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Development of Single Mode Photoplethysmography System for Measurement of Heart Rate and Blood Pressure

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ABSTRACT

Heart disease has been Malaysia's leading cause of mortality for 20 years. Aging stiffens the heart and blood vessels, leading to heart disease in older people. Therefore, heart disease is common in seniors. From 2014 to 2021, heart disease-related mortality in people aged 41 to 59 rose 6.2%. This paper presents the design of a monitoring system for early cardiac condition identification in young individuals. Single photoplethysmography (PPG) estimated the mean arterial pressure (MAP) and pulse rate. These physiological signs and health risk variables were utilized to map heart disease progression. 50 healthy 20–40-year-olds were sampled. The experimental design compares the prototype's stability and precision to a commercial device. Heart rate accuracy showed a mean difference of 0.30 bpm and a variance difference of 1.43 bpm. Thus, most MAP values are 60–100 mmHg. 20% had MAPs beyond 100 mm Hg. As demonstrated by subjects with risk factors with higher resting heart rates and higher MAP values, a correlation exists between heart rate, blood pressure, and the likelihood of heart disease progression over time. In conclusion, the most significant contribution of this research is an enhanced method for the early detection of coronary artery disease using heart rate and blood pressure data linked to variable risk factors.

Keywords:

Photoplethysmography; Heart rate; Blood pressure

1. Introduction

Cardiovascular illness is a disorder of the blood vessels often known as heart disease or stroke [1-3]. In Malaysia, heart disease has been the leading cause of death over the previous two decades. Normal aging causes the heart and blood arteries to harden, which can lead to heart disease in older people. As a result, heart disease is thought to be frequent among older adults. Observation of statistical trends from 2014 to 2021 reveals an increase of 6.2% in the overall number of heart disease-related fatalities among adults aged 41 to 59 [4,5]. This indisputably proves that the risk of acquiring heart disease much earlier in life exists. According to statistical trends, the disease is progressively impacting the younger population. Therefore, monitoring physiological factors for

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predicting the development of heart disease in young adults has become a crucial topic of research [6-8].

Monitoring physiological factors such as heart rate and blood pressure on a regular basis is essential for maintaining optimal health [9]. Due to the low perceived need for medical treatment and the high cost of medical care, many avoided the hospital [10]. Many medical devices have been developed to meet specific demands for monitoring heart disease-related health concerns, however, the bulk of these equipment have restricted parameter measurements, only provide single-subject assessments, and are difficult for continuous measurement monitoring due to their contact foundation [11-17]. Thus, monitoring clinical physiological markers and knowing their values alone is insufficient for predicting the risk of developing heart disease. In several studies, linking the monitored value with a range of parameters can assist in predicting the likelihood of developing heart disease and assessing heart health [18-23]. Identifying the risk factor may be advantageous. Heart disease risk factors include age, gender, family history, diabetes, obesity, and unhealthy behaviours such as smoking, which increase the risk of heart disease.

Recent research has connected the coronavirus (Covid-19) post-covid survivor to heart disease [24,25], and blood type predicts cardiac health [26-29]. Hence, the bigger the number of risks factors a person has, the greater their likelihood of developing heart disease. Moreover, several studies have been conducted until recent years to investigate the potential of using a single PPG sensor for monitoring physiological factors related to heart disease risks, such as blood pressure and arterial stiffness. Researchers have developed novel algorithms that enable the extraction of physiological parameters from PPG signals, providing valuable information for the early detection and management of heart disease [30-35]. The aim of this research was to develop a monitoring device for the early diagnosis of cardiac disease. To achieve the aim, a single photoplethysmography (PPG) is used to determine heart rate and blood pressure based on mean arterial pressure (MAP). In addition, these physiological signals are combined with established health risk factors to map the potential development of cardiac disease. The developed device is inexpensive, portable, user-friendly, and compact.

2. Methodology

The purpose of this article was to perform continuous monitoring and analysis of the subject's heart rate and blood pressure to estimate their risk of developing cardiovascular disease. In addition to systolic and diastolic blood pressure measurements, the data collected also includes the pulse signal and inter-beat interval (IBI). A pulse sensor must be attached to or situated on the index finger for the prototype to function. Arduino is responsible for receiving signals after the pulse sensor has detected them. The Arduino will perform the calculations necessary to ascertain the systolic, diastolic, and overall heart rates. The organic light-emitting diode (OLED) display will indicate normal, low, and rapid heart rates. It will also display the heart rate in beats per minute, the systolic value, the diastolic value, the mean arterial pressure (MAP) value, the pulse wave signal, and the pulse wave signal.

2.1 Hardware Design

The primary microcontroller board employed in this work is an ESP8266 NodeMCU. The board is affordable, straightforward to operate, and occupies a little amount of space. When coupled through general purpose input/output (GPIO) pins, the NodeMCU can interact with the device sensor. With a single pulse sensor, both the systolic and diastolic blood pressure of the patient may be determined.

The pulse sensor was created using the technique of photoplethysmography, which detects fluctuations in the volume of blood flowing through an organ. It is a plug-and-play, low-power, Arduino pulse sensor that was created with care. Its portability and user-friendliness have led to its broad acceptance. It has a Microchip MCP6001, an op-Amp to amplify the signal of the picture sensor, which is typically weak and irregular, a low pass filter network for cleaner output, and a reverse protection diode to prevent power lead incidents from causing device damage. All these factors contribute to the device's reliability. To activate the sensor, the finger is placed on its front. It is equipped with a small ambient light photosensor and a back-mounted light emitting diode (LED), allowing the screen brightness to be changed according on the surrounding lighting [36].

In addition, the display is a 0.96-inch OLED since this size is both tiny and simple to manufacture. The TP4056, a 1A linear lithium-ion battery charger, may be used to charge a single-cell lithium-ion battery. It is ideally suited for the application of the portable device, making it a great option. The charging connection employs USB type-C connectivity, which enables the highest degree of efficiency and the most advanced level of functionality. Figure 1 depicts the overall architecture of the prototype's system. This component consists of a microcontroller board coupled to a display module, a power module, and a sensor module.

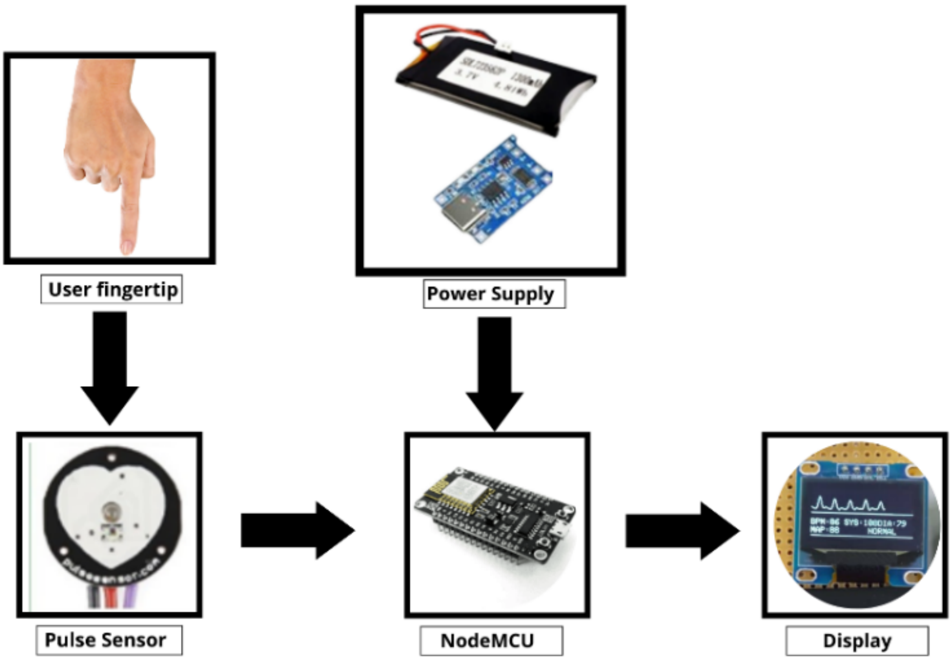
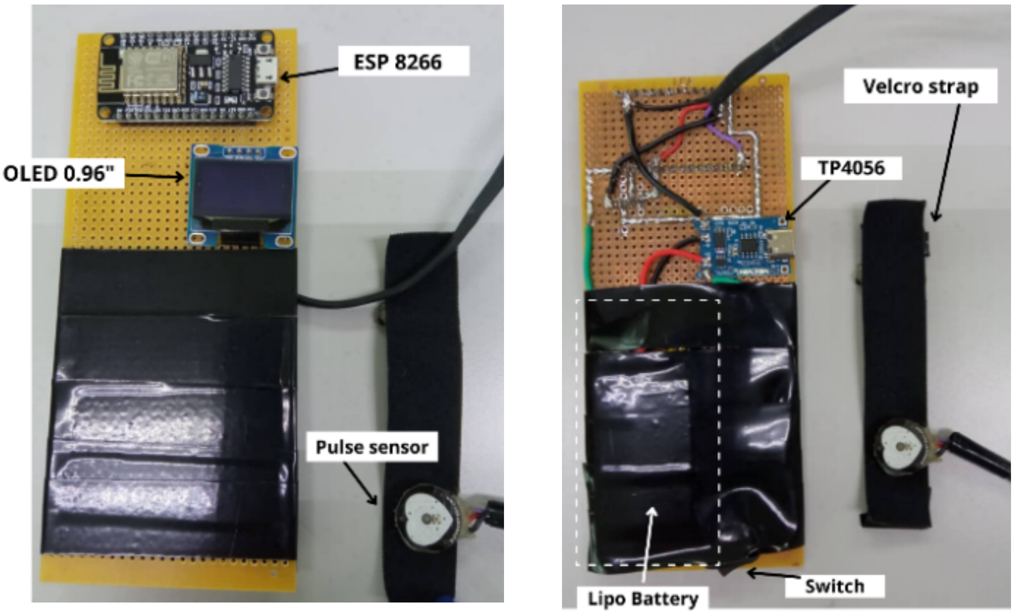


Fig. 1. The Overall System Architecture

Specifically illustrated in Figure 2 is a completed circuit with a power module that enables the prototype to function as a portable device. It contains a rechargeable lithium-ion battery, and any charging cable with a type-C connection may be used to charge it. The instrument is intended to be utilized often and for a prolonged duration. A switch that can turn off the device's battery while it is not in use has been added.



(a) (b)

Fig. 2. Physical Appearance Prototype (a) Front View and (b) Back View

Figure 3 illustrates the output display of the OLED. The viewer may view the pulse wave, heart rate in beats per minute (BPM), estimated systolic and diastolic values, mean arterial pressure (MAP), and a description of the heart rate as slow, normal, or fast.

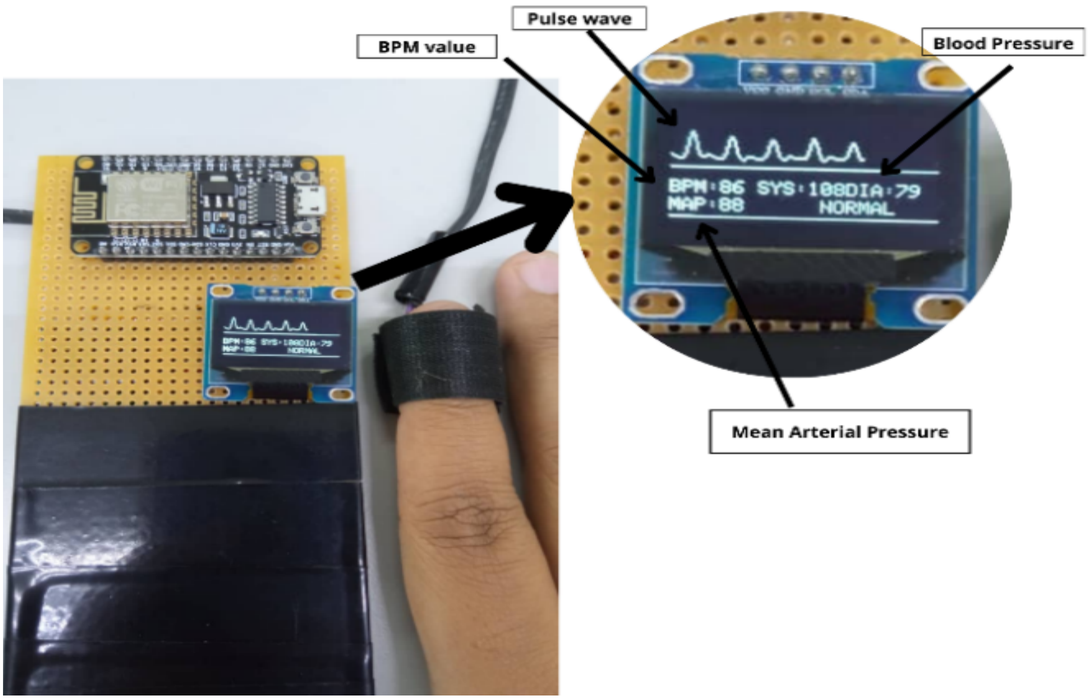


Fig. 3. Display Output from The Prototype

2.2 Software Design

The signal that is received from the pulse sensor contains the data that is being converted from analogue to digital (ADC), as well as the "threshold" that decides which signals are "counted as a beat" and which signals are ignored. The processing entails determining the inter-beat-interval array, as well as the peak that is highest and the peak that is lowest in a single full cardiac cycle. The heart rate and blood pressure computation system's flowchart are shown in Figure 4. The computed heart rate is then analysed and divided into three categories (low, normal, or high) based on the criteria that has been satisfied. A resting heart rate is considered normal when it is between 60 and 100 beats per minute (BPM), high when it is higher than 100 BPM, and low when it is less than 60 BPM. In addition to this, the calculation of blood pressure is based on the greatest and lowest peak value received from the signal and computed using MAP. These values are compared to one another.

The first step in programming an Arduino is to determine the peak and throughput of the pulse wave. There is a possibility that the signal that is sent out by the internal operational amplifier of the pulse sensor will include a secondary pulse that is referred to as the dicrotic notch. The detection of pulses is hampered by this extra pulse. In addition to that, the signal itself is contaminated by a sizeable quantity of background noise [37].

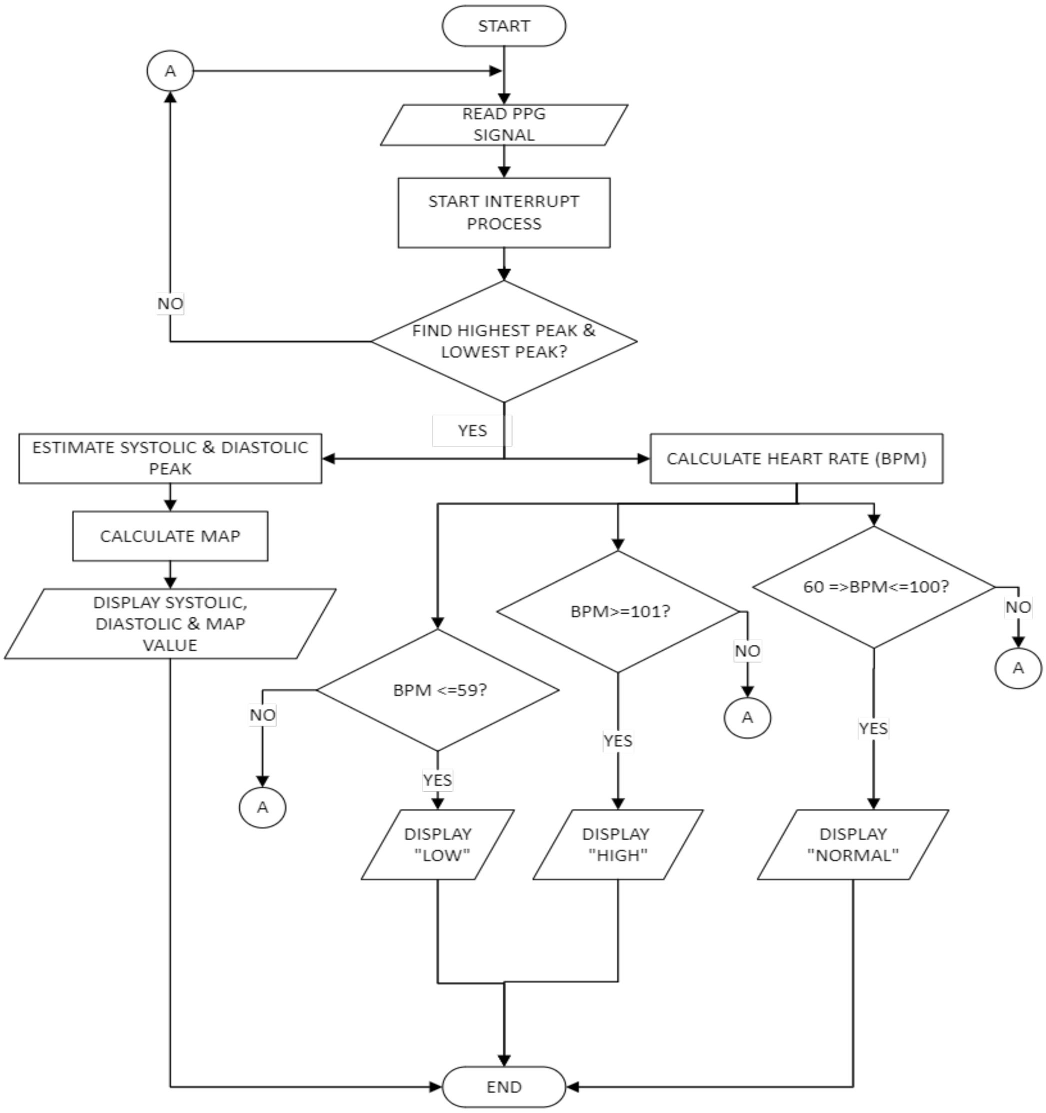


Fig. 4. System Flowchart

The pulse sensor is read and recorded every 2 milliseconds, with delays of 3 over 5 times the previous inter-beat interval (IBI) [38]. This is done to avoid dicrotic noise from occurring and as an effort to reduce the overall volume of the noise that is produced.

The value of the signal will rise each time there is a pulse. The lowest and highest points of the pulse wave are identified using coding. Calculations and subsequent analysis can be carried out during the pause that exists between beats. An array method is utilized to collect 10 IBI data points to do the calculation for the heart rate in beats per minute. To determine the number of heartbeats that may be recorded in one minute, the heart rate is computed by dividing 60000 milliseconds by an average of 10 IBI, calculated from Eq. (1). The method is also intended to monitor blood pressure; hence it is designed to identify both the highest and lowest peaks that occur within a single cycle. This allows the cycle to be monitored in its entirety. The results for the systolic and diastolic components of blood pressure show, respectively, the highest and lowest blood pressure levels that are possible. After two readings have been obtained, the approach may be used to compute the mean arterial pressure (MAP) from Eq. (2).

$$BPM = \frac{60000}{Mean\ IBI} \tag{1}$$

$$MAP = \frac{2DBP+SBP}{3} \tag{2}$$

3. Results

Fifty individuals between the ages of twenty and forty who were clear of heart disease and had no family history of the ailment participated in the experiment. Comparable procedures are utilized to determine an individual's heart rate and blood pressure. For the duration of the session, the subject stays sitting in a relaxed and comfortable position. During this period, there is no speaking, and there are no unwanted disturbances of any type. Table 1 displays the measuring technique.

Table 1
Technique Used for Measurement

Procedure of measurement	Equipment
Take finger size circumference	Digital caliper
Take reference heart rate and blood pressure	OMRON HEM-8712 and pulse oximeter
Take prototype heart rate and blood pressure	Observation from output display on prototype and recorded in experiment sheet

As shown in Figure 5, digital calliper with inch units is used to measure the circumference of a person's finger.

Fig. 5. Finger Circumference Measurement with A Digital Caliper

To estimate heart rate and blood pressure from the PPG signal in a resting state, each patient sat for a 5-minute recording with a 30-second interval. Figure 6 depicts the subjects' body positions during observation.

Fig. 6. Body Posture

Figure 7 depicts the monitoring procedure for heart rate and blood pressure that was utilized during the whole experiment. The Arduino programming approach is applied to automate the heart rate computation based on the prototype. The approach uses the minimum and maximum values of systolic and diastolic blood pressure to calculate mean arterial pressure (MAP).

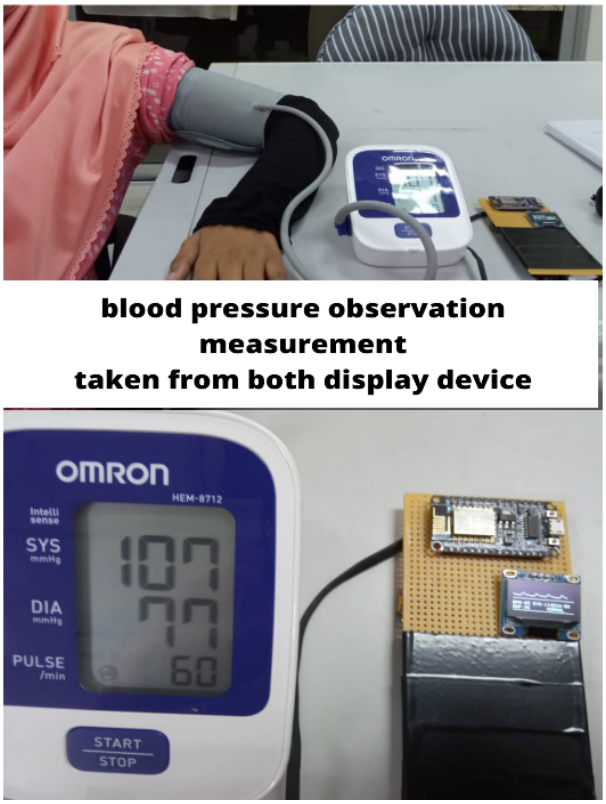


Fig. 7. Heart Rate and Blood Pressure Observation

The prototype is portable, lightweight, and easy to use. The output value, which is heart rate, is compared to available risk factors such as age, gender, and BMI. The obtained demographic and physiological data are included. The data distribution is summarized in Table 2.

Table 2
Data Distribution [39]

BMI (kg/m^2)	No.	Female (%)	Male (%)
Underweight: Below 18.5	7	6 (21%)	1 (5%)
Normal: 18.5 - 24.9	25	14 (48%)	11 (52%)
Overweight: 25.0 - 29.9	10	4 (14%)	6 (29%)
Obese: 30.0 above	8	5 (17%)	3 (14%)
Total	50	29	21
Gender		58%	42%
AGE GROUP			
20-24	31	18 (62%)	13 (61%)
25-29	6	2 (7%)	4 (19%)
30-34	6	4 (14%)	2 (10%)
35-40	7	5 (17%)	2 (10%)

The prototype is accurate, with a mean difference of 0.30 BPM and a variance difference of 1.43 BPM, showing a difference between +1 and -1 BPM. The average 5-minute monitoring while wearing both the prototype and the pulse oximeter in a resting condition reveals an error rate of less than 3%, indicating that the stability and accuracy of the prototype's output warrant further examination. Table 3 displays the results of the measurement between the two devices.

Table 3
Output Of Prototype Versus Pulse Oximeter

Record (subject)	Prototype (BPM) Reflective Mode	Pulse Oximeter (BPM) Transmissive Mode	Error Rate (%)
1	73	74	1.35
2	73	72	1.39
3	72	70	2.86
4	88	87	1.15
5	68	68	0.00
6	82	80	2.50
7	80	79	1.27
8	84	83	1.20
9	82	81	1.23
10	79	80	1.25
11	70	68	2.94
12	76	77	1.30
13	72	71	1.41
14	88	88	0.00
15	70	71	1.41
16	75	74	1.35
17	87	86	1.16
18	72	72	0.00
19	84	83	1.20
20	80	82	2.44
21	90	91	1.10
22	70	69	1.45
23	87	86	1.16
24	80	80	0.00
25	72	70	2.86
26	84	85	1.18
27	86	84	2.38
28	76	75	1.33
29	90	89	1.12
30	87	87	0.00
31	82	82	0.00
32	90	88	2.27
33	81	81	0.00
34	89	88	1.14
35	90	90	0.00
36	85	86	1.16
37	76	77	1.30
38	89	89	0.00
39	81	82	1.22
40	83	83	0.00
41	82	81	1.23
42	78	77	1.30
43	72	71	1.41
44	73	73	0.00
45	69	70	1.43
46	87	87	0.00
47	89	90	1.11
48	85	86	1.16
49	77	77	0.00
50	84	84	0.00

Table 4 summarizes the output measurement's performance in determining systolic, diastolic, and MAP blood pressure. Mean absolute error (MAE) values for systolic, diastolic, and MAP BP were 7.4 mmHg, 11.73 mmHg, and 9.79 mmHg, respectively. For systolic, diastolic, and MAP BP, the standard deviation error (SDE) values were 1.08 mmHg, 0.70 mmHg, and 0.71 mmHg, respectively. In addition, greater than 96 percent of systolic blood pressure estimates have an absolute error of less than 10 mmHg, while 94 percent of diastolic blood pressure estimates and 88 percent of MAP BP estimations, respectively, have an absolute error of less than 15 mmHg. This shows that future algorithms for assessing diastolic blood pressure can be improved. With continuous monitoring, the systolic blood pressure, which performs well in most measurements, may assist in identifying any abnormalities in high blood pressure. When the measurement of diastolic blood pressure improves, the absolute error of the MAP BP measurement can be decreased.

Table 4
Overall Performance Evaluation BP Measurement

	Systolic (mmHg)	Diastolic (mmHg)	MAP (mmHg)
Mean absolute error (MAE)	7.4	11.73	9.79
Standard deviation error (SDE)	1.08	0.7	0.92
< 10 mmHg (%)	48 (96%)	3 (6%)	6 (12%)
< 15 mmHg (%)	2 (4%)	47 (94%)	44 (88%)

Among fifty subjects, most of the subjects have a mean arterial pressure (MAP) between 60 to 100mmHg which is a good sign there is enough blood flow to supply blood to all major organs. 20 percent of the subjects shows a MAP greater than 100 mmHg which is considered high MAP and it indicate that there is a lot pressure in the arteries. If prolonged, it can lead to blood clots or damage heart muscle thus increasing the risk of developing heart disease. Figure 8 illustrates the MAP values from the monitoring session.

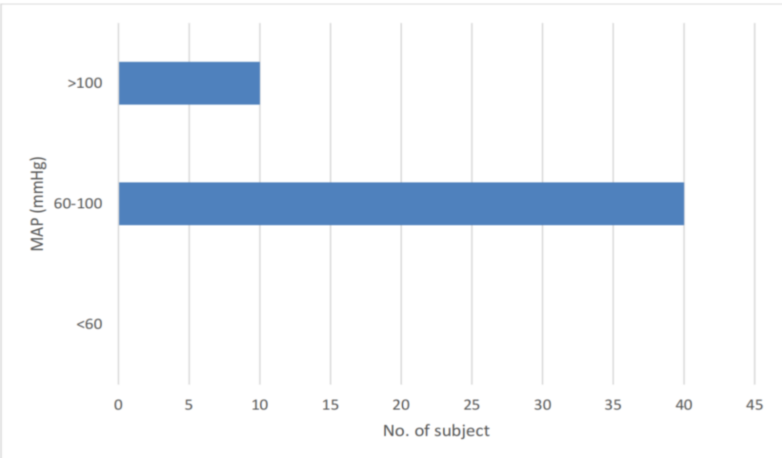


Fig. 8. MAP Values Monitor Among 50 Subjects

4. Conclusions

This paper presents the development of a portable pulse monitoring device employing a single photoplethysmography (PPG) sensor. The device can continuously measure and monitor short- and long-term characteristics, including pulse rate and blood pressure. The present development system can monitor both systolic blood pressure and heart rate simultaneously and continuously. This allows the system to provide solutions in a variety of medical contexts and to detect prolonged cardiac abnormalities at an early stage. Standard blood pressure monitors can be painful, but the PPG sensor's ability to estimate blood pressure alleviates the discomfort. The prototype can accurately measure and monitor heart rate, with an error rate of less than 1%. Due to the system's dependability, it can numerically determine the frequency of the heartbeat and as a signal composed of continuous pulse waves. In addition to systolic pressure detection, the output demonstrates a robust performance by utilizing the Arduino processor and the C programming language to locate the value point. In addition to functioning accurately when connected to a computer and in portable mode, the prototype could function correctly when not connected to a computer and when used independently. Without the need for a blood pressure monitor, a single PPG has the potential to measure blood pressure continuously and conveniently for research purposes. Since the mean absolute error in diastolic pressure is less than 15 mmHg, there is an opportunity to investigate and develop a more accurate algorithm in the future so that it can predict blood pressure using the MAP formula. Considering an error rate of 1%, the system's performance in terms of heart rate demonstrates very high accuracy and stability in monitoring, while the 7.4 mmHg mean absolute error in systolic value is a strong indicator that blood pressure can also be measured by using the peak and the PPG raw signal. Thus, most MAP values are 60–100 mmHg. 20% had MAPs beyond 100 mm Hg. As demonstrated by subjects with risk factors with higher resting heart rates and higher MAP values, a correlation exists between heart rate, blood pressure, and the likelihood of heart disease progression over time. The peak and unprocessed PPG signals demonstrate that blood pressure can be measured. As the conclusion, the most important contribution of this research which is an improved method for the early identification of coronary artery disease using heart rate and blood pressure data that are linked to variable risk factors have been achieved. On the other hand, diastolic detection can be investigated in the future to improve blood pressure detection. In addition, machine learning will be used to classify cardiac arrhythmias. Current work can be expanded to include ambulatory heart rate and blood pressure monitoring and combined with previous study [40], as well as resolving PPG signal instability when moving.

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