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# A Systematic Approach to the Development of an IoT-Enabled Cardiovascular Monitoring Device

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**ABSTRACT**

***Cardiovascular diseases are a major health concern and a leading cause of global mortality. Conventional cardiovascular monitoring devices are expensive and cannot remotely monitor the cardiovascular system. This study aimed to apply a systematic approach for the development of an IoT-enabled cardiovascular monitoring device. The system is powered by two 3.7V lithium-ion batteries and consists of an electrocardiogram (ECG) module, a blood oxygen level and heart rate module, a 16×2 liquid crystal display screen, an I2C interface, a Wi-Fi microcontroller unit, a resistor, a transistor, a buzzer, and several connecting wires. The circuit was designed and simulated, followed by device construction. The microcontroller was programmed to collect and transmit patient data to a database over a Wi-Fi network. The data are accessed by a desktop application at an interval of thirty seconds, and displayed in tables and ECG graphs. Pilot testing was conducted to determine the efficacy of the device. The ECG waveforms obtained exhibited typical ECG features, with consistent and periodic peaks, indicating a regular heart rhythm. The recorded mean $SpO_2$ and heart rate values of 97.5 ± 1.01 and 81.27 ± 22.97 Beats per minute (BPM) align closely with values reported in previous studies involving healthy adults. Test results demonstrate the device's feasibility and safety for real-time cardiovascular patient monitoring.***

## INTRODUCTION

Cardiovascular diseases (CVDs) are a group of heart and blood vessel disorders and conditions that affect the heart and blood vessels. They are a significant global health issue, affecting millions of individuals annually. The World Health Organization (WHO) reports that cardiovascular diseases are responsible for about 32% of all global deaths and are the primary cause of death worldwide (WHO, 2023). These diseases affect over 500 million people across various demographics, resulting in approximately 20.5 million deaths in the year 2021(World Heart Federation, 2023). The economic costs of managing cardiovascular diseases are quite substantial. For example, in the United States, over $400 billion is spent annually as direct and indirect costs (Tsao et al., 2023). Common risk factors, comprising behavioral and environmental risk factors, include unhealthy diets, physical inactivity, tobacco use, harmful use of alcohol, and air pollution (WHO, 2025). Similarly, CVDs could lead to a heart attack, heart failure, and even stroke. Therefore, it is critical to have early and precise diagnosis and monitoring for effective treatment and management of complications linked with cardiovascular diseases. Biomedical Engineering continues to play a significant role in the development of diagnostic and therapeutic medical devices for the management of cardiovascular diseases.

The basic and most common investigation of choice for CVD diagnosis is the 12-lead Electrocardiogram (ECG), designed to measure and record the electrical activity of the heart (Rubio et al., 2024). Through ECG, heart rhythm can be tracked, and heart rate variability can be assessed, along with the detection of cardiac conduction abnormalities (Ho et al., 2011). This method provides valuable insight into the heart's electrical activity and can identify various conditions such as arrhythmias, pericardial and myocardial disease, and electrolyte imbalances (Rafie et al., 2021). While not as widely used as the ECG, pulse oximetry is a non-invasive measure of the oxygen saturation in the blood and heart rate (Xiaoliang Yan et al., 2020). Similarly, photoplethysmography is used to measure various parameters related to the cardiovascular system, including heart rate monitoring, blood oxygen saturation measurement, heart rate variability, and peripheral perfusion. In recent times, the Internet of Things (IoT) has been integrated into medical devices (Nwaneri & Osuagwu, 2022). The development of a cardiac monitoring device integrated with IoT technology has the potential to improve the diagnosis of cardiovascular diseases and provide timely intervention in emergencies. Innovations in medical devices have led to the enabling pre-emptive intervention to prevent further progression of deteriorating heart failure and subsequent hospitalizations (Ezer et al., 2022).

Heart rate sensors that are unobtrusive and wearable are currently being used to collect and report data automatically (Hashim et al., 2023). Also, there are medical smartphone apps such as the Samsung ECG monitor app and the ECG. Previous studies on cardiovascular disease diagnosis explored various approaches for CVD monitoring. Li et al. (2017) developed a remote cardiac disease monitoring system based on the IoT architecture. The study used an Android smartphone as a connector and linked it to a sensing device. Hashim et al. (2023) proposed a real-time health monitoring system to improve data reliability and transmission. The system uses a three-tier architecture consisting of a Polar H10 wearable sensor to collect heart rate data and transmit it via Bluetooth to a smartphone application.

Nwaneri and Ogbuji (2019) developed an affordable, simple, and non-invasive cardiovascular monitoring system for low-income countries. The study did not demonstrate the remote access capabilities of the device. Heaney et al. (2022) introduced a dual-function ECG monitoring device designed to cater to both patients and healthcare practitioners. Umer et al. (2023) developed an integrated IoT and AI framework-based remote monitoring system that combined an ensemble extra tree and CNN model to monitor and classify heart failure risk in real-time. The study demonstrates the feasibility of coupling sensor networks, cloud infrastructure, and AI for remote cardiac care, and in contrasting multiple models to support their choice. Chan et al. (2025) developed a device for cardiovascular system monitoring by combining IoT sensors and machine learning. The study was innovative as it incorporated hemodynamic parameters (SVI, CO) and data-enhancement techniques. However, the sample size was small and the study was limited to young obese women in one region, which affects its generalizability.

Real-time, patient-centred heart monitoring using smartphones, wearable technology, and cloud computing holds promise, but implementing these systems in Nigeria faces significant challenges. These include expensive monitoring devices, doubts about the accuracy of heart readings, dependable data transmission, notifying relevant parties about abnormal heart readings, inconsistent power supply, and the ease of use of the system. This study aimed to design and construct an IoT-based cardiovascular monitoring system. The objectives of this study are to (i) design and construct a cardiovascular monitoring system using ECG and pulse oximetry. (ii) Integrate the system with IoT technology for remote monitoring. (iii)

Evaluate the performance of the cardiovascular monitoring system.

Timely intervention could prevent dire emergencies and save lives. Similarly, medical device development projects should be properly scheduled to achieve the desired project objectives of time and budget. Effective project management of medical device development projects will help to lower the cost of medical devices and make them accessible to a larger number of persons in low- and middle-income countries. There is a need for affordable IoT-enabled cardiovascular monitoring systems to meet the growing demands due to the increasing number of persons suffering from cardiovascular diseases in Nigeria. This study aimed to develop a device that can detect anomalies in patients' vital cardiac signs and transmit the data obtained to physicians or caregivers remotely in a cost-effective manner. This is particularly beneficial to patients who require continuous monitoring but may not always be able to visit healthcare facilities regularly.

It can be used at home by patients and/or caregivers, or in a clinical or convalescence setting by a physician or healthcare professional.

## MATERIALS AND METHODS

### Materials

A component selection matrix implemented is shown in Table 1. The weights were assigned through expert judgement. The scores were assigned on a 0–5 scale to evaluate components. Each score represents a specific level of performance or suitability, defined by distinct criteria. This ensures that the assessment is objective, repeatable, and transparent. Table 2 shows the components used to design the circuit and their respective functions.

**Table 1:** Component Selection Matrix for ECG Module

| Criteria | Weight | AD8232 | | MAX30003 | | ADS1292R | |
|---|---|---|---|---|---|---|---|
| | | Score | Weighted Score | Score | Weighted Score | Score | Weighted Score |
| Cost | 0.15 | 5 | 0.75 | 3 | 0.45 | 2 | 0.30 |
| Power | 0.12 | 4 | 0.48 | 5 | 0.60 | 4 | 0.48 |
| Signal Quality and Noise | 0.25 | 3 | 0.75 | 4 | 1.00 | 5 | 1.25 |
| Integration /Peripherals | 0.12 | 3 | 0.36 | 4 | 0.48 | 5 | 0.60 |
| Ease of Use | 0.18 | 5 | 0.90 | 3 | 0.54 | 3 | 0.54 |
| Availability | 0.10 | 5 | 0.50 | 4 | 0.40 | 3 | 0.30 |
| Size | 0.08 | 4 | 0.32 | 4 | 0.16 | 3 | 0.24 |
| **Weighted Total** | **0 -5** | | **4.06** | | **3.63** | | **3.71** |

### Design Requirements

There is a need to develop a low-cost, IoT-based cardiovascular monitoring system based on time and cost constraints. The functional and non-functional requirements are shown in Tables 3 and 4, respectively.

**Power Consumption Analysis and Battery Runtime Estimation**

The power unit comprises two rechargeable lithium-ion batteries with a rating of 3.7V, 1200mA connected in parallel, and a battery management system (BMS) connected to the batteries at their positive and negative terminals.

**Table 2:** Materials and Their Function

| S/N | Component | Description and Function |
|---|---|---|
| 1. | ECG Module (AD8232) | The ECG module uses an AD8232 sensor with three electrodes to detect and amplify heart signals. |
| 2. | Blood Oxygen and Heart Rate Sensor Module | The sensor module measures $SpO_2$ and heart rate, and minimizes external light interference. |
| 3. | ESP32 Microcontroller Unit | It serves as the central processing unit and integrates an in-built Wi-Fi module. |
| 4. | Power Supply Unit | This consists of two 3.7V, 1200mA lithium-ion batteries connected in parallel and managed by a BMS that controls charging and discharging. |
| 5. | I2C Liquid Crystal Display Module | The I2C LCD module displays text on a 16×2 screen using the PCF8574 chip for control. |
| 6. | Buzzer | The buzzer produces a buzzing sound when triggered by the microcontroller. |
| 7. | Stripboard | This is a prototyping board made of insulating material. |
| 8. | Plastic Casing | Designed to house and protect sensitive electronic and electrical circuit components. |
| 9. | Resistors | The device was implemented with resistors to regulate current flow in the circuit. |
| 10. | NPN BC547 Transistors | The NPN BC547 transistor acts as a switch, controlling the circuit's current path ON or OFF. |

$$Q_{pack} = Q_{cell1} + Q_{cell2} \quad (1)$$

Given that $Q_{cell1} = 1200\ mAh$,

$Q_{cell2} = 1200\ mAh$

$Q_{pack} = 1200\ mAh + 1200\ mAh$

$Q_{pack} = 2400\ mAh$

The energy stored in the batteries is calculated:

$$E_{batteries} = V_{nom} \times Q_{pack} \quad (2)$$

With $V_{nom} = 3.7\ V$, $Q_{pack} = 2.4Ah$

Therefore,

$E_{batteries} = 3.7\ \times 2.4 = 8.88\ Wh$

The system efficiency, $\eta = 0.90$. The battery run time is given by:

$$t_{run} = \frac{E_{bat} \times \eta}{P_{out}} \quad (3)$$

$$t_{run} = \frac{8.88 \times 0.90}{2.5} = 3.1968\ \approx 3.20\ hours$$

This means the device's battery is estimated to last for 3.2 hours before it needs recharging. The BMS module monitors and controls the charging and discharging process. The BMS module consists of: a charging circuit; a protection circuit, which connects the batteries' negative terminal to the common ground shared by all components in the system, and disconnects the battery in event of discharge, overcharge, or short circuit; and a buck-boost converter which ensures that a constant voltage is maintained in the system irrespective of the level of the battery charge. It acts as a step-down converter when the voltage is high and a step-up converter when boosting the 3.7V output from the batteries to the 5V required by the system components. The operating currents for the different modules of the device are:

NodeMCU (ESP8266): $I_{MCU} = 80\ mA$, MAX30102 sensor: $I_{MAX30102} = 5$ mA

LCD (16 × 2): $I_{LCD} = 20$ mA

$Buzzer$ (driven through BC547, continuous tone): $I_{buzzer} = 30$ mA

ECG front-end/module: $I_{ECG} = 3$ mA

The total load current is given by:

$I_{total} = I_{MCU} + I_{MAX10302} + I_{LCD} + I_{buzzer} + I_{ECG}$ (4)

$I_{total} = 80mA + 5\ mA + 20\ mA + 30\ mA + 3\ mA$

$= 138\ mA$

The output power required is calculated as:

$P_{out} = V_{out} \times I_{out}$ (5)

$P_{out} = 3.7\ V\ \times 0.138 = 0.5106\ W$

To determine if a resistor, $R_1$, gives enough base current to saturate the BC547 when driving the buzzer.

Buzzer collector current,

$$I_C = I_{buzzer} = 30\ mA$$

NodeMCU GPIO output voltage $V_{GPIO} = 3.3\ V$

Base-emitter drop $V_{BE} \approx 0.7$,

Required Base current for forced-beta = 10;

$I_B = \frac{I_C}{10} = \frac{30\ mA}{10} = 3\ mA$

Required base resistor:

$R = \frac{V_{GPIO} - V_{BE}}{I_B} = \frac{3.3-0.7}{0.003} = 866.67\ \Omega$. The current for the $1k$ resistor,

$I_{B,1K} = \frac{3.3-0.7}{1000} = 2.6\ mA$

$\beta = \frac{I_C}{I_B} = \frac{30\ mA}{2.6\ mA} \approx 11.5$

amplifies, switches, and controls electrical signals. It is composed of three legs- the base, the collector, and the emitter. In the electric circuit of this device, the transistor is connected to the D8 GPIO pin of the ESP8266 MCU through a 1k ohm resistor connected to its base. The emitter is connected to ground, and the collector is connected to the load. This connection is done because the MCU outputs a voltage of 3.3V, which is less than the 5V needed to power the buzzer and LCD screen. The transistor used in the circuit is an NPN BC547 transistor, and this configuration is known as a switching circuit. Transistor switching involves modulating the current flow between the collector and emitter using the base as a control element. This control enables the switching of the current path ON or OFF, effectively functioning as a switch. The functional and non-functional requirements are shown in Tables 3a and 3b, respectively.

**Table 3a:** Functional Requirements

| S/N | Requirements | Description | Performance Criteria |
|---|---|---|---|
| 1 | ECG acquisition | Acquire a single-lead ECG signal from the patient. | Sampling rate ≥ 250 Hz; Signal-to-Noise Ratio ≥ 40 dB; amplitude accuracy ±5% |
| 2 | Heart rate calculation | Compute the average HR from the ECG. | HR accuracy ±3 beats per minute (bpm) |
| 3 | $SpO_2$ measurement | Measure arterial oxygen saturation. | Accuracy ±5% for $SpO_2$ in range 70–100%; measurement time ≤ 10 s; averaging window ≤ 8 s |
| 4 | Respiratory Rate (BPM) | Estimate respiration rate | Accuracy ±2 breaths/min or ±10%; update interval ≤ 15 s |
| 5. | Local Display | Show HR, $SpO_2$, on device screen. | Display update latency ≤ 1s |
| 6. | Power management | Safe battery charging | Provide the remaining run-time estimate within ±10% error |

**Principle of Operation**

The cardiovascular monitor is powered by two 3.7V batteries connected in parallel and managed by the BMS. The BMS delivers voltage to the ESP8266's input pin (Vin) when powered on, which then powers other components through its onboard voltage regulators. The MCU initialises its General-Purpose Input/Output (GPIO) pins and I²C bus for communication with the sensors and the LCD. It configures the MAX30102 sensor for measuring heart rate and $SpO_2$, and it prepares the ECG sensor for capturing the heart's electrical signals. The MCU activates its connection to a Wi-Fi network using its built-in Wi-Fi module. The device is tested by placing one finger on the exposed MAX30102 sensor while the ECG electrodes are properly positioned on the chest. . In this study, a standard three-lead electrocardiogram (ECG) configuration was employed to acquire the heart's electrical activity. The three electrodes are designated as Right Arm (RA), Left Arm (LA), and Right Leg (RL).

**Table 3b:** Non-Functional Requirements

| S/N | Requirements | Description | Performance Criteria |
|---|---|---|---|
| 1 | Measurement accuracy | Measurement accuracy of vital signs | $SpO_2$ ±5% (70–100%); HR ±3 bpm; BPM ±2 breaths/min |
| 2 | Reliability/ availability | Reliability of the device | Mean Time Between Failures (MTBF) ≥ 10,000 hours; uptime ≥ 99% |
| 3 | Safety | Ability to meet safety standards | Meet IEC 60601-1 basic safety principles and pass electrical safety tests |
| 4 | Battery runtime | The time for continuous operation of a full battery charge under normal load conditions | Minimum continuous operation ≥ 3 hours under normal load |
| 5. | Size and weight | Size and weight of the device | Device volume ≤ 120 × 70 × 30 mm; weight ≤ 250 g (including battery) |
| 6. | Environmental | Environmental conditions, including temperature and humidity | Operating temp 0–45 °C |
| 7. | Availability of components | Component's availability in the local market. | ≥ 90% of key components available locally |
| 8. | Usability | Ease of use and user interface | ≥ 12-point equivalent. ≤ 30s from power-on to vital sign display |

They were positioned on the patient's torso to ensure stable signal acquisition and minimize motion artifacts. The RA electrode is placed below the right clavicle, approximately over the right pectoral region, while the LA electrode is positioned symmetrically below the left clavicle. The RL electrode, serving as the reference or ground, is placed on the lower right side of the abdomen. This configuration, corresponding to the Lead I arrangement (RA–LA), was selected due to its simplicity and effectiveness in capturing the cardiac electrical potential difference across the chest. The MAX30102 continuously monitors blood oxygen saturation ($SpO_2$) and heart rate, transmitting raw data via the $I^2C$ interface (SCL and SDA lines) to the MCU. Simultaneously, the ECG module captures the heart's electrical activity through the electrodes, converts it into analogue signals, and feeds these signals to the MCU's analogue input pin (A0). The processed data is displayed on the 16×2 LCD screen connected to the MCU via the I2C interface. The display shows real-time beats per minute, $SpO_2$ levels, and numerical representations of the ECG signal. The processed data (heart rate, $SpO_2$, ECG signals) are then packaged and sent at thirty-second intervals over the Wi-Fi network to be stored in a database managed by a cloud server, and from there, it is sent through HTTP requests to a desktop application, which parses the incoming data and displays it in real-time on the user interface. Figure 1 shows the block diagram of the device.

**Ethical Considerations**

Ethical approval was obtained from the College of Medicine, University of Lagos Health Research Ethics Committee with approval number CMUL/HREC/05/24/1478. The device is non-invasive and poses minimal risks. Participation in the study was voluntary, and the data of participants were adequately protected.

## RESULTS AND DISCUSSION

### Results

To determine the workability of the IoT-enabled cardiovascular monitoring device, it was tested on selected healthy subjects, with the results presented in Tables 4 and 5. The ECG graph is presented in Figure 4. The device is shown in Figure 3.

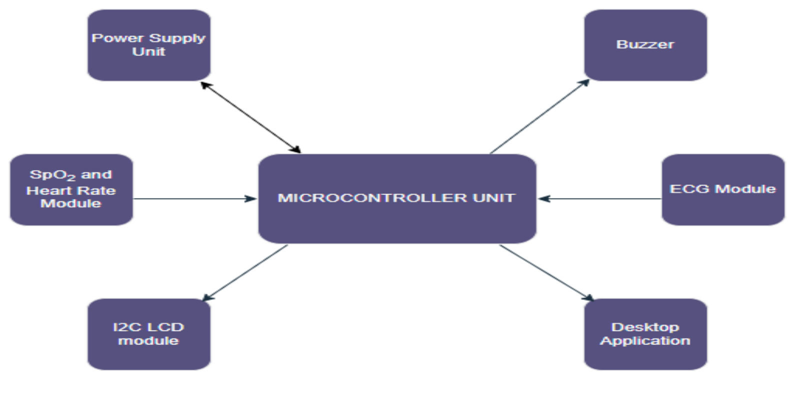


**Figure 1:** The Block Diagram of the Device

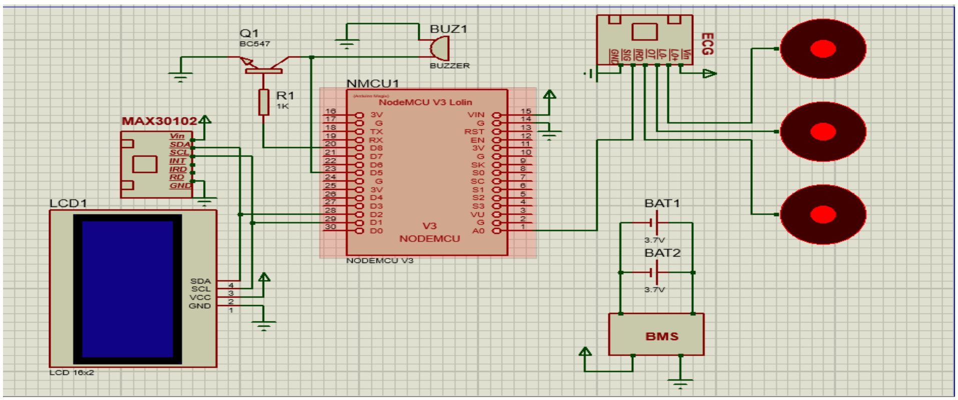


**Figure 2:** Circuit Diagram of the System

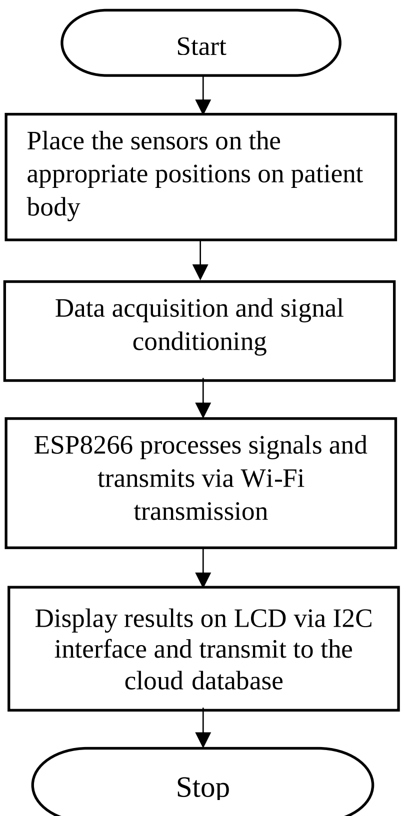

**Figure 3:** The Flowchart of Device Operation

**Table 4:** Result of prototype test on Subject 1

| TIME STAMP | $SPO_2$ (%) | BPM |
|---|---|---|
| | **Subject 1** | |
| 18:31:34 | 98 | 64.17 |
| 18: 32:04 | 98 | 65.04 |
| 18:32:34 | 97 | 72.38 |
| 18:33:05 | 99 | 97.56 |
| 18:33:35 | 98 | 70.67 |
| 18:35:06 | 98 | 98.36 |
| 18:35:37 | 96 | 101.87 |
| | Subject 2 | |
| 08:00:05 | 97 | 79.68 |
| 08:00:37 | 98 | 88.24 |
| 08:01:14 | 97 | 77.62 |
| 08:01:45 | 97 | 80.32 |
| 08:40:28 | 96 | 64.66 |
| 08:41:33 | 96 | 71.47 |
| 08:42:06 | 98 | 88.76 |
| | Subject 3 | |
| 21:04:42 | 98 | 95.69 |
| 21:05:12 | 98 | 19.74 |
| 21:05:42 | 99 | 95.09 |
| 21:06:13 | 98 | 127.93 |
| 21:06:43 | 99 | 102.39 |
| 21:07:14 | 96 | 84.99 |
| 21:08:15 | 98 | 107.53 |
| | Subject 4 | |
| 07:14:54 | 97 | 35.34 |
| 07:54:34 | 96 | 67.57 |
| 07:56:06 | 99 | 15.82 |
| 08:00:05 | 97 | 79.68 |
| 08:00:37 | 98 | 88.24 |
| 08:01:14 | 97 | 77.62 |
| 08:01:45 | 97 | 80.32 |

Descriptive statistics were primarily used to analyze the $SpO_2$ and BPM, as shown in Table 5. It was observed that $SPO_2$ was stable with low standard deviation; however, heart rate variability was observed. Furthermore, Figure 6 shows a histogram of the SpO2 and heart rate. The histogram of heart rate (HR) readings shows a unimodal and approximately normal distribution, indicating that most heart rate values cluster around the mean. The heart rate values ranged from 64 to 102 beats per minute (bpm). The slight right skewness observed suggests occasional increases in heart rate, possibly due to transient physical movement or emotional response during measurement.

## DISCUSSION

An IoT-enabled cardiovascular monitoring system was developed to measure and transmit vital signs associated with cardiovascular health, specifically, blood oxygen saturation ($SpO_2$), heart rate, and electrocardiogram (ECG) signals to physicians for remote monitoring. The ECG is recognized as a robust, non-invasive technique for assessing cardiac function (Sattar & Chhabra, 2023). The system recorded a mean $SpO_2$ of 97.5 ± 1.01%, consistent with normal physiological ranges of 95–100% reported by Jubran (2015) and similar findings by Lipnick et al. (2016) and Nitzan et al. (2014). This confirms the sensor's functionality in detecting blood oxygen levels with minimal variability, despite a few outliers. The mean heart rate of 81.27 ± 22.97 BPM falls within the normal resting range of 60–100 BPM (AHA, 2023), demonstrating the functionality under stable conditions. Comparable results were observed in earlier studies. Zhang et al. (2019) reported a mean error of <5 BPM in wrist-worn monitors, while Abbas et al. (2021) found strong agreement (r > 0.9) between optical and ECG-based heart rate measurements. ECG readings from the prototype displayed clear P-waves, QRS complexes, and T-waves, which represent normal cardiac activity. The periodicity and regular sinus rhythm align with prior evaluations by Zhao et al. (2020) and Acharya et al. (2018), confirming accurate cardiac signal capture essential for arrhythmia detection and cardiac health assessment. This IoT-enabled device holds significant potential for home-based cardiovascular monitoring, especially for elderly patients, those with chronic diseases, or individuals with limited mobility in low- and middle-income countries. By enabling continuous, real-time monitoring of ECG, $SPO_2$, and heart rate, the system can enhance early detection, reduce hospital visits, and support timely clinical interventions. This will ultimately improve patient comfort and reduce healthcare costs.

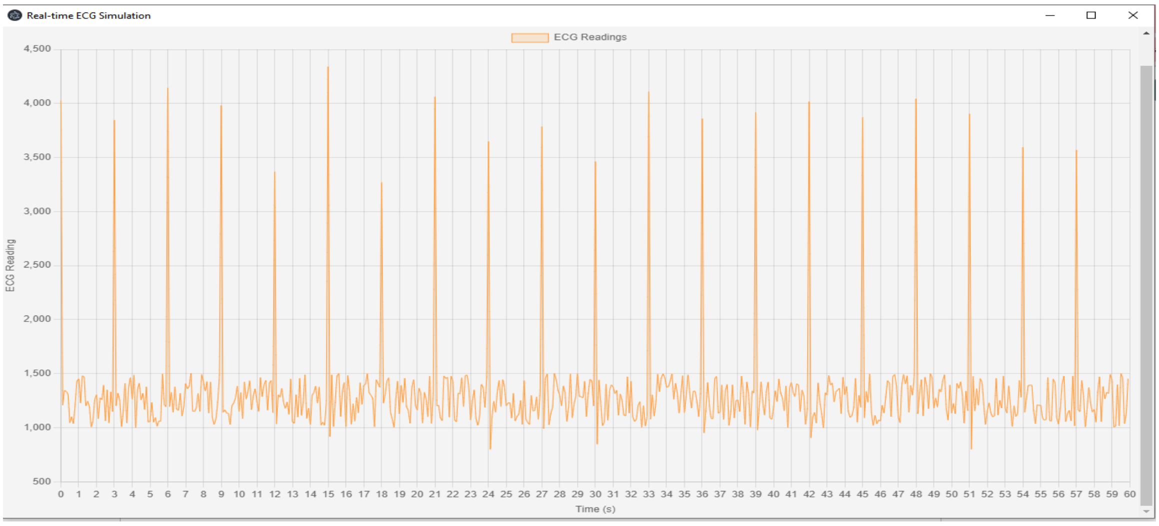


**Figure 5:** ECG graph

## CONCLUSION

The developed cardiovascular monitoring system represents a major step in affordable, wearable health technology with real-time data and remote monitoring. The prototype captured and transmitted ECG, $SpO_2$, and heart rate data, displaying results on a web-based platform. ECG readings reflected normal cardiac patterns, while $SpO_2$ and heart rate offered further insights. This study has a few limitations. The device is a three-electrode ECG device that may be unable to measure complex cardiac conditions. Also, it is susceptible to motion and noise artifacts. The device was also tested only on healthy persons. Despite minor outliers, the device demonstrates good potential for effective cardiovascular disease monitoring.

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