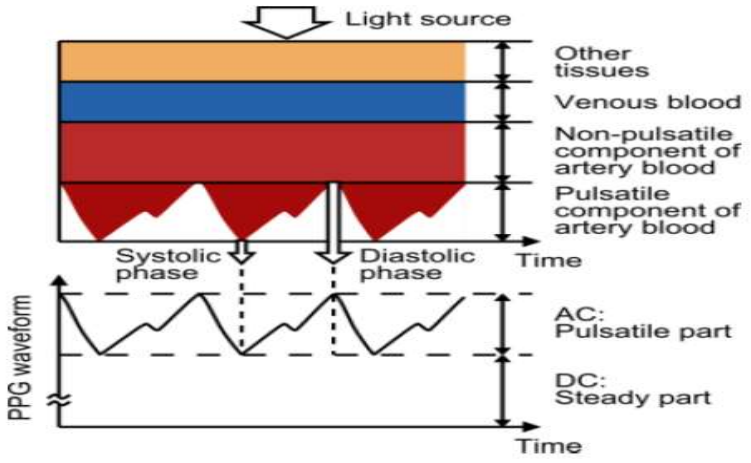

Fig. 2.2. Components of a PPG signal [18].

2.3 Features of PPG

The prominent features of a PPG signal reported in literature are described below [19].

Systolic amplitude (SA): It is the indicator of the blood volume changes and is related to stroke volume. Systolic amplitude has a good potential to estimate continuous blood pressure. Systolic amplitude is shown in Fig. 2.3.

Pulse width (PW): Pulse width is correlated to the systemic vascular resistance. It is the width of the signal measured at the half height of the systolic peak. Pulse width is shown in Fig. 2.3.

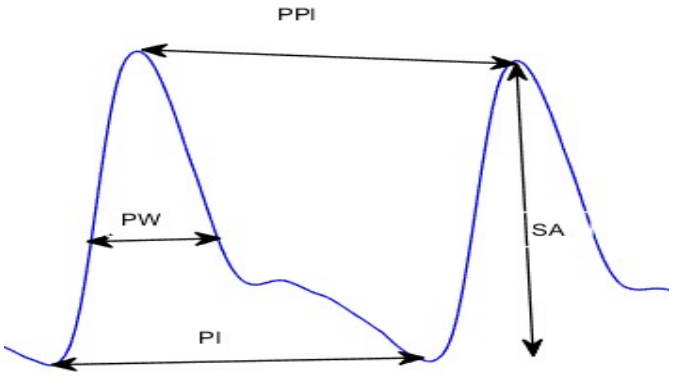

Fig. 2.3. Features of PPG signal.

Peak to Peak Interval (PPI): Peak to peak interval is defined as the difference between two consecutive systolic peaks (shown in Fig. 2.3).

Pulse Interval (PI): Pulse interval is the difference between the beginning and the end of a PPG wave (as shown in Fig. 2.3). Pulse interval and systolic amplitude ratio provide information about a person's cardiovascular system.

2.4 Modes of PPG operation

For non-invasive diagnostic, PPG operational configurations are of two types, these are transmission mode and reflection mode. In the transmission mode of operation, the sample is placed between the source and detector or photo sensor. On the other hand, in reflection mode operation, the light source and detector are placed side by side. The use of transmission mode PPG is more restricted than reflection mode PPG due to the availability of body location.

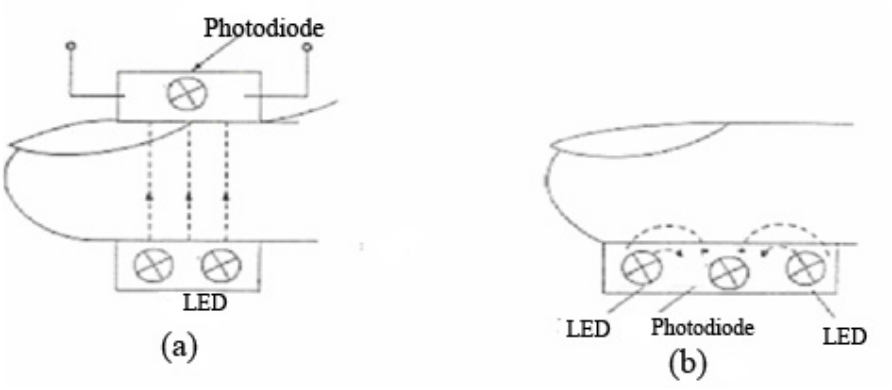

Fig. 2.4. a. Transmission mode operation b. Reflection mode operation [20].

2.5 Application of PPG

In various clinical setup PPG technology is used. Some notable applications of PPG signal include [21]:

1. Oxygen saturation in blood
2. Blood pressure
3. Cardiac output
4. Heart rate
5. Microvascular blood flow
6. Heart rate variability
7. Respiration

Chapter 3

3.1 Data source

In this study, MIMIC (Multiparameter Intelligent Monitoring in Intensive Care) database is used. MIMIC is an open source database [22]. It was developed by the MIT lab. MIMIC contains health data of more than 40,000 critical care patients. For our study we have selected 20 patient's ECG, ABP and PPG data. The ECG, ABP and PPG data were taken simultaneously at 125Hz sampling rate. The PPG data were taken from fingertip using the standard pulse oximeter.

3.2 Proposed Method

Two important features of PPG signal have been discussed in section 2.3. One of these is peak to peak interval (PPI) and the other is pulse interval (PI). PPI is the peak difference of two consecutive PPG wave and PI is the difference of start and end of a PPG wave. Accordingly, PPI and PI can be expressed as,

$$PPI_i = Tp_{(i+1)} - Tp_i \; [i = 1,2,3,.....n]$$

$$PI_i = Tv_{(i+1)} - Tv_i \; [i = 1,2,3,.....n]$$

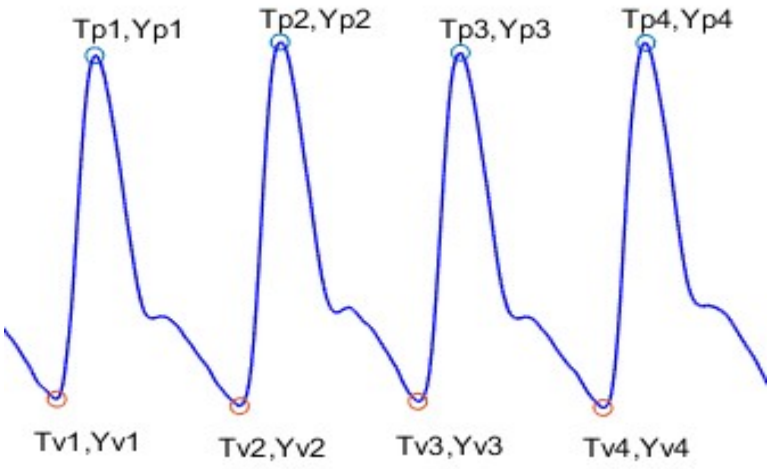

Fig. 3.1. Peak and valley points of a PPG wave.

SBP and DBP is expressed as,

$$SBP_i = SBP_o \times \frac{PPI_o}{PPI_i} \; [i = 0,1,2,3,.....n]$$

$$DBP_i = DBP_o \times \frac{PI_o}{PI_i} \; [i = 0,1,2,3,.....n]$$

Here,

PPI = Peak to peak interval.

Tp_i = Time of first peak (When, i=1).

$Tp_{(i+1)}$ = Time of second peak (When, i=1).

PPI_o = Initial value of PPI.

SBP_o = Initial value of SBP.

PI = Pulse interval.

Tv_i = Time of first valley (When, i=1).

$Tv_{(i+1)}$ = Time of second valley (When, i=1).

PI_o = Initial value of PI.

DBP_o = Initial value of DBP.

3.3 PTT and PIR based method

We will compare our estimated result with the PTT and PIR based method [23]. PTT is the Pulse Transit Time and PIR is Photoplethysmogram Intensity Ratio. PTT is the time interval between the R wave peak of ECG signal and the peak of the first derivative of PPG signal in the same cardiac cycle. PIR is the ratio of PPG peak intensity to the PPG valley intensity of one cardiac cycle. According to this method, SBP and DBP is calculated as:

$$DBP = DBP_o \frac{PIR_o}{PIR}$$

$$SBP = DBP_o \frac{PIR_0}{PIR} + (PP)^2$$

Where pulse pressure (PP) is defined as

$$PP = PP_o \left(\frac{PTT_o}{PTT} \right)^2$$

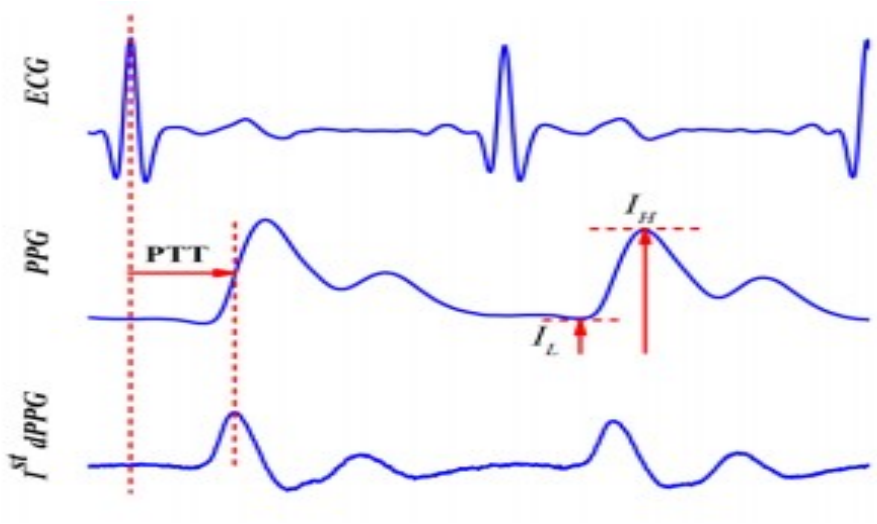

Fig. 3.2. Calculation of pulse transit time (PTT), photoplethysmogram intensity ratio (PIR) and 1stdPPG, where dPPG is the first derivative of PPG [19].

Chapter 4

4.1 Result

The continuous arterial blood pressure (ABP) data of a random patient taken from MIMIC database is shown in Fig. 4.1. The signal was collected invasively from one of the radial arteries. The initial systolic pressure is 142mmHg and the diastolic pressure is 45.54mmHg. The following signal is sampled at 125Hz and the duration of the given signal is 90s long.

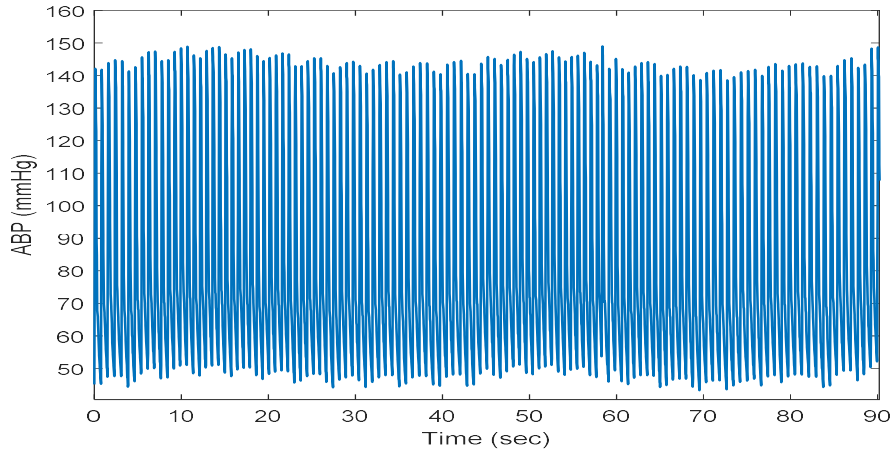

Fig. 4.1. Continuous Arterial Blood Pressure Waveform (Collected from radial artery).

The ABP wave of Fig. 4.1 is used as reference. The peak and the valley of an ABP wave represents the value of systolic and diastolic blood pressure. Beat-to-beat SBP and DBP value of the above ABP signal is shown in Fig. 4.2.

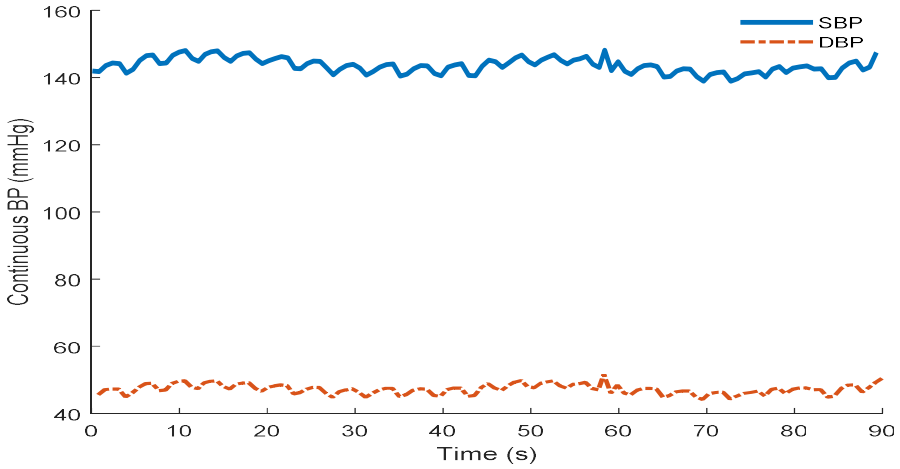

Fig. 4.2. Beat-to-Beat SBP and DBP signal.

The PPG signal collected from the same patient is shown in Fig. 4.3. This signal is also sampled at 125Hz and the length of PPG signal is as of the ABP signal, i.e. ,90s.

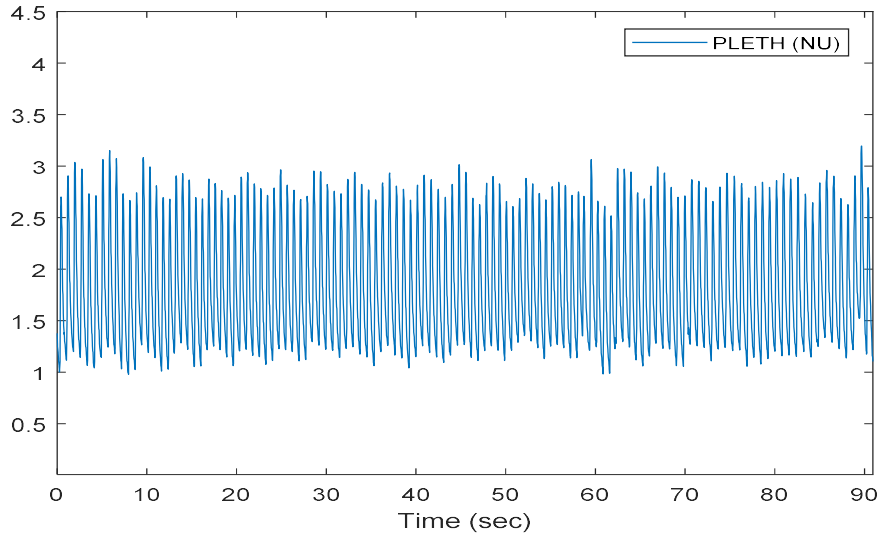

Fig. 4.3. PPG signal: X axis represents time and the Y axis represents the unit of measurement.

Our proposed method estimates SBP and DBP from this PPG signal. The results of the estimated continuous SBP and DBP is shown in Fig.4.4. For the better understanding of the result we compare it with the reference SBP and DBP, which is shown in Fig. 4.5.

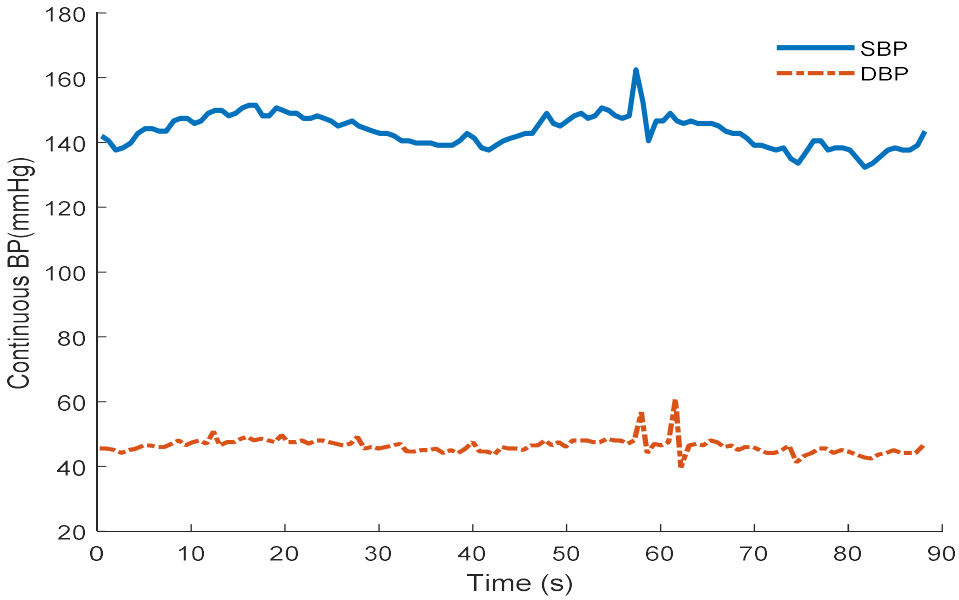

Fig. 4.4. Estimated SBP and DBP.

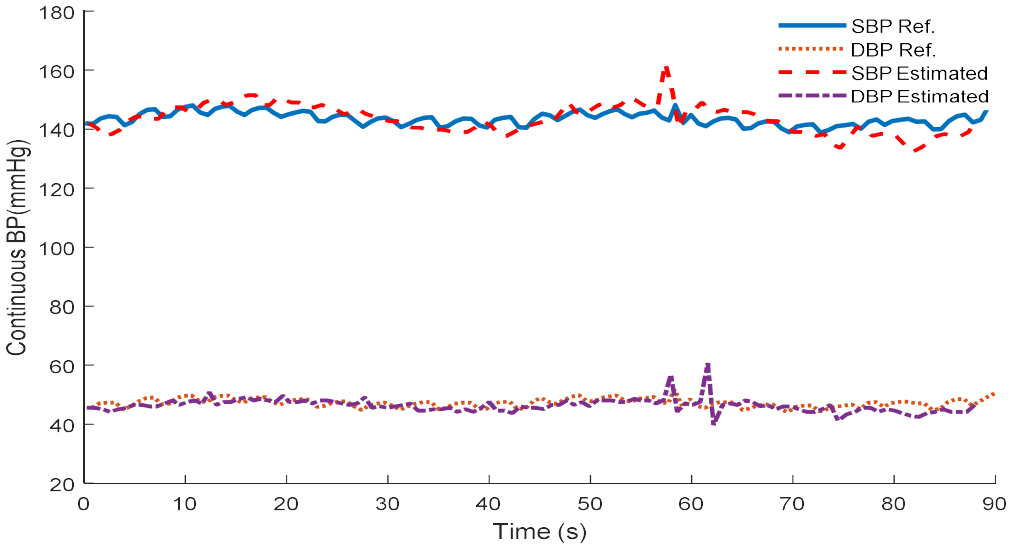

Fig. 4.5. Comparison between estimated and reference BP.

4.2 Correlation and Agreement

A comparison in regard to correlation and agreement was done between the results of proposed method and reference BP. The correlation plots of the reference SBP, DBP and the proposed SBP, DBP are shown in Fig. 4.6, and Fig. 4.7, respectively. The correlation coefficient between the proposed method's result and the reference is 0.39 for DBP and 0.50 for SBP.

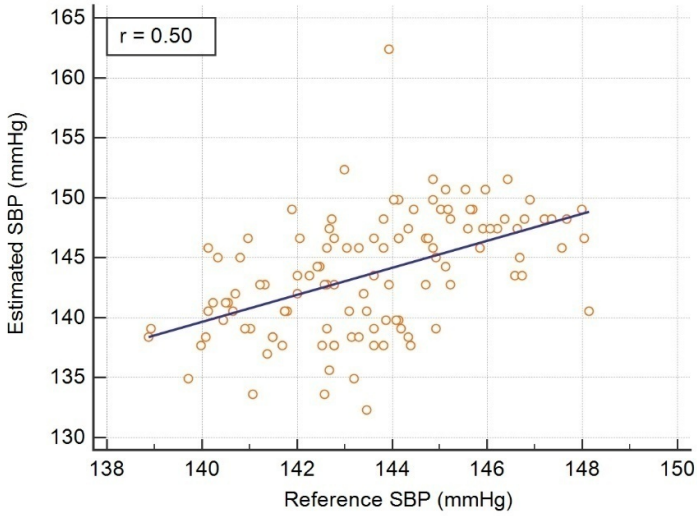

Fig. 4.6. Correlation plot of estimated SBP and reference SBP.

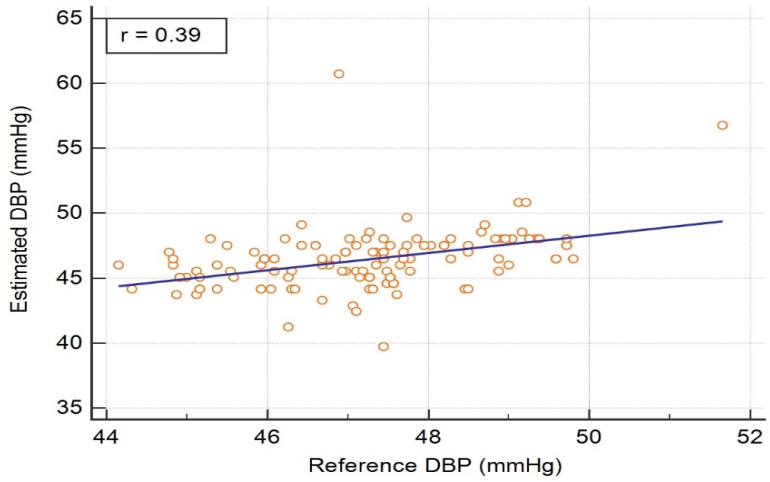

Fig. 4.7. Correlation plot of estimated DBP and reference DBP.

The Bland-Altman plot of SBP and, DBP is shown in Fig. 4.8, and Fig. 4.9, respectively. Bland-Altman plot is 'difference vs average' plot.

Here, difference = $SBP_{ref.}$-$SBP_{estimate}$

$$\text{Average}=\frac{SBP_{\text{Re}f.}-SBP_{estimate}}{2}$$

This plot also shows the standard deviation of the difference between the proposed method and the reference BP. From the plot we can see that the mean bias for SBP and DBP are 0.1 and -0.8 respectively. The bias line is shown by the blue line. The limits of agreement is calculated as $\mu \pm 1.96\sigma$, where μ is the mean bias and, σ is SD. The limits of agreement are shown with red dotted line. From the Bland-Altman plot of SBP and DBP, we can see that except a few, most of the points are within the limits of agreement.

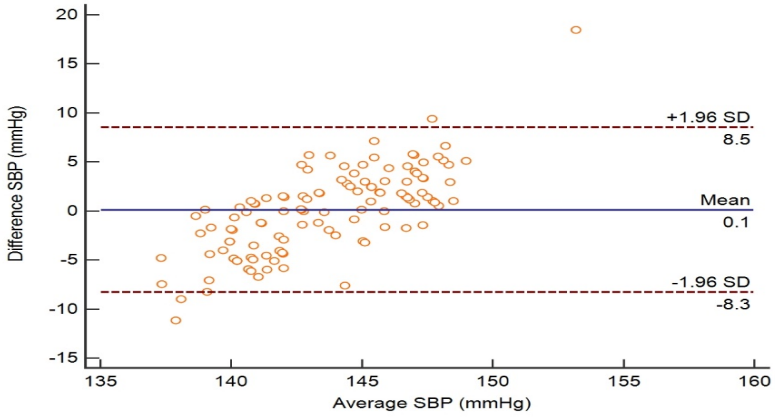

Fig. 4.8. Bland-Altman Plots of estimated SBP with reference SBP.

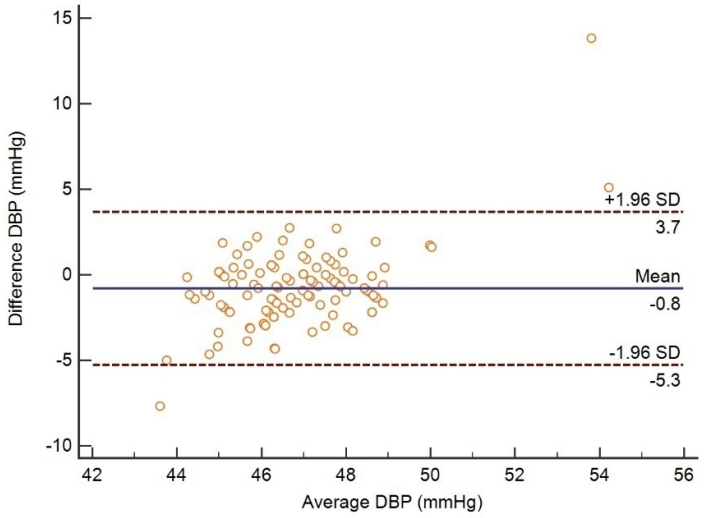

Fig. 4.9. Bland-Altman Plots of estimated DBP with reference DBP.

4.3 Comparison of the proposed method with PTT and PIR based algorithm

Fig 4.10 and Fig. 4.11 show the SBP and DBP comparison with estimated, DBP reference and DBP estimated from PTT and PIR based method.

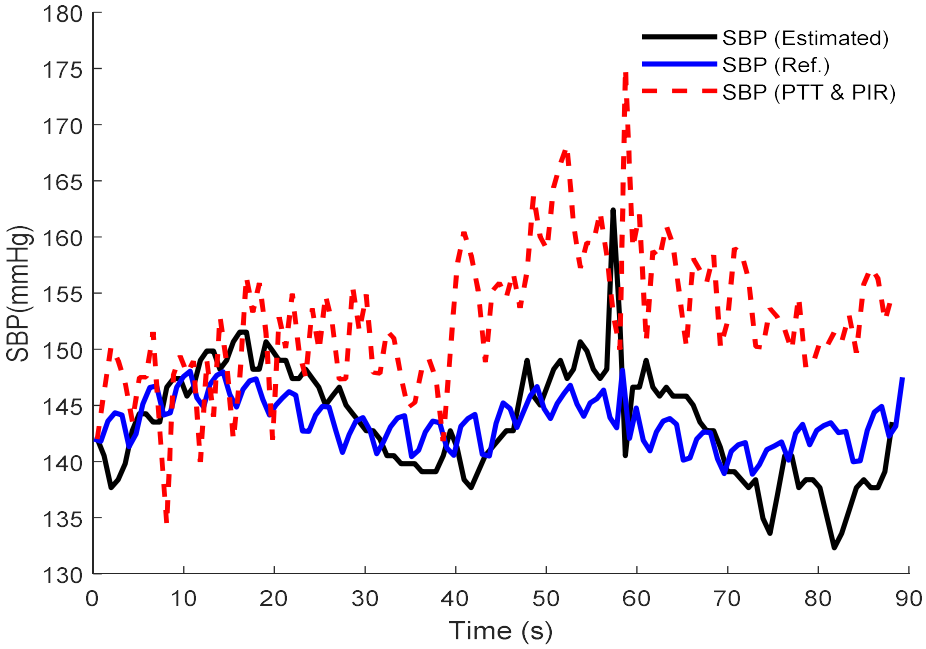

Fig. 4.10. Comparison of SBP estimated, SBP reference and SBP estimated from PTT and PIR based method.

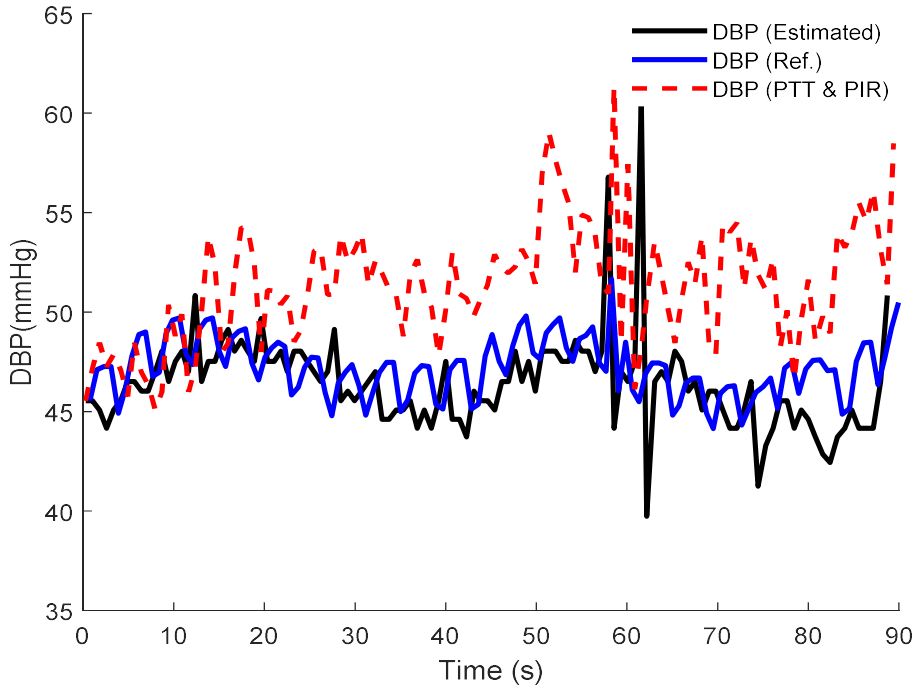

Fig. 4.11. Comparison of DBP estimated, reference and PTT and PIR based method.

From Fig. 4.10 and Fig. 4.11 we can see that the estimated SBP and DBP follow the reference values more closely than the PTT and PIR based method.

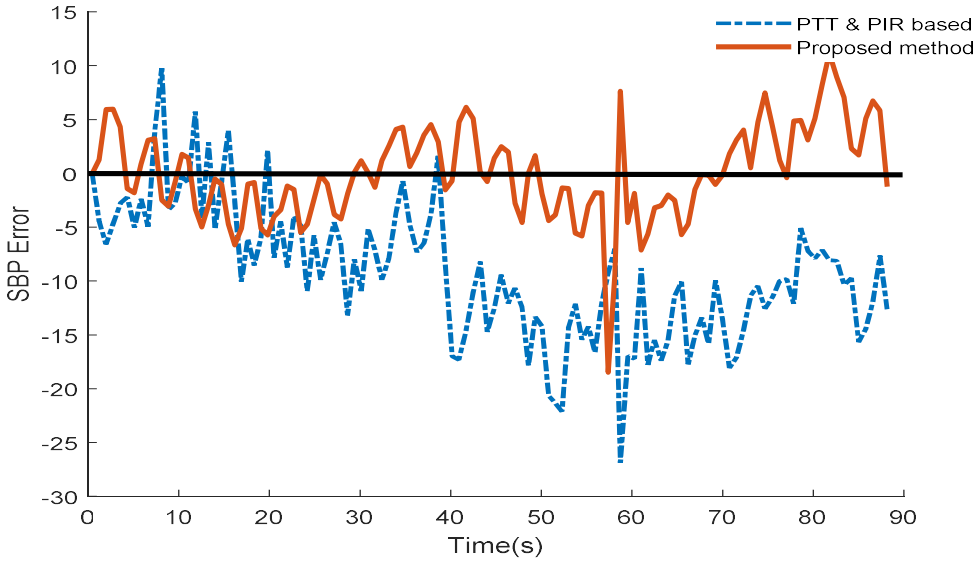

Fig. 4.12. Error plot of $SBP_{ProposedMethod}$ and $SBP_{PTTandPIR\ method}$.

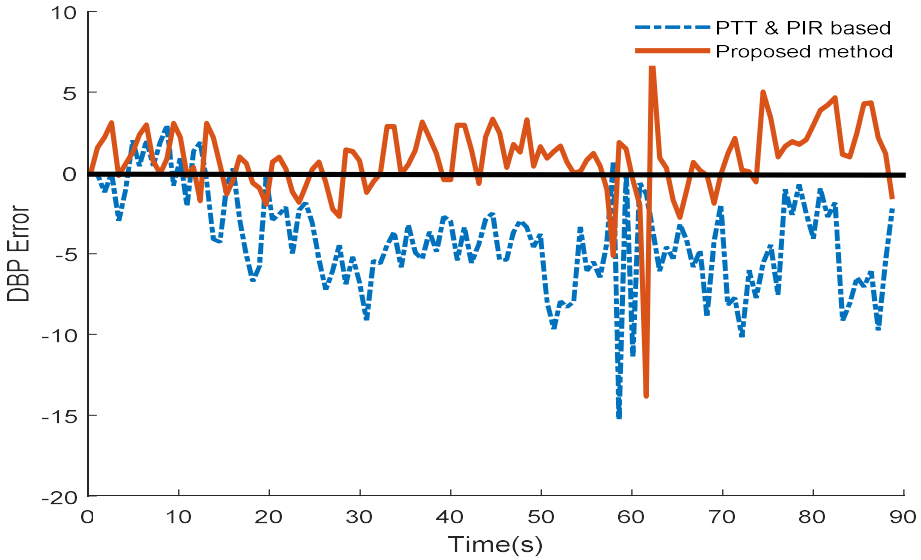

Fig. 4.13. Error plot of $DBP_{Proposed\ Method}$ and $DBP_{PTTandPIR\ method}$.

Fig. 4.12 and Fig.4.13 show the estimated error of proposed and PTT and PIR based method of SBP and DBP. From the plots we can see that the proposed method follow the zero line more closely than the PTT and PIR based method.

Table 4.1 Bland-Altman data for 20 patients.

	SBP			DBP proposed			DBP PTT and PIR based		
Data No.	μ+1.96σ	μ	μ-1.96σ	μ+1.96σ	μ	μ-1.96σ	μ+1.96σ	μ	μ+1.96σ
1	1.6	-3.2	-8.0	0.9	-1.6	-4.1	1.6	-2.5	-6.7
2	5.0	1.3	-2.4	6.2	1.1	-4.0	13.6	-0.2	-14.0
3	1.5	-6.3	-14	3.9	-3.2	-10.2	26.6	8.2	-10.1
4	6.3	1.6	-3.2	5.4	2.0	-1.5	5.0	1.0	-3.1
5	10.7	4.3	-2.2	1.1	-2.0	-5.1	1.4	-7.9	-17.3
6	5.4	0.4	-4.6	13.9	-4.6	-23.2	30.9	8.3	-14.4
7	21.0	-0.7	-22.4	30.5	10.4	-9.7	20.0	-8.2	-36.4
8	7.4	-0.5	-8.3	10.7	-0.4	-11.5	9.7	-10	-29.6
9	1.2	-3.9	-9.0	16.5	2.3	-11.9	5.7	-1.1	-7.9
10	23.7	6.5	-10.8	11.7	1.2	-9.3	8.0	0.0	-8.1
11	4.6	-0.2	-5.0	0.31	-1.08	-2.46	1.7	-1.7	-5.1
12	1.0	-1.7	-4.4	4.8	-1.5	-7.8	7.8	0.9	-6.1
13	39.3	10.1	-19.1	20.9	1.6	-17.7	31.6	-1.9	-35.4
14	4.1	-0.7	-5.5	4.8	-1.0	-6.7	16.7	2.4	-11.9
15	4.7	1.2	-2.3	2.4	-0.7	-1.1	9.9	-3.8	-17.4
16	13.6	4.1	-5.4	11.4	1.8	-7.9	14.7	3.8	-7.0
17	4.2	0.9	-2.5	5.1	1.7	-1.7	1.4	-0.2	-1.8
18	1.7	0.8	-3.2	3.8	-2.2	-8.2	2.0	-3.5	-8.9
19	8.4	-0.3	-8.9	22.9	7.6	-7.7	20.6	9.4	-1.8
20	10.6	3.5	-3.7	4.1	-1.2	-6.6	10.8	-0.7	9.4

According to the US Association for the Advancement of Medical Instrumentation (AAMI) validation standard for the measurement accuracy, the mean difference should be ≤ 5mmHg and the standard deviation should be ≤ 8mmHg [24]. Estimated Mean and SD for our proposed method is shown in table 4.2.

Table 4.2 Mean ± SD data for 20 patients.

Data No.	SBP (Mean ± SD)	DBP (Mean ± SD)
1	-3.20 ± 2.45	- 1.60 ± 1.28
2	1.30 ± 1.89	1.10 ± 2.60
3	-6.30 ± 3.97	-3.20 ± 3.62
4	1.60 ± 2.44	2.00 ± 1.79
5	4.30 ± 3.31	-2.00 ± 1.58
6	-0.40 ± 2.55	-4.60 ± 9.49
7	-0.70 ± 11.07	10.40 ± 10.26
8	-0.05 ± 4.03	-0.40 ± 5.66
9	-3.90 ± 2.66	2.30 ± 7.25
10	6.50 ± 8.82	1.20 ± 5.36
11	-0.20 ± 2.44	-1.08 ± 0.71
12	-1.70 ± 1.37	-1.50 ± 3.21
13	10.10 ± 14.89	1.60 ± 9.85
14	-0.70 ± 2.44	-1.00 ± 2.96
15	1.20 ± 1.78	-0.70 ± 1.58
16	4.10 ± 4.84	1.80 ± 4.95
17	0.90 ± 1.73	1.70 ± 1.73
18	0.80 ± 2.04	-2.20 ± 3.06
19	-0.30 ± 4.43	7.60 ± 7.81
20	3.50 ± 3.67	-1.20 ± 2.80

In this 20 patients data (shown in table 4.2) we have found 14 patients BP estimation as satisfactory and 6 patients BP estimation as unsatisfactory.

4.4 Discussion

In this study we have proposed a method to estimate the continuous blood pressure using PPG. The peak to peak interval and pulse interval of PPG signal are used to estimate BP. For the validation of our proposed method we have taken the same patient's ABP data as the reference. We also take another method in consideration to compare the performance of the proposed method. From the correlation plot we find the positive correlation of the estimated SBP and DBP with the reference values. From the Bland-Altman plot we find that the majority points lie within the limits of agreement. The graphical representation of the estimated and proposed method shows that the proposed SBP and DBP values closely follow the reference. This assessment is further validated using the error plot of SBP and DBP. In the error plot we have also shown the error result from a report method which uses both PPG and ECG. In this method DBP is estimated from the PPG then the SBP is estimated using combined PPG and ECG. The Bland-Altman plot is also produced to measure the accuracy of the proposed algorithm. The accuracy of the proposed method is satisfactory compared to the reported one. Additionally unlike other reported techniques the proposed one eliminates the need of ECG along with PPG to measure BP.

Chapter 5

Conclusion

In this work a non-invasive and easy way to estimate blood pressure is developed using only PPG signal. Pulse oximeters are commonly used in clinics and hospitals to acquire PPG signals. Therefore, only PPG is convenient for continuous assessment of blood pressure. The reliability of this method is verified satisfactory for twenty dataset. In future we aim to test this on a large database and thereby eliminates the limitations of the proposed algorithm and rectify accordingly.

References

[1] S. S. Mader, *Understanding human anatomy and physiology*, McGraw-Hill,5th Ed,pp-224-249.

[2] J. Moini, *Phlebotomy*. Burlington, MA: Jones & Bartlett Learning, 2013.

[3] "Cardiac Catheterization", *Heart.org*, 2018. [Online]. Available: http://www.heart.org/HEARTORG/Conditions/HeartAttack/SymptomsDiagnosisofHeartAttack/Cardiac-Catheterization_UCM_451486_Article.jsp#.WraAt4hubIU. [Accessed: 24- Mar- 2018].

[4] D. Paskalev, A. Kircheva and S. Krivoshiev, "A Centenary of Auscultatory Blood Pressure Measurement: A Tribute to Nikolai Korotkoff", *Kidney and Blood Pressure Research*, vol. 28, no. 4, pp. 259-263, 2005.

[5] X. Teng and Y. Zhang, "Continuous and noninvasive estimation of arterial blood pressure using a photoplethysmographic approach", *Proceedings of the 25th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (IEEE Cat. No.03CH37439)*, Vol.4, pp. 3153-3156, 2003.

[6] F. Lamonaca, K. Barbe, Y. Kurylyak, D. Grimaldi, W. Van Moer, A. Furfaro and V. Spagnuolo, "Application of the Artificial Neural Network for blood pressure evaluation with smartphones", *2013 IEEE 7th International Conference on Intelligent Data Acquisition and Advanced Computing Systems (IDAACS)*, 2013.

[7] W. Chen, T. Kobayashi, S. Ichikawa, Y. Takeuchi and T. Togawa, "Continuous estimation of systolic blood pressure using the pulse arrival time and intermittent calibration", *Medical & Biological Engineering & Computing*, vol. 38, no. 5, pp. 569-574, 2000.

[8] Xing, Xiaoman, and Mingshan Sun. "Optical Blood Pressure Estimation with Photoplethysmography and FFT-Based Neural Networks." *Biomedical Optics Express* 7.8 (2016): 3007–3020. *PMC*. Web. 2 Apr. 2018.

[9] M. Team, "3 Types of Blood Pressure Monitoring Devices - Sphygmomanometers - Medicwiz", *Medicwiz.com*, 2018. [Online]. Available: https://www.medicwiz.com/medtech/diagnostics/3-types-of-blood-pressure-monitoring-devices-sphygmomanometers. [Accessed: 24- Mar- 2018].

[10] "New ACC/AHA High Blood Pressure Guidelines Lower Definition of Hypertension", American College of Cardiology, 2018. [Online]. Available: http://www.acc.org/latest-incardiology/articles /2017/11/08/11/47/mon-5pm-bp-guideline-aha-2017. [Accessed: 24- Mar- 2018].

[11] "High blood pressure (hypertension)", *nhs.uk*, 2018. [Online]. Available: https://www.nhs.uk/conditions/high-blood-pressure-hypertension/. [Accessed: 20- Mar- 2018].

[12] "Low blood pressure (hypotension)", *nhs.uk*, 2018. [Online]. Available: https://www.nhs.uk/conditions/low-blood-pressure-hypotension/. [Accessed: 20- Mar- 2018].

[13] "Photoplethysmogram", *En.wikipedia.org*, 2018. [Online]. Available: https://en.wikipedia.org/wiki/Photoplethysmogram. [Accessed: 18- Mar- 2018].

[14] J. Allen, "Photoplethysmography and its application in clinical physiological measurement", *Physiological Measurement*, vol. 28, no. 3, pp. R1-R39, 2007.

[15] A. Alian and K. Shelley, "Photoplethysmography", *Best Practice & Research Clinical Anaesthesiology*, vol. 28, no. 4, pp. 395-406, 2014.

[16] M.Mukunda Rao & R. Ramana Ram, "Photoplethysmography: A noninvasive tool for possible subtle energy monitoring during yogic practices." *Energies and Energy Medicine.* Volume 17, Number 2, pp 163-179.

[17] X. Xing and M. Sun, "Optical blood pressure estimation with photoplethysmography and FFT-based neural networks", *Biomedical Optics Express*, vol. 7, no. 8, p. 3007, 2016.

[18] T. Tamura, Y. Maeda, M. Sekine and M. Yoshida, "Wearable Photoplethysmographic Sensors—Past and Present", *Electronics*, vol. 3, no. 2, pp. 282-302, 2014.

[19] M. Elgendi, "On the Analysis of Fingertip Photoplethysmogram Signals", *Current Cardiology Reviews*, vol. 8, no. 1, pp. 14-25, 2012.

[20] Selected Cardiovascular Studies Based on Photoplethysmography Technique - Scientific figure on ResearchGate. [Online]. Available: https://www.researchgate.net/Arrangement-of-photodiode-and-LED-in-a-PPG-probe-a-Transmission-method-b_fig2_47799749 [accessed 25 Mar, 2018]

[21] M. SushaCheriyedath, "Photoplethysmography (PPG)", *News-Medical.net*, 2018. [Online]. Available: https://www.news-medical.net/health/Photoplethysmography-(PPG).aspx. [Accessed: 25- Mar- 2018].

[22] Physiobank, physiotoolkit, and physionet components of a new research resource for complex physiologic signals. Goldberger AL, Amaral LAN, Glass L, Hausdorff JM, Ivanov P, Mark RG, Mietus JE, Moody GB, Peng C, and Stanley HE. Circulation. 101(23), pe215–e220. 2000.

[23] X. Ding, Y. Zhang, J. Liu, W. Dai and H. Tsang, "Continuous Cuffless Blood Pressure Estimation Using Pulse Transit Time and Photoplethysmogram Intensity Ratio", *IEEE Transactions on Biomedical Engineering*, vol. 63, no. 5, pp. 964-972, 2016.

[24] Stergiou, G., Alpert, B., Mieke, S., Asmar, R., Atkins, N., Eckert, S., Frick, G., Friedman, B., Graßl, T., Ichikawa, T., Ioannidis, J., Lacy, P., McManus, R., Murray, A., Myers, M., Palatini, P., Parati, G., Quinn, D., Sarkis, J., Shennan, A., Usuda, T., Wang, J., Wu, C. and O'Brien, E. (2018). A Universal Standard for the Validation of Blood Pressure Measuring Devices. *Hypertension*, 71(3), pp.368-374.