Study on Cuff-Less Blood Pressure Measurement Based on Electrocardiography and Photoplethysmography Signal

Putri Indes Oktabriani *, Fuad Ughi & Aulia Arif Iskandar

Department of Biomedical Engineering, Faculty of Life Sciences and Technology Swiss German University, Indonesia

*oputriindes@gmail.com

Abstract: The continuous blood pressure measurement research is widely known for helping the development of ambulatory blood pressure monitoring where it measures blood pressure every 15 to 30 minutes throughout the day. The cuff is a problem for the patient with Ambulatory Blood Pressure Monitor. It can make a person feel uncomfortable and must stay still when the cuff starts to inflate. It is limiting and disturbing their daily activity when the device is starting to measure the blood pressure. Blood pressure measurement without cuff is being proposed in this research, called cuff-less blood pressure measurement. It will be based on Photoplethysmography (PPG) and Electrocardiography (ECG) signal analysis. ECG (Lead 1, Lead 2, and Lead 3) with PPG signal produced from index finger on the left hand are compared and analyzed. Then the relation of PPG and ECG signal and the optimum location for daily use can be obtained. The optimum location will be based on the electrode's position that produced the optimum ECG lead Signal to measure blood pressure. Based on the result, PPG and ECG signal have a linear relation with Blood Pressure Measurement and Lead 1 is more stable in producing the ECG signal. The equation from Lead 1 appeared as one of the optimum equations for measuring Systolic Blood Pressure (SBP) or Diastolic Blood Pressure (DBP).

Keywords: Photoplethysmogram, Electrocardiogram, Cuff-less Blood Pressure Measurement, Ambulatory Blood Pressure, Blood Pressure.

1. Introduction

Blood pressure is one of the factors regarding the body condition. Blood pressure will show the condition of the blood in the body. Blood pressure measurement is divided into two, the systolic and diastolic blood pressure measurement. The systolic blood pressure is known as blood pressure when the heart is beating and the diastolic blood pressure is known as blood pressure when the heart is relaxed. Nowadays, blood pressure monitoring also attracts people attention in viewpoint lifestyles disease prevention (Atomi et al., 2017).

The continuous blood pressure measurement research is being done for helping the development of ambulatory blood pressure monitoring. It will allow people to maintain and observe these blood pressure changes for 24 hours. In Figure 1, it can be seen that ambulatory blood pressure monitor is blood pressure measurement device where the monitor is connected to a cuff by plastic tube on the upper arm. The device is usually worn by people with hypertension, throughout the day even when they are sleeping. Hypertension is a condition where the blood pressure is always above normal blood pressure. There are probably 20% person that do not know when their blood pressure is high and there are no definitive causes of 90% cases in Hypertension (Hypertension and Hypotension, 2018). Ambulatory blood pressure monitoring records the blood pressure 24 hours automatically while patients are doing their daily activities. It measures blood pressure every 15 to 30 minutes throughout the day. The ambulatory monitor can be used as a standard to predict the risk related to blood pressure. The prediction of an ambulatory monitor on clinical outcome is better than conventional blood pressure measurement (Pickering et al.,2006).

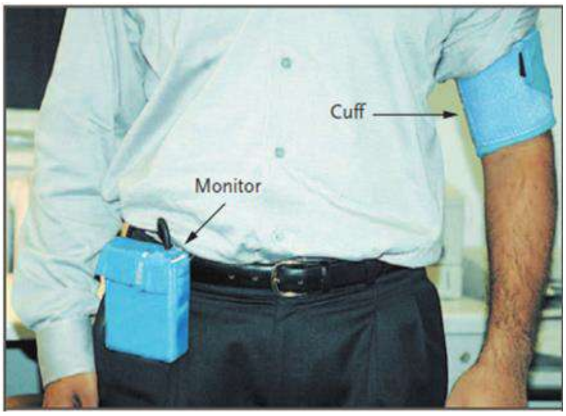


Figure 1. Ambulatory Blood-Pressure Monitor (Pickering et al.,2006).

The continuous monitoring of blood pressure is impossible with digital blood pressure measurement because the measurement result is only at that time (Ma, 2014) and it has limitations and risks (Sun et al.,2016). The cuff makes a person feel uncomfortable when measuring the blood pressure. A person with ambulatory monitor must stay still when the cuff starts to inflate (Pickering et al.,2006).

Blood pressure measurement without cuff is being proposed in this research and by several researchers, called cuff-less blood pressure measurement. The cuff-less blood pressure measurement will be based on Photoplethysmography (PPG) and Electrocardiography (ECG) signal analysis. From the signal analysis, an equation for blood pressure measurement can be obtained and blood pressure can be measured.

To analyze the ECG and PPG signal, the ECG and PPG signal must be noiseless. To obtain it without noise is quite hard since some noises come from the environment. One factor that also effects the ECG and PPG signal result is the location of the sensor. By finding the optimum location for the sensor, The ECG (represent by Lead 1, Lead 2 and Lead 3) and PPG sensor can produce a signal without any noises. This research will focus on finding the optimum ECG location or configuration for measuring blood pressure.

This research will show the relation of ECG and PPG signal for blood pressure measurement since cuff-less blood pressure measurement is based on it. From the relation, the equation for measuring the blood pressure can be found.

The measurement of cuff-less blood pressure has some limitations too. The problem is the equation for each people is different. The equation is personalized based on their blood vessel characteristics. The measurement of Diastolic part is also hard to determine because the diastolic blood pressure does not change just because of physical activities (Joenarto, 2017). This produces low correlation coefficients between Diastolic Blood Pressure (DBP) and parameters computed from ECG and PPG (Špulák et al., 2010). The accuracy to determine DBP is not high as determined Systolic Blood Pressure (SBP).

2. Materials and Research Methodology

2.1. *Materials*

2.1.1. *Photoplethysmography (PPG) Sensor*

The PPG sensor is built on printed circuit board (PCB) at Swiss German University Biomedical Engineering Laboratory based on OPT101 datasheets.

The raw PPG signal has a lot of noise on the signal, band pass filter is needed to eliminate the noise. The band pass filter is made of second order High Pass Filter (HPF) and Low Pass Filter (LPF). The HPF has cutoff frequency 0.3 Hz and the LPF has cutoff frequency 5 Hz where this is set based on heartbeat 12-120 beat per minute (Ughi and Dewanto, 2018). Notch filter is also added to remove the main noise.

2.1.2. Electrocardiography (ECG) Module

The 1-Lead ECG module that will be used is commercial ECG for research that based on Integrated Circuit (IC) AD8232 but not for the medical purposes. The IC AD8232 has cutoff 0.5 Hz for the HPF and 40 Hz for the LPF. It has a lot of amplifiers, there are Instrumentation, Operational, and Right Leg Drive amplifier. The operational amplifier is set with gain 11, resulting a total system gain with 1100 (AD8232 Datasheet and Product Info, 2017).

The 1-Lead ECG needed additional Notch Filter to eliminate main noises with frequency 50 Hz. The Notch Filter is built on PCB together with the notch filter for PPG Sensor. The notch filter for filtering signal ECG and PPG is built based on Notch filter circuit by Nasiqin *et al*, 2015.

2.1.3. Data Storing and Analysis

A data acquisition program based on LabVIEW is used to store the data on a computer. The first signal analysis which determining the time difference between R-peak of ECG and the peak of PPG, will be done with peak detection program (Iskandar, 2017) and analysis further on Microsoft Excel. The Analysis on Microsoft Excel is required to find the relation of Pulse Arrival Time (PAT) - time difference between ECG and PPG peak - with blood pressure, finding the equation to measure blood pressure and calculating the accuracy of the equation. The accuracy can be determined by seeing the R^2 rate or calculating the Mean Square Error (MSE) and Root Mean Square Error (RMSE).

2.1.4. Digital Blood Pressure Measurement

The digital blood pressure measurement device is also needed to compare the estimation of blood pressure comes from the equation and the actual blood pressure at the time of measurement. The Digital Blood Pressure Measurement used in this research is ABN DU-120 blood pressure monitor.

2.2. Research Methodology

This research has been approved by Ethic Committee of University of Indonesia at Salemba, Central Jakarta based on the released approval letter number 0174/UN2.F1/ETIK/2018.

The first thing to do is deciding the group of the category of person. Most previous research chooses healthy young person as subjects. This research will also choose 10 healthy young people (7 Women and 3 Men) as subjects with range 21-25 years with normal Body Mass Index (BMI). The weight and height of subject will be measured and recorded on the book. The Body Mass Index is measured using BMI Calculator on open website from National Heart, Lung, and Blood Institute.

The next thing is collecting the data from the subjects. The data will be taken from the subjects 10 times with 5 minutes interval from each measurement. It was done to make the personal calibration is possible. The four electrodes are placed on right arm, left arm, right leg and left leg. The electrode on the left leg is acting as ground.

The ECG signal that is collected from the subjects is Lead 1, Lead 2, Lead 3 and PPG Signal. The ECG signal of Lead 1, Lead 2, and Lead 3 are obtained at the same time. Three 1-Lead ECG configuration modules are parallel connected and used for measuring the signal from each Lead. The PPG signal is obtained by placing the index finger of the left hand on the PPG Sensor. The data is collected for 35 seconds to make it easier for heartbeat calculation and to avoid cramps and inconvenience for the subjects. The data is taken while the subjects is on sitting position.

There are ten measurements for each subject with different preconditions, which is basically a set of resting and exercising activities to stimulate different blood pressure conditions out of the subject. The set of resting and exercising activities is as below.

1. Rest 1: the subject is on rest condition.
2. Exercise 1: the subjects will be exercising a little bit by going up and down upstairs from 3rd floor to 1st floor for 4 sets.
3. Rest-After 1: the subject is asked to rest by sitting for 5 minutes.
4. Day 2: measured on another day. The subject is on rest condition.
5. Rest 2: measured after 5 minutes interval of the fourth measurement. On this 5-minute interval, the subject is asked to sit and relax.
6. Exercise 2: the subject will run on a place for 3 minutes straight.

7. Rest-After 2: measured after 5 minutes interval of the sixth measurement. During these 5 minutes, the subject needs to sit down and rest.
8. Rest 3: measured after 5 minutes interval of the seventh measurement. They need to be calm and relax.
9. Exercise 3: the last measurement of blood pressure when the subject is on exercise. For this ninth measurement, the subjects need to wait for 5 minutes after the eight measurement and then exercise by running on a place for 3 minutes.
10. Rest-After 3: the last measurement is taken 5 minutes after the ninth measurement in resting condition.

The overall steps for taking the data from the subject is shown on the Flowchart in Figure 2 below. When the signal comes from subject is clear and without noise the data can be stored in computer and analyzed on peak detection program (Iskandar, 2017) to obtain the time difference (PAT).

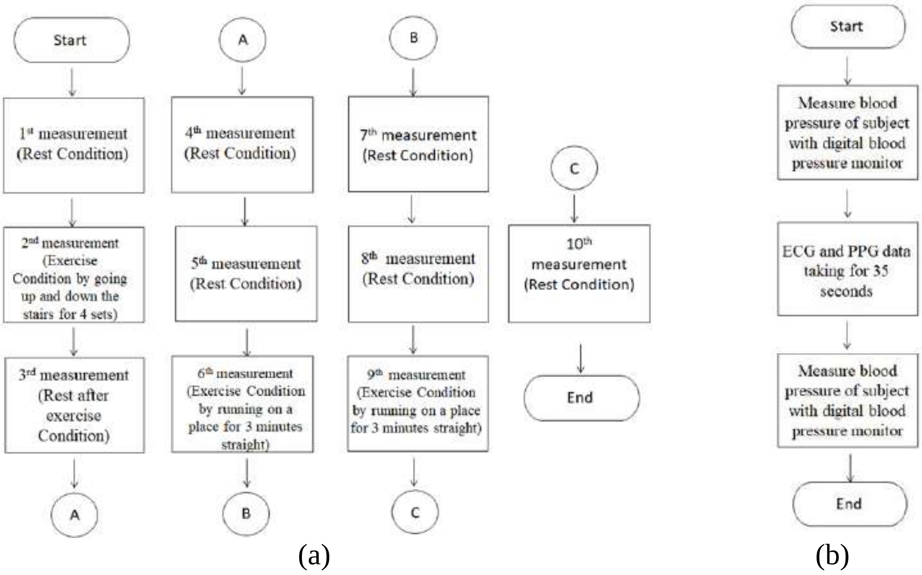


Figure 2. The flowchart of data acquisition. (a) Set of resting-exercising activities. (b) Data taking on each measurement.

After the time difference is obtained, personal calibration of each subject is needed. This calibration is done by finding Pulse Wave Velocity (PWV). It is done on the Microsoft Excel. After all subject have been calibrated, the optimum personalized equation and the relation its PAT to blood pressure for each subject can be obtained by plotting the PWV and average actual blood pressure.

3. Result and Discussion

3.1. PPG Sensor Results

The signal after being filtered is clear and readable, as shown in the graph in Figure 3. The peak amplitude is rising from 0.14 V to 1.46 V.

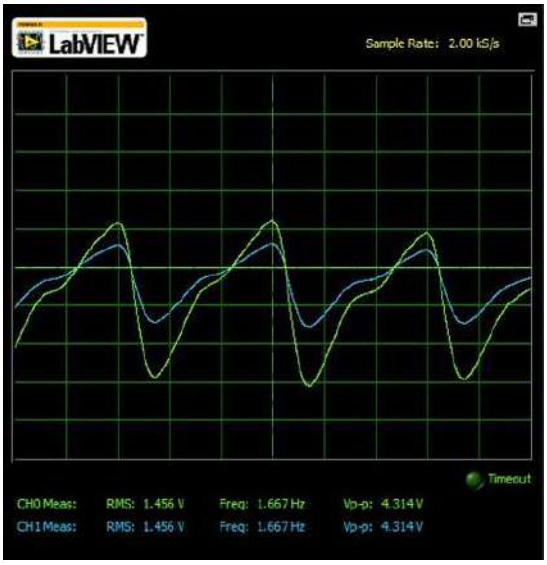


Figure 3. PPG Signal Final Result.

3.2. ECG Sensor Results

The EGC signal after being filtered, is also clear and readable, as shown in the graph in Figure 4. The signal can be used to be analyzed.

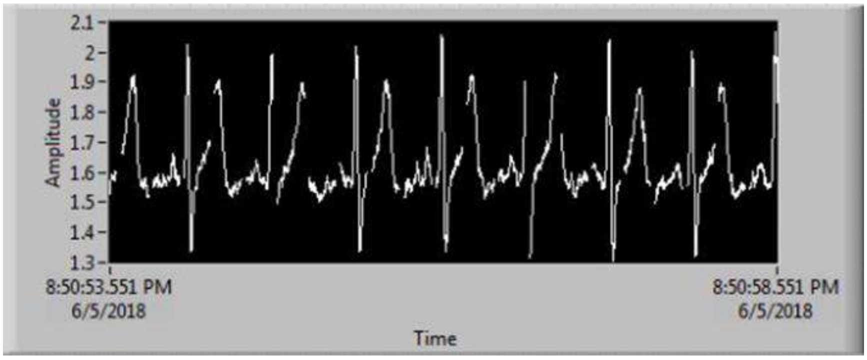


Figure 4: ECG Signal Final Result

3.3. Data Analysis

The data analysis for this research is divided into three steps, (1) the detection of Peak using peak detection program (Iskandar, 2017); (2) the Personal calibration; (3) the finding of equation for calculating the blood pressure.

3.3.1. The Detection of ECG and PPG Peak

The detection of the peak is done by inserting the data into the program. The program analyzed the peak in every 500 samples since it has 500 Hz sampling rate. First, the program detects the peak of ECG signal on every 1.03 s, it means every 500 samples. After the ECG peak is found, the program then analyzes the PPG signal. The analysis starts from PPG peak to the next PPG peak also every 1.03 s. Then, the program records the time of occurrences of ECG peaks and PPG peaks, to get the PAT from the time difference. Figure 5 illustrates the peak detection analysis.

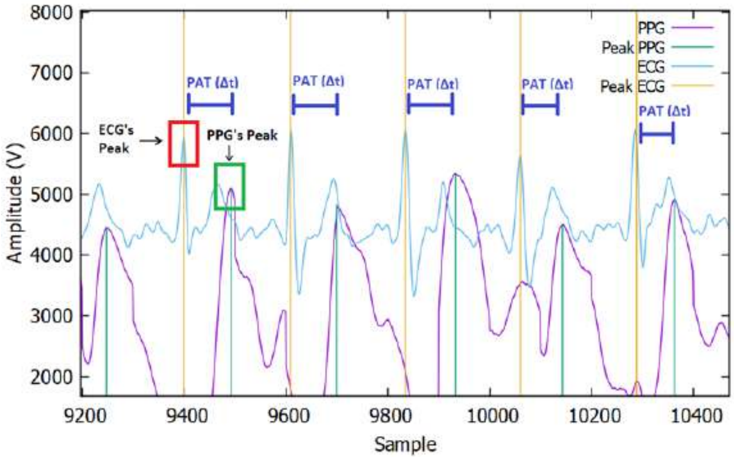


Figure 5: ECG and PPG signal peak detection on the program.

3.3.2. Personal Calibration

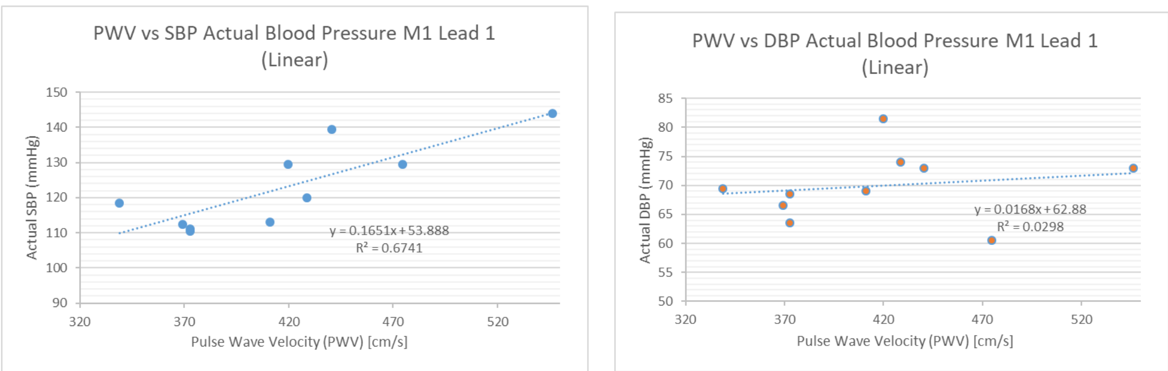
The second part is personal calibration of each subject. The personal calibration is needed since every person has different characteristics regarding their blood pressure. One factor that is affected the diversity of blood pressure is arterial stiffness. Every person has different arterial stiffness. This factor must be included in calibration since it has correlation with the time of blood to travel around our body, which known as PAT or PTT. The arterial stiffness can be represented by Pulse Wave Transit (PWV) time (Goli and T, 2014). The PWV is proportionally related to the blood pressure (Ye et al, 2010). Equation below was used to find the PWV.

$$\text{PWV} = \frac{L}{PAT} = \frac{(Subject's\ Height/2)}{PAT} \quad (1)$$

(Goli and T, 2014)

3.3.3. PAT Relation with Blood Pressure Measurement

To clearly stated the relation of blood pressure with PAT or PTT, the linear regression is used to show the relation. Graph in Figure 6 depicts the picture of linear relation of Lead 1 on a subject.



(a) (b)

Figure 6: The relation of PWV and a) SBP and b) DBP of subject M1 on Lead 1 ECG Signal.

From the graph in Figure 6, the relation of PWV and blood pressure can be clearly seen. Lead 2 and Lead 3 ECG signal and the other subject analysis is also showing that relation. Most of the subjects has graph that stated, the higher the PWV value which means the lower the PAT, the higher the blood pressure will be. This statement is supported on research called "Cuff-less continuous Blood Pressure Monitoring System Using Pulse Transit Time Techniques" (Zaki, 2016) and "Cuff less Continuous

Non-Invasive Blood Pressure Measurement Using Pulse Transit Time Measurement" (Goli and T, 2014).

The linear model is not good enough for predicting the blood pressure but it can be used to find the relation of the PAT or PTT to measure blood pressure (Sharma et al, 2017). This statement is supported by the data above. On some subject the linear regression is not good enough in predicting the blood pressure, then another regression is proposed to find the optimum regression.

3.3.4. Personal Equation for Calculating Blood Pressure

On this chapter the optimum personal equation for each subject is shown. The optimum equation is determined by R^2 rate that is obtained from the regression analysis and Mean Square Error (MSE) and Root Mean Square Error (RMSE).

Table 1 is showing the optimum equation based on R^2 rate that is obtained from the regression analysis and Table 2 is showing the optimum equation based on Mean Square Error (MSE) and Root Mean Square Error (RMSE).

Based on Table 1 and Table 2, the optimum equation for each subject and which Lead that appeared a lot to produce optimum equation can be obtained.

Table 1. The Optimum Equation based on R^2 rate.

No	Subject	Lead ECG Signal		Optimum Equation		R^2 rate		Mean Square Error (MSE)		Root Mean Square Error (RMSE)	
		SBP	DBP	SBP	DBP	SBP	DBP	SBP	DBP	SBP	DBP
1	M1	Lead 1	Lead 2	Polynomial $y = 0.0002x^2 + 0.0204x + 85.152$	Polynomial $y = -0.0015x^2 + 1.2208x - 178.11$	0.6772	0.148	87.2641	30.4067	9.3415	5.5142
2	M2	Lead 1	Lead 3	Polynomial $y = 0.0026x^2 - 2.1178x + 565.82$	Power $y = 7.8451x^{0.3762}$	0.5904	0.087	72.5421	50.8828	8.5172	7.1332
3	M4	Lead 2	Lead 3	Polynomial $y = 0.0001x^2 + 0.0291x + 83.218$	Polynomial $y = -0.0011x^2 + 1.0047x - 163.15$	0.158	0.2989	108.9705	35.6638	10.4389	5.9719
4	F1	Lead 1	Lead 3	Polynomial y = -0.0007x2 + 0.6581x - 36.672	Polynomial $y = 1E\text{-}05x^2 + 0.0316x + 60.803$	0.3384	0.5717	111.5022	50.8733	10.5595	7.1325
5	F2	Lead 1	Lead 1	Power $y = 9.2837x^{0.4103}$	Polynomial $y = 0.0003x^2 - 0.1849x + 94.478$	0.2159	0.2683	57.2260	5.4490	7.5648	2.3343
6	F3	Lead 1	Lead 1	Polynomial $y = 0.0015x^2 - 1.2726x + 371.33$	Polynomial $y = 0.0005x^2 - 0.3998x + 140.76$	0.5959	0.2433	69.4909	26.6643	8.3361	5.1638
7	F4	Lead 3	Lead 1	Polynomial $y = 0.0013x^2 - 0.8945x + 260.86$	Polynomial $y = -0.0001x^2 + 0.1392x + 36.535$	0.7328	0.2763	40.8812	15.3805	6.3938	3.9218
8	F5	Lead 2	Lead 3	Polynomial $y = -0.0008x^2 + 0.8674x - 106.12$	Polynomial $y = 0.0002x^2 - 0.1336x + 89.866$	0.8608	0.2309	44.6329	9.0261	6.6808	3.0043
9	F6	Lead 3	Lead 3	Polynomial $y = -0.0044x^2 + 3.7702x - 681.42$	Polynomial $y = -0.0024x^2 + 2.0389x - 361.84$	0.7444	0.6199	29.2113	11.7406	5.4048	3.4265
10	F7	Lead 2	Lead 3	Polynomial $y = 0.0008x^2 - 0.4796x + 179.18$	Polynomial $y = -0.0006x^2 + 0.6208x - 35.026$	0.6144	0.4638	83.0071	57.7810	9.1108	7.6014

Table 2. The Optimum Equation based on MSE and RMSE.

No	Subject	Lead ECG Signal		Optimum Equation		R^2 rate		Mean Square Error (MSE)		Root Mean Square Error (RMSE)	
		SBP	DBP	SBP	DBP	SBP	DBP	SBP	DBP	SBP	DBP
1	M1	Lead 1	Lead 1	Exponential $y = 70.911e^{0.0013x}$	Logarithmic $y = 7.7521\ln(x) + 23.192$	0.6643	0.0337	43.4526	30.3813	6.5919	5.5119
2	M2	Lead 2	Lead 3	Polynomial $y = 0.0022x^2 - 1.9208x + 547.26$	Polynomial $y = 0.0001x^2 - 0.0297x + 71.169$	0.5752	0.069	20.1749	50.7468	4.4917	7.1237
3	M4	Lead 2	Lead 3	Linear $y = 0.1428x + 58.707$	Logarithmic $y = 43.714\ln(x) - 194.69$	0.1579	0.2783	69.9422	9.67113	8.3631	3.1098
4	F1	Lead 1	Lead 3	Logarithmic $y = 31.574\ln(x) - 73.896$	Linear $y = 0.0437x + 58.32$	0.2562	0.5715	77.5994	6.43361	8.8091	2.5365
5	F2	Lead 1	Lead 1	Logarithmic $y = 43.743\ln(x) - 153.31$	Linear $y = 0.0387x + 52.65$	0.2089	0.2207	57.1759	5.39278	7.5615	2.3222
6	F3	Lead 1	Lead 2	Power $y = 2581.1x^{-0.543}$	Logarithmic $y = -4.888\ln(x) + 95.456$	0.4939	0.0316	58.1688	7.9915	7.6268	2.8269
7	F4	Lead 3	Lead 1	Polynomial $y = 0.0013x^2 - 0.8945x + 260.86$	Logarithmic $y = 18.331\ln(x) - 36.523$	0.7328	0.2748	40.8812	8.33286	6.3938	2.8867
8	F5	Lead 2	Lead 2	Logarithmic $y = 63.685\ln(x) - 276.27$	Linear $y = 0.03x + 55.857$	0.8321	0.2165	11.1926	8.0805	3.3455	2.8426
9	F6	Lead 3	Lead 3	Polynomial $y = -0.0044x^2 + 3.7702x - 681.42$	Polynomial $y = -0.0024x^2 + 2.0389x - 361.84$	0.7444	0.6199	29.2113	11.7406	5.4048	3.4265
10	F7	Lead 2	Lead 3	Linear $y = 0.1723x + 43.788$	Logarithmic $y = 6.8317\ln(x) + 30.831$	0.5844	0.0952	61.1188	8.82138	7.8178	2.9701

4. Conclusion

In conclusion, the relation of PAT and blood pressure was obtained. The higher the PWV which means the shorter PAT, the higher the blood pressure will be. The general equation for measuring blood pressure is not found. The Polynomial equation appeared a lot as optimum equation. However, each subject has its own equation for measuring SBP and DBP. Lead 1 and Lead 3 appeared as one of the Lead that give the optimum equation for SBP or DBP. However, ECG Lead 1 gave more stable signal result.

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