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Wireless Photoplethysmography (PPG) Measurement with Pulse Wave Velocity (PWV) Method for Arterial Stiffness Evaluation

Ervin Masita Dewi*, Dini Rahmawati, and Nurista Wahyu Kirana
Politeknik Negeri Bandung
Jl. Gegerkalong Hilir, Ciwaruga, Bandung Barat 40559
*e-mail: ervinmasita@polban.ac.id

Abstract—**Indications of symptoms of cardiovascular disease can be seen from the level of elasticity of the arteries. The Pulse Wave Velocity (PWV) method using PPG signal analysis is used to determine the level of arterial stiffness based on the time difference between pulse waves of Photoplethysmography (PPG) signal measurements. PWV measurements use a non-invasive technique using pulse sensors on the fingers and toes, and the measurement data is sent wirelessly using the ESP-NOW protocol. Analysis of the measured PPG signal is used as an approach to calculating the PWV value. Realization and testing can be used to measure the pulse in BPM and classify the index of arterial stiffness using the PWV method. The results of testing on 15 test volunteers from 3 age groups showed the results of an arterial stiffness index with indications of normal, stiff, and very stiff arteries. The PWV value for the 20-year-old group was 4.30-6.77 cm/s, which is normal arterial conditions. The age group of 30-40 years has a PWV value ranging from 5.11-8.77 cm/s, with normal arterial conditions. The age group of 50-60 years had PWV values in the range of 10.69-18.43 cm/s, and they had stiff and very stiff arterial conditions. Increasing age linearly affects the increase in PWV value. An increased PWV value may indicate an increase in arterial stiffness..**

Keywords: ***photoplethysmography, pulse wave velocity, wireless***

I. Introduction

Cardiovascular disease is related to the presence of impaired blood flow due to the level of elasticity of the arteries. Increased aortic stiffness reflects advanced vascular changes associated with aging, CVD (cardiovascular disease), diabetes, and kidney disease. The arterial stiffness index can be used as an early indication of cardiovascular disease [1-3].

PWV (Pulse Wave Velocity) measurement using PPG (Pothoplethysmography) can be applied to several parts of the arteries to assess arterial stiffness. Volumetric waveforms can be easily detected by measuring the transmission of infrared light through the skin using a finger, toe, or earlobe. PWV measurements are ideally measured using a pressure sensor or ultrasonic probe at two locations due to the peaks in the three ECG waveforms. In this study, PPG waves were used to assess PWV [4]. The PPG that has been used so far is PPG with a cable connected to a computer for PWV analysis. In this study, wireless PPG, which was attached to the tips of the fingers and the tips of the toes with simultaneous data collection, was used.

It is important to detect cardiovascular disease early so that preventive measures, treatment, and consultation can be carried out immediately. In this study, the design of an early detection tool for cardiovascular disease with the PWV method will be made based on observations of the arterial stiffness index classification. Arterial stiffness measurement will be carried out non-invasively using a light sensor (PPG). PPG signals are measured at the tips of the fingers and the tips of the toes wirelessly. From the time difference obtained between the PPG signal at the fingertips, and the PPG signal at the toes, PWV can be calculated. Then, the measurement results data were sent wirelessly [5-6].

II. Materials and Method

A. Pulse Wave Velocity (PWV)

Arterial elasticity is the change in artery diameter through the cardiac cycle associated with changes in blood pressure. Several stiffness indices can be estimated from changes in diameter and pressure. Generally, the PWV in the aorta is measured from the carotid and femoral arteries. Arterial observations can be accessed from the pressure waveform by measurement using pressure tonometry or velocity-time flow waveform obtained using a Doppler ultrasound device. The PWV value can be estimated from the time difference between the initiation of blood flow waves at different points compared to the distance between measuring points. The distance between the two measuring locations was measured using a measuring tape on the patient. When the PWV is measured in this way, it provides an initial assessment of stiffness arteries [7-10].

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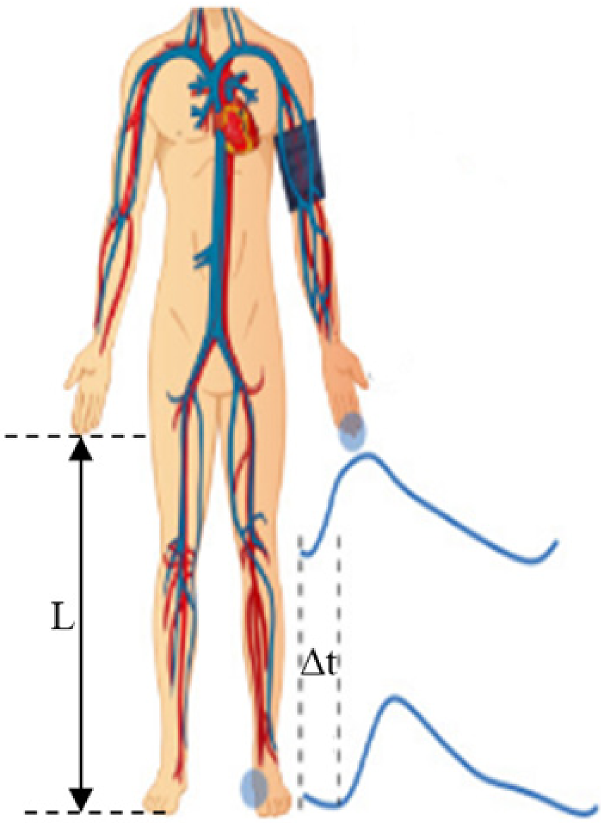

Figure 1. PWV measurement with PPG sensor

Table 1. The mean PWV measurement in Latin America

Age (years)	Total population (n=1416)		Healthy subjects (n=455)	
	n	Mean PWV (SD), m/s	n	Mean PWV (SD), m/s
<30	160	5.20 (1.18)	105	4.98 (0.91)
30-39	216	5.77 (0.79)	110	5.65 (0.73)
40-49	261	6.54 (0.70)	87	6.35 (0.78)
50-59	272	7.79 (0.81)	75	7.55 (0.77)
60-69	264	9.14 (0.86)	49	8.93 (0.99)
70-79	102	10.37 (1.36)	19	9.93 (1.86)
>79	41	12.35 (1.86)	--	--

Technically, it is possible to judge the pulse wave velocity by simultaneously recording the pressure waveform at two measuring locations, as seen in Figure 1. This allows the time delay between the pressure waveform recorded in the distal segment with respect to the proximal one to be calculated. Velocity equals displacement/time, as a result, the speed of the pulse wave is calculated using Equation 1[11-12].

$$PWV = \frac{L}{\Delta t}, \quad (1)$$

where L is the distance between the tip of the finger and the tip of the toe, while Δt is the distance between the PPG wave at the tip of the finger, and the PPG wave at the tip of the toe.

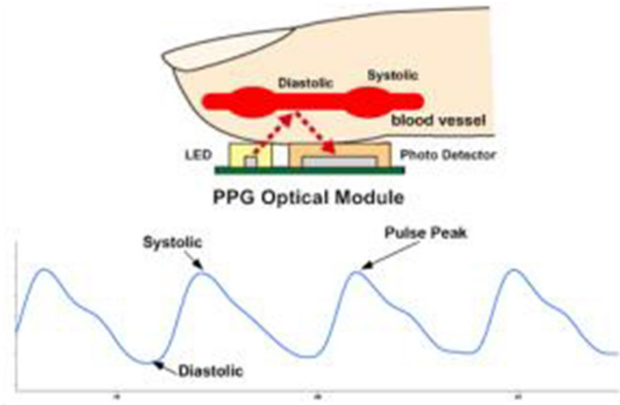

Figure 2. PPG measurement

According to Journal of Human Hypertension, with the research is abaut Frequency of early vascular aging and associated risk factors among an adult population in Latin America: the OPTIMO study, The mean PWV to age categories in total population and in healthy subjects is written in Table 1.

B. *Pothoplethysmography (PPG)*

PPG signal measurements can be carried out using reflective and transmittive light sensors. When using a reflective PPG, the light source and sensitive elements are placed on the same side. This configuration is used when the tissue introduces a significant absorption coefficient in the path of light, usually in devices used on fingers or wrists as seen in Figure 2 [13].

The LED emits light which will fall on the veins directly. Blood vessels will have blood flow in them only when the heart is pumping, so if we monitor blood flow, we can also monitor heart rate. If blood flow is detected then the ambient light sensor will pick up more light as they will be reflected by the blood, these small changes in the received light are analyzed over time to determine the heart rate [14].

The PPG signal from the measurement results is still a raw signal that needs to be normalized using Equation 2.

$$X(t) = \frac{PPG - PPG_{\min}}{PP_{\max} - PPG_{\min}}, \quad (2)$$

where $X(t)$ is the normalized result of PPG raw, PPG is the original PPG signal, *PPGmin* is the minimum value of the raw PPG signal, and *PPGmax* is the maximum value of the raw PPG signal [6].

C. *Wireless PPG*

Wireless is connecting two devices that do not use wired media. Wireless technology is a technology without wires, in conducting telecommunications relations it no longer uses cable media or facilities but uses electromagnetic waves instead of cables. Wireless networks provide convenience and flexibility that is quite high and comfortable to use as long as in the wireless

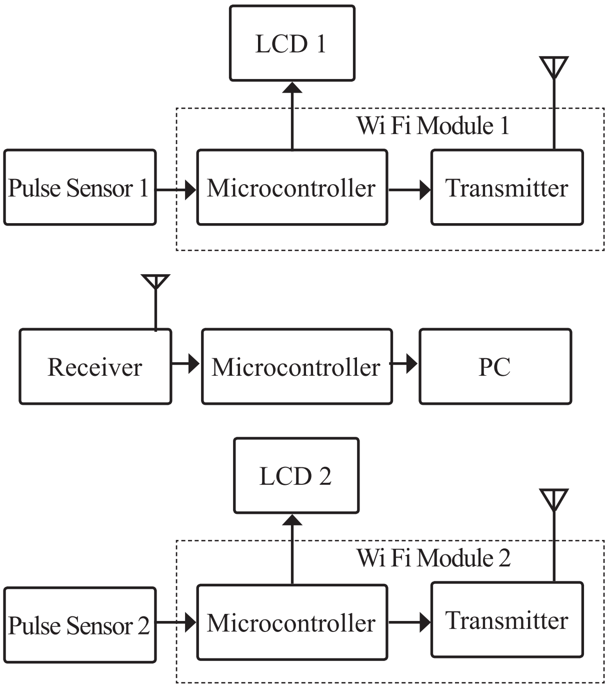

Figure 3. Block diagram system

network coverage area.

The way this system works is that each pulse sensor is used to measure the pulse on the left finger and toes. In Figure 3, the system block diagram, there are 2 fingertip circuits and 1 receiver circuit. Each fingertip device is equipped with a pulse sensor that detects the PPG signal, a display that displays the pulse measurement results and a built-in Wi-Fi microcontroller as a data processor as well as sending data via a Wi-Fi connection. In the receiver block there is a built-in Wi-Fi microcontroller as a data processor and receiver of data sent by the transmitter block wirelessly, this block is connected directly to a PC for further processing of received data [15-17].

III. Result and Discussion

A. Wireless PPG Sensors

The realization of the mechanical design of this system is the manufacture of fingertip and receiver box. This fingertip mechanism functions as a means of measuring heart rate on the fingers and toes which is detected by the pulse sensor. In the mechanical realization, the fingertip is used to store a series of electronic components that are connected according to the wiring system. The fingertip dimensions are 7 x 4 x 5.5 cm, made from 1 pair of PLA (Poly Latctic Acid) plastic filaments. Realization of the fingertip mechanical heart rate measurement is shown in Figure 4.

Figure 4 shows the integration of mechanical and electronic parts, including Fingertip mechanics integrated with OLED (top view), Internal Fingertip mechanics integrated with Pulse Sensors, Fingertip mechanics in the Wi-Fi Microcontroller Integration section built in and sensors.

Data transmission was carried out on two built-in Wi-Fi module microcontrollers as data senders and one other module as a data receiver. Figure 5 shows the electronic circuit of wireless PPG sensor.

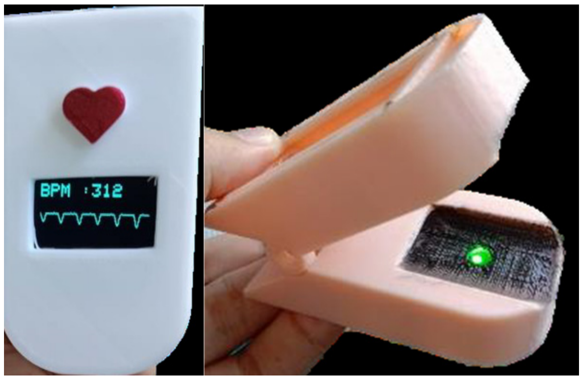

Figure 4. Realization of wireless PPG sensor

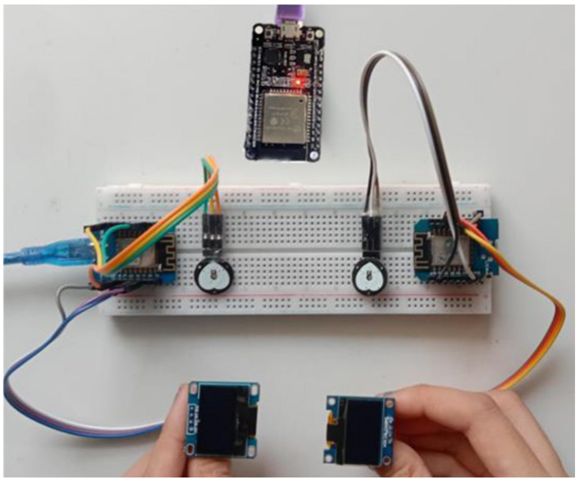

Figure 5. Electronic circuit of wireless PPG sensor

This test was carried out to find out whether the pulse sensor can measure PPG waves and heart rate. This test is carried out by connecting the pulse sensor according to the electronic circuit design, then the test is run to measure the pulse on the fingers and toes. The serial plotter in Figure 6 is the data obtained from the pulse sensor test in fingertips. The displayed PPG signal shows results that are in accordance with the theoretical basis, namely the presence of PPG waveforms at the fingertips. Based on these data it can be seen that the pulse sensor can work by measuring the pulse on the fingers and toe too [18-20].

This tool detects arterial stiffness by measuring the PPG signal of the fingers and toes using the PWV method. The results of the classification of the arterial stiffness index are used as early detection cardiovascular disease. The PWV method is used to calculate the speed of pulse waves from the fingers and toes at the same time. The pulse measurement output is displayed on the LCD display and the PWV computation is performed via a PC.

B. Measurement Result

The PWV method can be used to measure arterial stiffness by measuring the pulse wave velocity per unit time from one point to another. In this tool the measurement is

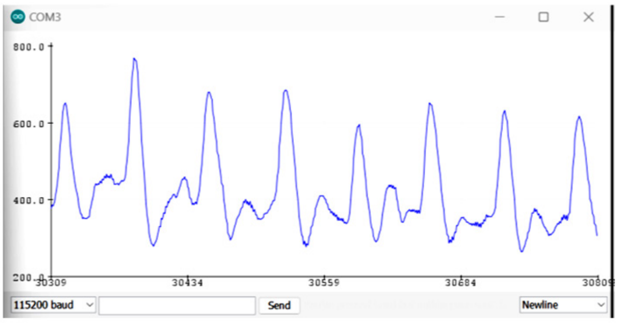

Figure 6. Serial plotter of PPG measurement- in fingertips

Figure 7. Respondents measurement

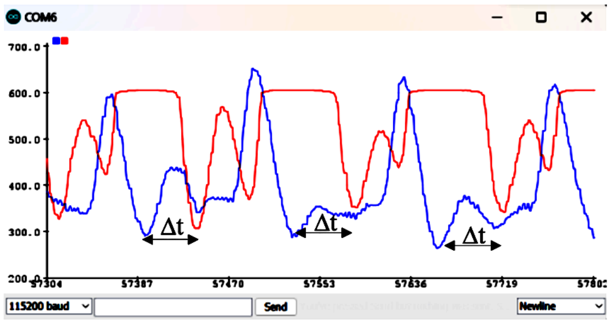

Figure 8. PPG Measurement result

aimed finger-to-toe or finger to toe. The difference in the measured wave velocity is then used to classify arterial stiffness. The detection technique used is PPG, this non-invasive technique uses reflected light (reflective) which can be used to detect heart rate. Measurement of heart rate using PPG to find the value of arterial stiffness index with the PWV method is simulated as follows.

1. Get PPG Measurement Data.
2. Measuring PPG (Pulse Plethysmography) on the fingers and toes can use a pulse sensor. This sensor can measure the pulse of blood passing through the finger. The PPG sensor generates a signal that records the change in arterial volume with each heartbeat.
3. Analyze PPG Signals.
4. Use software to analyze PPG signals and identify peaks in the signal. These peaks indicate the heart rate.
5. Calculate the time interval between two peaks in the PPG signal. This time interval indicates the time interval between two consecutive heartbeats.
6. Use the time interval calculated from step 3 and the calculated distance between the two measurement points to calculate the arterial pressure wave velocity. This calculation will produce a PWV value.
7. Calculate the arterial stiffness index by dividing the distance between the two measurement points by the PWV value.

Table 2. PWV measurement result

Age	Resp	L (cm)	PPG hand (ms)	PPG toe (ms)	Δt (ms)	PWV (m/s)	PWV Avg (m/s)
	1	45	0.86	11.32	10.46	4.30	
	2	46	1.20	9.51	8.31	5.54	
20-25	3	42	3.77	0.43	3.00	6.77	5.33
	4	30	0.68	6.20	5.52	5.43	
	5	42	9.54	18.64	9.10	4.62	
	1	45	5.62	12.03	6.41	7.02	
	2	40	2.45	8.35	5.90	6.78	
30-35	3	50	6.07	15.85	9.78	5.11	6.44
	4	46	2.13	7.69	5.56	8.27	
	5	49	6.07	15.85	9.78	5.01	
	1	40	16.04	19.66	3.62	11.06	
	2	25	7.51	9.38	1.87	10.69	
50<	3	51	0.14	2.31	2.17	18.43	13.73
	4	27	0.95	3.06	2.11	12.80	
	5	30	0.25	0.25	2.17	15.65	

Figure 7 shows PWV measurements using PPG wireless. Measurements are taken in a supine position so that the position of the heart is parallel to the hands and feet so that there are no obstacles to blood flow. Measurements were carried out for approximately 1 minute to obtain a stable signal. The measurement results can be seen in Figure 8, the blue signals are measurements on the fingertips, while the red ones are the results of measurements on the toes. The path length is the distance between the fingertips and the toes, while Δt is the time difference between the fingertip and toe signals.

Based on the test data in the table above, it was found that the classification of the arterial stiffness index was obtained from the classification of the PWV value from the calculation of the distance between measuring points with the initial difference in PPG signals 1 (fingers) and 2 (toes).

The results of the PWV test based on the variation in the age range are shown in Table 2. Based on these data it can be seen that the 20s age group has a relatively low PWV value of 4.30-6.77 m/s, with a normal arterial stiffness index. This indicates that in the 20s age group they still have arteries that tend to be elastic or normal. In the 30-40 year age group, this has a calculated PWV value ranging from 5.11-8.77 m/s, this value is grouped higher than the 20-year age group, with varying arterial stiffness indices, namely some are stiff and normal. The PWV value in the age group of 50-70 years is calculated in the range of 10.69-18.43 m/s, in this age group it can be seen that it has the highest PWV value compared to other measured age groups. Based on the PWV value, the age group of

50-70 years is classified as a relatively had stiff arteries. Test respondents in the age range of 50-70 years with the highest PWV values had stiffness indices.

IV. Conclusion

The classification of the arterial stiffness index obtained from the PWV method testing data in the table above shows the results of the classification of test volunteers with different age groups, namely 20 years, 30-40, and 50-60 years, having varying PWV values. Based on the analysis of measured and calculated data, an increase in age affects the PWV value, where the addition of a person's age is linear with an increase in the PWV value. An increased PWV value may indicate an increase in arterial stiffness. The PWV method can be used as an early detection and early description of symptoms of cardiovascular disease, arterial stiffness is usually caused by loss of elastin in the blood vessels which indicates a disturbance in the blocked or obstructed blood flow cycle that is not working properly.

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