Development of Wearable Wireless Electrocardiogram Detection System using Bluetooth Low Energy

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Abstract: Wearable monitoring devices can provide patients and doctors with the capability to measure bio-signals on demand. These systems provide enormous benefits for people with acute symptoms of serious health conditions. In this paper, we propose a novel method for collecting ECG signals using two wireless wearable modules. The electric potential measured from a submodule is transferred to the main module through Bluetooth Low Energy, and the collected values are simultaneously displayed in the form of a graph. This study describes the configuration and outcomes of the proposed system and discusses the important challenges associated with the functioning of the device. The proposed system had 84% signal similarity to that of other commercial products. As a band-type module was used on each wrist to check the signal, continuous observation of patients can be achieved without restricting their actions or causing discomfort.

Keywords: wearable electrocardiogram (ECG); wireless communication; Bluetooth; synchronization; bio-signal

1. Introduction

Advances in medical technology have significantly influenced the diagnosis and treatment of diseases, improving modern life. However, various diseases, such as obesity, diabetes, and cardiovascular disease (CVD), have become increasingly common. CVD is the leading cause of death worldwide, resulting in 17.3 million deaths per year, and this figure is expected to rise to more than 23.6 million by 2030 [1]. Cardiac problems cause serious damage to the body and are associated with high mortality rate. Thus, onset of symptoms such as chest pain, angina, dyspnea, palpitations, and syncope must be immediately diagnosed for optimal treatment [2]. Evaluation and surgical procedures are recommended within 90 min of the onset of symptoms of ST-elevation myocardial infarction [3]. However, in reality, it is difficult to meet the ideal door-to-balloon time because patients often do not recognize the seriousness of their symptoms. Therefore, portable [4,5] and wearable ECG monitoring devices [6–9] have been developed to promptly evaluate heart conditions in a rapid and convenient manner. In addition, these devices can transmit their results to remote terminals, such as smartphones, using wireless communication technologies such as Bluetooth Low Energy (BLE) and mobile communication [10–12]. These remote transmission capabilities can facilitate doctors to evaluate a patient’s symptoms in real time. However, to measure potential differences, current commercial portable modules are operated by bringing both hands into contact with the dry electrode [13] of the device, and a module is attached to the chest of the user. Such a self-operated monitoring device will not be useful if patients do not consider their symptoms seriously. In addition, the recorded ECG signal cannot be printed, and its poor quality makes it impossible for a cardiologist to provide proper diagnosis. Furthermore, there is a problem of losing important information about cardiac activity due to excessive filtering.
Takahashi et al. designed a new wearable device capable of conducting a child’s electrocardiogram (ECG) from the wrist by applying dry electrodes to an elastic cuff [14]. Rachim et al. proposed a system for performing ECG through the implementation of a capacitive coupling electrode on an armband. However, these are single-lead wearable devices that are not clinically recognized for monitoring/diagnosing heart diseases [15].

Rosenberg et al. developed a smart helmet that is particularly useful for recording and monitoring vital signs in uncertain or dangerous situations, such as during racing or military activities [16]. However, the power consumption of this system is relatively high.

A low power consumption implies that the device can operate for a longer period, which is especially important for long-term monitoring of body conditions using wearable devices without causing discomfort [17].

In this study, we developed a new system that uses BLE to collect single-lead ECG signals from the individual’s wrists and verify raw data and signals without wiring the module or touching the patient. The system consists of two modules capable of wirelessly communicating with each other and measuring potential differences. To collect the ECG data using the band-type module, we fabricated miniaturized circuits with BLE 4.0, and a microcontroller unit (MCU) to process the raw signal, and then we experimentally verified the performance of the module. We obtained a signal similarity of 84% in comparison to that of commercial products. In this study, we discuss the application challenges.

2. Materials and Methods

2.1. System Architecture

Figure 1 shows the configuration of the proposed system. The MCU (CY8C4247LQI-BL493, Cypress, USA) includes an analog-to-digital converter (ADC), an operational amplifier (op-amp), and BLE, and it can be used through the design tools provided by Cypress. Analog devices are composed of passive elements. To implement a filter by utilizing the op-amp embedded in MCU, resistors, and capacitors are among the included passive elements, together with Bluetooth antennas. It contains a band-pass filter to filter the raw signal in the circuit.

Figure 1. Configuration of the proposed system. ECG (electrocardiogram), MCU (microcontroller unit), ADC (analog to digital converter), OP-AMP (operational amplifier ), RA (right arm), LA (left arm), UART (universal asynchronous receiver-transmitter), BLE (Bluetooth Low Energy).
During the measurement of an ECG signal, the system is configured as a wrist-type system and aims to minimize the discomfort experienced by the user owing to restricted movements.

The Left Arm (LA) and Right Arm (RA) electrodes were placed on the left and right forearms, respectively. The potential difference was measured through a wireless node on each wrist. A 3.7 V, 120 mAh lithium polymer battery was used to perform operations for 290 min, including data processing and BLE. The sub-module collecting negative potential data and the main module measuring the positive potential data were fabricated with the same hardware architecture.

The main and sub-modules were synchronized using wireless communication. The main module measures the potential of the left wrist, and the ECG signal measured in this module is compared with that transmitted from the sub-module, and the final result is then transmitted. The sub-module (slave) measures the potential of the right wrist, and all the processes proceed based on the main module (master).

Typically, differential amplifiers [18] or op-amp [19] are used to limit the bandwidth and amplify microscopic electrical signals to measure heart signals. We fabricated miniaturized monitoring modules using a programmable analog block and a small number of elements. In addition, filters for noise processing were implemented using monitoring software.

Figure 2 presents the analog blocks and the circuit structure of the analog signal operation. Different bandwidths have been used for different applications in ECGs; a bandwidth in the range of 0.05–100 Hz has been used as the clinical bandwidth for recording the standard 12-lead ECG, and a bandwidth in the range of 0.5–50 Hz has been used for critical applications, such as in intensive care units and ambulatory patients [20]. Two amplifiers with bandwidths in the range of 0.5–45 Hz were used for the filter, and a mid-level voltage was generated to raise the baseline of the signal. Because a single power source was used, we added a potential divider to supply a reference signal as the base level of the ECG signal. Analog blocks, such as the op-amp and ADC, have typical input voltages in the range of 0–3.3 V, and the filtered analog signal was converted to digital data at a sampling rate of 500 Hz.

![Figure 2. Block diagram of the monitoring module using PSoC 4.2.](image-url)

The sub-module and main module simultaneously measured the potential difference between each wrist, and both results were combined and calculated in the main module. Sample data collected from the sub-module were converted into a six-byte packet and subsequently transmitted to the main module via BLE. Then, the received data were inverted before being added to the results from the main module to generate the ECG
Because noise is introduced into the internal circuitry during signal processing, we designed a digital notch filter to limit a portion of the bandwidth using Python 3.6.

2.2. Specifications of the ECG System

The circuitry of the ECG monitoring device was fabricated using an MCU to process analog signals with a low-power structure by programming the analog block. This system was built without using separate integrated circuit chips, such as communication modules, analog-to-digital converters, or operation amplifiers, to achieve a miniaturized module. The specifications of the detection system are listed in Table 1 and Figure 3 illustrates the proposed system.

Table 1. ECG (electrocardiogram) Detection module specifications.

| Parameter                      | Specification                  |
|--------------------------------|--------------------------------|
| System Size                    | 3.2 × 2.4 × 0.6 cm             |
| ADC Resolution                 | 12 bit                         |
| Sampling Rate                  | 500 Hz                         |
| Packet Size                    | 6 bytes                        |
| Acceptable Voltage Range       | 0–3.3 V                        |
| Gain Value                     | 1100                           |
| Band-pass filter (Analog)      | 0.5–45 Hz                      |
| Notch Filter (Digital)         | 60 Hz                          |

Figure 3. Basic PCB (printed circuit board) of wrist-type ECG (electrocardiogram) detector. MCU (microcontroller unit), BLE (Bluetooth Low Energy).

2.3. Experimental Environment

The study protocol was approved by the Institutional Review Board (IRB) of the ethics committee of Chosun University Medical Centre, Gwangju, South Korea. The experiments were conducted in accordance with the approved guidelines of the IRB. The subject (sex: male, age: 28 years, height: 168.3 cm, and weight: 66 kg) signed an informed consent agreement before the experiment. The subject was asked to sleep for at least 7 h on the night before the experiment and not to consume any alcohol or caffeine-containing substances to ensure accurate ECG detection. When the subject arrived for the experiment, the purpose of the study and the experimental procedures were explained to him.

To examine the performance of the system, we used an ECG simulator (SECG 4.0; Whaleteq Co., Taiwan) capable of generating various alternating current signals, including ECG signal-based IEC60601-2-25, 2-27, and 2-47. A reference system (Bino-kit; Segang, Korea) was used to analyze and compare the results. In addition, the data measured for
digital filtering were processed using Python 3.6 band MATLAB R2017B, and signals were collected using an oscilloscope (MSO9105A; Keysight Co., US).

2.4. Signal Processing

Two modules were used to collect the electric potentials from both the wrists and communicate with each other via BLE. The microcontroller embedded in the module can build analog blocks such as an op-amp to amplify and filter the signals, an ADC to output digital values, a timer to control the sampling rate, and a BLE module. To synchronize the communication between the modules, a timer/counter was used to sample the signals in a defined cycle. Because the system clock rate of the device was set to 1 MHz, the timer/counter was set to 2000, indicating that digital data were generated every 2 ms (500 Hz) and transmitted to the main module via BLE. If the 250 Hz sampling period is altered and both the modules exhibit an asynchronous delay, the output of the ECG module may yield severely distorted results. Therefore, we designed the monitoring modules with a sampling period 500 Hz higher than the above-mentioned rate, and synchronization issues were not considered.

Figure 4 shows the synchronization and signal output between the main and sub-modules. As the ECG potentials measured by the two modules are different by depolarization and repolarization, the difference in the signals must be calculated. When initial synchronization was achieved, data send/receive packets were created and stored in sync.

![Figure 4. Sampling process of the two modules used to detect values according to the timer/counter. ADC (analog to digital converter).](image)

2.5. Synchronization of Wireless Modules

Abnormal signals due to asynchronous communication between modules may occur because of an improper sampling period. This can lead to severe issues for the generated ECG; thus, the minimum rate of sample collection was set to >250 Hz (4 ms) during the configuration of the monitoring device [21]. If the required operation time from sampling to communication exceeds 4 ms, the main device may output an abnormal signal while calculating the digital values from both modules. It is impractical to acquire ECG signals at high sampling frequencies of 500 and 750 Hz in a real environment. With the increasing penetration of remote monitoring and wearable devices, the device’s small size is limited to low-capacity batteries. Wireless communication, such as Bluetooth and Zigbee, limit the number of transmission packets. Thus, the number of cycles per sample, timer counter, and packet size must be adjusted accordingly.

Figure 5 shows the structure of the synchronization process. Our proposed system uses flag signals to minimize errors that may occur in the synchronization process.
Figure 5. Configuration diagram of the synchronization structure. MCU (microcontroller unit), ADC (analog to digital converter), UART (universal asynchronous receiver-transmitter).

Step 1: When the module is attached to the body and the power is turned on, a fine voltage is automatically applied to the module.

Step 2: The measured signal is amplified to a voltage (gain voltage of 1100) sufficient to be processed by the MCU using an internal amplifier.

Step 3: In the main module, the flag signal is transmitted to the sub-module during the sampling period.

Step 4: The sub-module operates the ADC whenever it receives a flag signal. The ADC was also performed in the main module. In this structure, it is used to synchronize the signals measured by both arms.

Step 5: The value processed in the sub-module is transferred to the main module, and a valid result value is generated by calculating it with the processed value. For synchronization between the sub-module and main module, delays and interrupts are used, and the operation is performed when the two received values are valid.

Valid data are transmitted to the PC application through BLE or UART communication, filtered, and then graphed. If an error occurs in the flag signal during processing, a re-signal is required. This process can minimize the drift that can occur when collecting data from each module.

3. Results
3.1. Preliminary Study

Two commercial analog circuitry devices were used, namely, the Bino-kit, used as the training board, and a Bino-amp (Segang, Korea), used to detect the signal, as in preliminary studies (Figure 6a). Two Bino-amp modules were organized with differential amplifiers, and an op-amp was used to measure the electric potential via silver metal and salt-silver chloride (Ag/AgCl) electrodes attached to each wrist. The positive port of one module was connected to the right wrist, and the right leg drive (RLD) was wired with the negative port in the differential amplifier and brought into contact with the right leg. The negative port of the other module was wired to an electrode on the left wrist, and the RLD and the positive pin were constructed at the same location as mentioned above. The sampling frequency of the oscilloscope was set to 10 kHz, and a digital notch filter of 60 Hz was used in both experiments for a clear comparison.
Figure 6. (a) Specifications of the Bino-Kit and the experimental setup to measure bio-signal from the wrists using two amplifiers. (b) Experimental environment of developed system. (c) Results of the filtered and calculated digital signals for the proposed system. RLD (right leg drive), ADC (analog to digital converter).

Figure 6-b shows the measurement method of our developed system. The electrodes were attached to both wrists, as shown in the figure, for the wireless synchronization of the signal measurement. The filtered data calculated from each module were used to generate the ECG graph presented in Figure 6-c. In the experiments with the aforementioned setup, the digital values from the two-analog amplifier were used to display an intact ECG graph.

3.2. Performance of the Proposed System

Figure 7 shows a photograph of a PC program monitoring the measured ECG results. This figure shows ECG measurements using the proposed system using data generated by the ECG simulator and data derived directly from the body. The PC monitoring application displays the results of the two signals in real time. In each figure, the upper graph represents the raw data, whereas the lower graph shows the notch filter applied to the monitoring application. The notch filter in the 60 Hz band is also applied to the hardware part, but it is included in the application in the second order for a thorough removal. In addition, the monitoring application can save the displayed data as a comma separated value file. The Bino-kit and the proposed system were observed with a Lead-I
waveform using three electrodes. To minimize noise from the ECG system, a notch filter was included in the PC monitoring program. Comparing Figs. 7(a) and 7(c), a signal of approximately 95% was achieved with the simulator, but the data measured from the body were somewhat lower (approximately 84%). These two signals were compared using the correlation coefficient included in MATLAB 2019A that showed a 95% agreement. The ECG simulator consistently produced high-quality data, but signals from the body were influenced by many variables, resulting in a noisier cardiograph. Although the signal recorded from the body contained more noise than that obtained with the ECG simulator, the ECG waveform, as a series of component waves including P, Q, R, S, and T, was clearly demonstrated without other distortions.

![Figure 7](image_url)

Figure 7. ECG-measurement-result (electrocardiogram) in the monitoring system: (a) ECG simulator with the proposed system, (b) using the body with the proposed system, (c) ECG simulator with the reference system, and (d) using the body with the reference system.

We confirmed the possibility of applying the developed ECG detector in everyday life. Figure 8 shows the ECG signal measured during the movement. A healthy volunteer performed the test with physical movements and breathing. The procedure is as follows:

1. Sitting on a chair (12 s) -> 2. Get to one’s feet (3 s) -> 3. Standing (10 s).

When the applicant sits comfortably in a chair, it can be observed that a good quality ECG signal is obtained as output. However, while standing on a chair, the quality rapidly deteriorates due to motion artifacts. This was because of the noise in the skin muscles due to physical movements and the change in the coupling capacitance between the electrodes and the skin. When the volunteer stopped moving and stood still, the wearable ECG signal was restored to its normal state.
4. Discussion

To display the ECG, a voltage of approximately 1–5 mV, generated from the wrists, was amplified and filtered by the circuitry of the device. In general, analog circuitry is isolated from digital circuitry to reduce digital noise during the measurement of bio-signals because the results are typically vulnerable even to a small amount of noise. However, it is difficult to specifically isolate analog and digital circuitry because analog filtering and digital processing are operated from the same controller in the adopted MCU [22]. To address this problem, a recently developed circuit architecture using programmable controllers can be applied to alleviate the interference. Additional software filtering is also essential to calibrate the signal [23–27].

5. Conclusions

In this study, we developed a wearable ECG monitoring module that can be worn on each wrist and communicate wirelessly. According to previous studies, an ECG signal can be generated through the digitized potential difference of both hands, resulting from the connection of the cables to both modules, and the data were transmitted via wireless communication [28,29]. Although the proposed system poses several challenges that are yet to be solved, we expect it to enable easy-to-perform ECG monitoring in the form of a portable, wearable device. To detect abnormal physiological states, bio-signal sensors must operate without conscious real-time manipulation. However, in conventional wearable systems (e.g., Apple Watch), measurement is possible only when the ground is formed by touching the opposite finger to the worn module. In addition, a miniaturized module attached to the chest or a commercial Holter device with multiple channels wired to the electrodes may be inconvenient to use.

Thus, the developed device will significantly improve the convenience of patients by monitoring heart conditions without requiring proactive steps. In addition, using multiplex (one-to-many or many-to-many) wireless communication, poor reliability of single-lead ECG can be addressed [30–33], especially if the technology is improved to accept result packets from multiple devices. The performance of the module was verified using an ECG simulator and signals generated from the body of a voluntary subject. No significant differences were observed between the commercial ECG measurement module and the device fabricated in this study. Existing monitoring devices used to detect potential differences often cause discomfort during operation and must be constantly checked by patients. Meanwhile, the device developed in this study is predicted to significantly

Figure 8. ECG (electrocardiogram) Signal measured from with body movement: (a) reference system and (b) proposed system.
improve the wearability and usability of health tracking systems that can be applied in clinical, sports, and military fields.

6. Patents

We have a patent registered by the Korean Intellectual Property Office and are pending in the US.

Apparatus and method of measuring electrocardiogram signal using wireless communication and computer-readable medium (Registration Number: KR 10-2139121, Registration Date: July 23, 2020; Application Number: US 16/174,494, Application Date: October 30, 2018 Work)

**Author Contributions:** J.J. constructed the Wireless ECG detection system and suggested the concepts for the work; S.S., M.K. and K.H.K., analyzed the data and performed the experiments; Y.T.K. supervised the writing of the article, gave suggestions, and analyzed the data for the research. All of the authors wrote and critically revised the paper. All authors have read and agreed to the published version of the manuscript.

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**Data Availability Statement:** The data presented in this study are available on request from the corresponding author. The data are not publicly available due to privacy.

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