LETTER

A Flexible Wireless Sensor Patch for Real-Time Monitoring of Heart Rate and Body Temperature

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SUMMARY Real-time monitoring of heart rate (HR) and body temperature (BT) is crucial for the prognosis and the diagnosis of cardiovascular disease and healthcare. Since current monitoring systems are too rigid and bulky, it is not easy to attach them to the human body. Also, their large current consumption limits the working time. In this paper, we develop a wireless sensor patch for HR and BT by integrating sensor chip, wireless communication chip, and electrodes on the flexible boards that is covered with non-toxic, but skin-friendly adhesive patch. Our experimental results reveal that the flexible wireless sensor patch can efficiently detect early diseases by monitoring the HR and BT in real time.

key words: *flexible patch, wireless sensor patch, real-time monitoring, heart rate, body temperature*

1. Introduction

Sudden cardiac arrest, also known as sudden cardiac death, occurs when the heart suddenly and unexpectedly stops beating, leading to mortality in elderly individuals in minutes if not treated immediately [1]. Additionally, the elderly are vulnerable to adjust sudden changes in temperature, which causes heat stroke or hypothermia because of difficulties in body temperature control. In particular, these are highly related to the most serious heart-related illness. Thereby, up to date, real-time monitoring of heart rate (HR) and body temperature (BT) has been considered as one of the most important vital signs and makers in a broad range of human health. Although, these signals can be easily measured by clinicians and nurses, but real-time monitoring of each patient over all day is almost impossible and requires expensive medical cost. Additionally, the cardiac monitors require wired sensors to detect abnormal events in signals, but it may not be suitable to apply in real life due to the discomfort and the lack of portability.

To satisfy such demands, wireless patch sensors for remote monitoring of HR and BT can be suitable approach among currently developed techniques including mercury thermometer, infrared thermometer and conventional cardiac monitors. However, compactness, integration, flexibility, and portability are major bottleneck to implement patch sensors for real-time monitoring of biomedical signals for ultimate healthcare [2]–[4].

Many research groups have developed real-time monitoring systems for various vital signs, which enable to communicate with the smartphone platform for the analysis and information display from the gathered vital signals. For the wearable or portable monitoring system, well-known wireless technologies such as Bluetooth, Zigbee, and Wi-Fi are adopted in the sensor module. One of the paramount considerations in the design is to make the device very compact and portable and then to minimize power consumption. In this case, we need to carefully consider the tradeoff between power consumption and communication range.

In body area networks, Bluetooth technology is widely used thanks to the low power features and the cost effectiveness. Taehwan Roh et al. [8] developed the wireless wearable monitoring system for the mental stress analysis based on the heart-rate variability (HRV) and electrocardiogram (ECG) monitoring system. Liang Kai et al. [9] showed the portable ECG monitoring system which is composed of the Bluetooth module with ECG monitoring circuit and smartphone application for the display software.

For wider area monitoring systems, Zigbee or LoRa wireless technologies have been deployed due to their wireless characteristics in sub-GHz in [10], [11]. The patch-type wearable monitoring systems is also a promising area of huge potential. The small form factor, papery thickness, and the low-power consumption are more challengeable points in the patch-type devices. Mozziyar Etemadi et al. [12] presented a low power multi-modal patch for measuring activity, altitude, ECG, and seismocardiogram (SCG) under 2 mA current consumption.

In this paper, we implement flexible wireless sensor patch for measuring HR and BT by integrating sensor chip, wireless communication chip and electrodes on the flexible boards covered with non-toxic but skin-friendly adhesive patch. Especially for the flexible patch, we utilize the similar processes used in semi-conductor fabrication. The performance of the developed wireless sensor patch is also described based on the test results of real-time monitoring of

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HT and BT of a healthy male. The developed sensor patch with Bluetooth communication can be operated with lower power consumption less than 3 mW.

2. Wireless Monitoring System

Figure 1 represents a block diagram of a health monitoring system, which is comprised of sensors, signal conditioning, flexible battery, and wireless communication parts. Heart beating produces the electrical signals through the heart rate electrodes. The electrical signals produced by the electrodes are directly amplified at the sensor's front-end, and then converted at the analog-digital convertor (ADC). The converted signals are wirelessly transmitted to the host via the modem and the RF transceiver modules. The resistance of the thermistor is measured as the temperature sensor is transduced to the voltage, amplified at the sensor's front-end, and converted by ADC. The converted signals are also wirelessly forwarded to the mobile phone, which displays the HR and BT.

2.1 Wireless Communication Block

There are many wireless communication standards such as UHF RFID, WLAN, ZigBee, and Bluetooth. In this paper, we choose Bluetooth as a wireless technology for heart rate and temperature monitoring patch considering frequency bands, data rate, antenna size, security, compatibility with mobile phones, power consumption, etc.

To monitor the HR and the BT, we produce the flexible system board capable of wireless communication by Bluetooth protocols. For Bluetooth communication, the system board adopts a CC2541 chip of Texas Instrument, which has 2.4 GHz RF transceiver, 8051 MCU, 8 KB RAM, 12-bit ADC, a temperature sensor, and other functional units. As for the performance of CC2541 chip, at 0 dBm output, it provides the current consumption of 18.2 mA, the receiver sensitivity of −94 dBm, the data rate of up to 2 Mbps, and the stand-by power mode with a current consumption of 1 μA.

The detailed information about CC2541 is described in [5].

2.2 Heart Rate Measurement Block

The ADI's AD8232 chip is used to amplify and to filter the heartbeat signal. All electrodes are connected to the electrode portion for detecting the physiological signal. The signal input through the electrodes is amplified and filtered out. In heart rate measurement application, the user's arm and upper body movement creates large motion artifacts, which is added to the input signal. A very narrow band-pass characteristic is required to separate the heart signal from the interferers. The circuits for a two-pole high-pass filter and a low-pass filter are integrated with AD8232 to suppress other interferences and noise. The detailed information on AD8232 is described in [6].

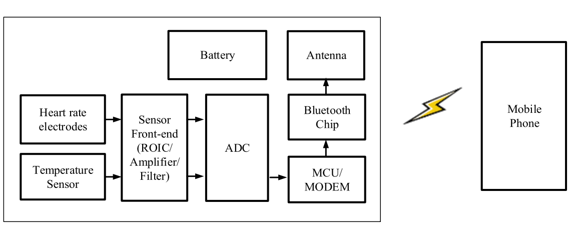

Fig. 1 The block diagram of the health monitoring system

2.3 Flexible Sensor Patch Implementation

The patch-sensors are mainly composed of two sections, i) the flexible battery with the chips for wireless communication and ii) the sensors for monitoring the HR and BT [7]. Additionally, the Bluetooth communication system board is designed to communicate with the patch sensors for gathering vital signals of HT and BT. The total size of healthcare-on-a-patch is 30 × 30 × 3 mm in length (L), width (W), and height (H), respectively. This board is consisted of two blocks for the wireless communication and the sensor electrode parts. The sensor parts are in a flexible PCB (fPCB) to increase the flexibility and to be able to attach on the chest. Also, the flexible battery of 30 (L) × 18 (W) × 1 (H) mm is put on the top of the sensor board. Figure 2 (b) represents the back-side of the health-on-a-patch. This side has three electrodes for measuring heart rate and one temperature sensor. The Bluetooth part is the size of 30 (L) × 10 (W) × 2 (H) mm, respectively, and is made by 4-layer PCB as shown in Fig. 2 (c). Figure 2 (d) is a photograph showing the flexibility of the board.

The protection of main sensor and communication modules need to be carried out due to the potential malfunction of the sensor due to moisture, especially from human sweat. To enhance the protection and the attachment to human skin, the top and the bottom of the sensors are encapsulated between polyurethane resins and orientated polypropylene (OPP) film with 35 μm thickness and the silicon-based adhesive film, which are fabricated using dimethyl silicone,

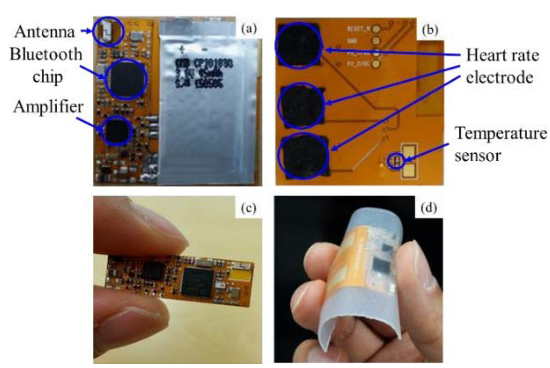

Fig. 2 The wireless sensor boards (a) the front-side of board, (b) the back-side of board, (c) bluetooth communication system board, and (d) the flexibility of PCB board

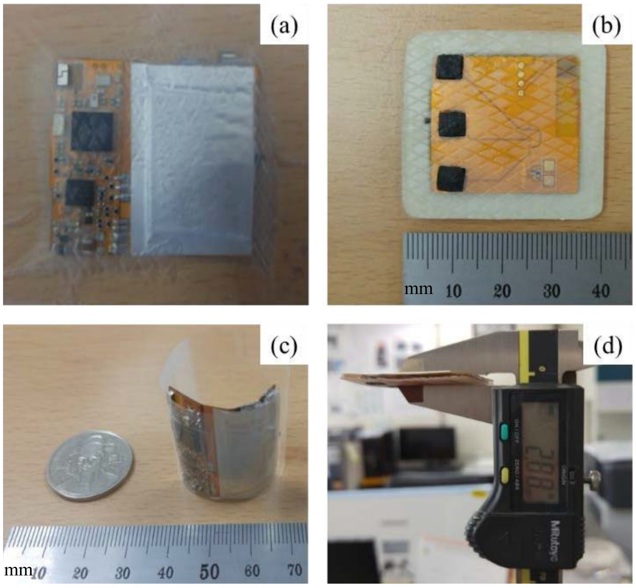

Fig. 3 The wireless sensor patch (a) the front-side of board with the patch, (b) the back-side of board with the patch, (c) the flexibility test of the PCB board in the 15 mm-diameter barrel test, and (d) thickness test results

MQ resin, and Pt catalyst as shown in Fig. 3. Meanwhile, four holes are punched on the adhesive silicon film to expose main HT and BT sensor to monitor the signals. After encapsulation, we made the transparent and rhombus-patterned patch sensor so that its total thickness is about 2.88 mm. Since this patch is normally used in a condition attached to the human chest, it is necessary to evaluate the performance of the device operated on a curved surface. Thus, we carried out the measurement of the heart beating and the temperature change through the wireless board placed inside a cylinder with two diameters of 2 cm and 3 cm, which demonstrate it is operated well even on curved surfaces.

3. Experimental Results

Figure 4 (a) shows the healthcare-on-a-patch attached to the chest of a person in order to monitor the HR and BT. The flexible patch is located, where the HR can be most clearly measured, and then covered with a pad on it. By performing remote sensing capability test of the patch through wireless communication system, we can demonstrate that the attached patch operates well even in remote sensing condition. To demonstrate the operating function of as prepared patch sensors, the common activities of human in real life such as resting, walking, climbing stairs, and jogging states are selected to measure the HR and the BT. Here, Android app is programmed to communicate with the sensors, so the mobile screen displays the results. The HRs of each scenario of resting, walking, and climbing stairs states are 73, 90, and 98 bpm, respectively (Fig. 5). BTs are 36.65, 37.74, and 36.11°C, respectively. The unique green peaks and the period in-between them on the displayed screen correspond to the human HR and the counting of the interval in a minute, respectively.

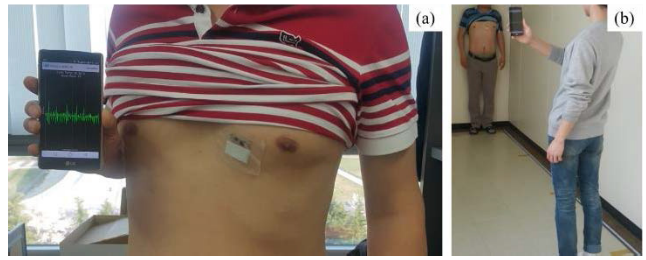

Fig. 4 (a) the healthcare-on-a-patch attached to the human chest for monitoring heart rate and body temperature by android based mobile application and (b) its remote sensing test

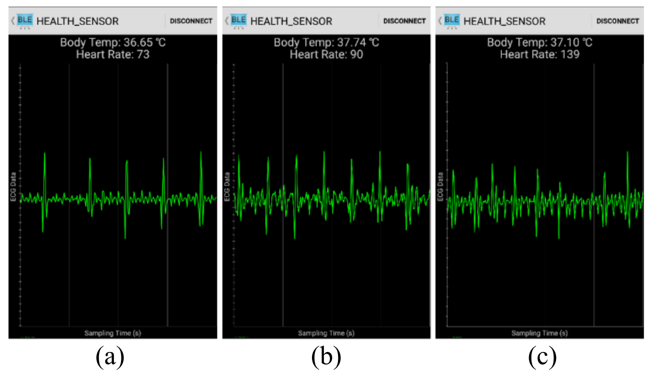

Fig. 5 The measured heart rates and body temperatures at (a) the rest, (b) walking, and (c) climbing stairs.

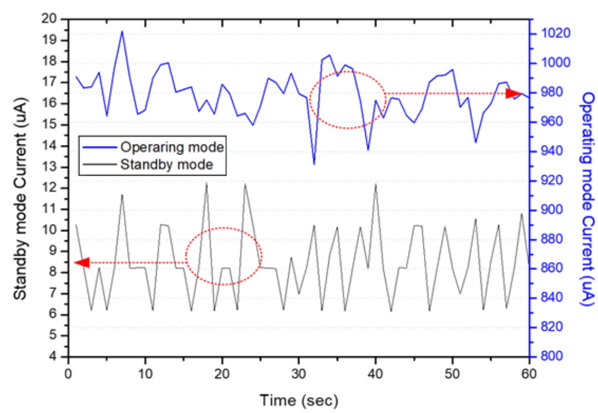

Fig. 6 Current consumption in standby mode and operating mode

The wireless patch sensor is powered by a small ($30 \times 18 \times 1\ mm^3$) flexible Li-MnO2 battery of 45 mAh. Figure 6 represents the current consumption in the standby and operating mode. In order to minimize the current consumption, the chip repeats the operating and standby mode every 10 seconds. Current consumption in the standby and operating modes is approximately 85 uA and 980 uA, respectively. The estimated power consumption can be 3 mW which is sufficient enough to monitor vital signals. Figure 7 shows the variation of operating voltage for the patch sensor with respect to time, which ensures 38 hours of operation. We adopt Bluetooth Low Energy (BLE), which is one of Bluetooth standards especially for low energy applications and

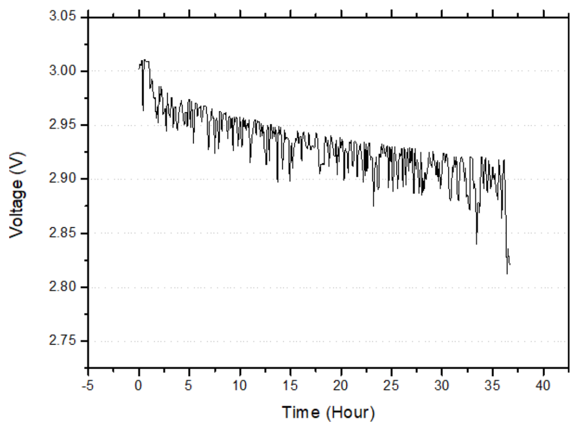

Fig. 7 Current consumption in standby mode and operating mode

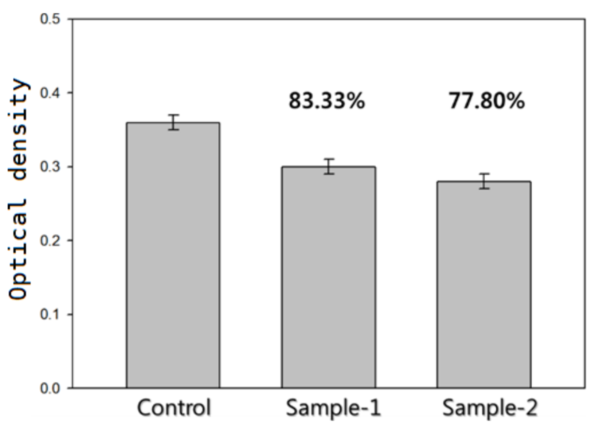

Fig. 8 Cytotoxicity test results

operates around 2 V.

We investigate the biocompatibility of patch sensor by studying cellular cytotoxicity using NIH3T3 cells before applying it to human body aided by Yonsei Medical Technology & Quality Evaluation Center, which is one of the official certificate organizations. The experimental protocols are referred to as International Organization for Standardization (ISO) 10993-5 guideline through immersing patch sensors in a medium for 24 hours and then transfer the solution for the cell culture. The experimental results indicate that the NIH3T3 cells have more than 83% and 78% viability (Fig. 8). These results imply that the adhesive patch has a relatively high biocompatibility when monitoring human vital signals.

4. Conclusions

In this paper, we developed a flexible wireless sensor system to measure HR and BT in real time. We implemented a flexible patch with a total size of 30 (L) × 30 (W) × 3 (H) mm, which is comprised of the HR and BT sensors, signal conditioning parts, flexible battery, and Bluetooth wireless communication. Our flexible and wireless sensor patch measures well the HR and BT for the common activities of a human such as resting, walking, climbing stairs, and jogging. Our sensor patch showed a relatively high biocompatibly and a lower power consumption less than 3 mW to monitor vital signal.

Acknowledgments

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