A Wearable Mobile Electrocardiogram Measurement Device with Novel Dry Polymer-based Electrodes

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Abstract—**A Wearable Mobile Electrocardiogram Monitoring System (WMEMS), which mainly consists of a wearable Electrocardiogram (ECG) acquisition device, a mobile phone with global positioning system, and a healthcare server, was developed in this study. Most of telemedicine systems for long-term ECG monitoring focus on the application of communication techniques. However, how to monitor long-term ECG state more comfortably in daily life is also an important issue. In this study, a novel dry foam electrode was designed and applied for the wearable ECG acquisition device in our WMEMS. These novel dry foam electrodes without conduction gels can provide good conductivity to acquire ECG signal effectively, and can adapt to irregular skin surface to maintain low skin-electrode impedance and reduce motion artifacts under movement. Therefore, the wearable ECG acquisition device is suitable for long-term ECG monitoring in daily life. Moreover, by combining with wireless communication technique, our WMEMS can monitor patient's heart rate continuously anywhere in the globe if they are under the coverage of GSM cellular network. Experiment results showed that our WMEMS really provides a good system prototype for ECG telemedicine applications.**

Keywords- ECG, Dry foam electrode, Atrial fibrillation Telemedicine.

I. INTRODUCTION

CARDIOVASCULAR Disease (CVD) covers all diseases and conditions of the heart and blood vessels, and is one of the main death causes across most of the world. According to an estimate of World Health Organization, cardiovascular diseases kill almost seventeen million people around the globe each year, and about twenty million people are at a risk of sudden heart failure [1]. Most countries face high and increasing rates of cardiovascular disease. In fact, if prompt emergency care and cardiac surgery can be provided within golden hour, some of these lives can often be saved. Therefore, real-time Electrocardiogram (ECG) monitoring is important for patients with cardiovascular disease.

In order to enable mobile patients to get their cardiac health from anywhere at any time, many modern telemedicine systems were integrated with communication technology recently [2-3]. Lin et al. used a Personal Digital Assistant (PDA) with a physiological signal module to monitor and transmit physiological signals to a remote central management unit via Wireless Local Area Network (WLAN) [2]. Rasid and Woodward designed a Bluetooth telemedicine processor which pre-processed and transmitted physiological signals to a mobile phone via Bluetooth, and then this mobile phone uploaded physiological information to a medical healthcare institute via General Packet Radio Service (GPRS) mobile network [4]. Lee et al. proposed a role-based intelligent mobile care system with alert mechanism [5]. If abnormal condition was identified by the recognition algorithms in the mobile phone, the mobile phone would send an emergency alert message to back-end healthcare center, and physicians. Most of the above mentioned telemedicine systems focus on the application of communication techniques. However, how to monitor ECG state more comfortably in daily life is also an important issue. Here, the conventional wet electrodes, which have the advantages of simple, light-weight, reliable, and cost effective, have widely used in the above telemedicine systems. The gel-coated sponge of the wet electrode was used to reduce the impedance between the skin and electrode. However, the major drawback is that conduction gel inevitably leaves its residues on the skin, which makes users uncomfortable easily. Moreover, conduction gel which trends to be drying, is not suitable for long-term monitoring. In particular, the motion artifact is easily induced by friction and slipping of the electrode when the gel-coated sponge becomes dry.

In this study, we proposed a Wearable Mobile Electrocardiogram Monitoring System (WMEMS). Our WMEMS mainly consists of a wearable ECG acquisition device, a mobile phone with Global Positioning System (GPS), and a healthcare server. Here, the wearable ECG acquisition device contains three proposed dry foam electrodes, and an ECG acquisition module. These novel dry foam electrodes without conduction gels can provide good conductivity to acquire ECG signal effectively, and are feasible to be embedded into the wearable ECG acquisition device. Different from MEMS electrodes, it does not need to penetrate into the skin, and can adapt to the skin topography such as curvatures, and guarantees small relative motion of the skin to electrode because of its flexibility and cushioning effect. Under the consideration of long-term ECG monitoring, the ECG acquisition module was designed as a low-power-consumption and small-volume module, and also can be embedded into the wearable ECG acquisition device. By using the wearable ECG acquisition device, patients can monitor their ECG states more comfortably in daily life.

Moreover, the mobile phone with GPS in this system contains an ECG monitoring MIDlet program. The ECG monitoring MIDlet program will continuously monitor patient's Heart Rate (HR), and transmit the averages of one-minute HR every two hours to healthcare server via Short Message Service (SMS) message to completely record the patient's daily HR. Moreover, the ECG monitoring MIDlet program will send a SMS alert message which contains raw ECG data and GPS information to the healthcare server and physicians to provide emergency treatment when abnormal HR condition is detected. The rest of the paper was organized as follows. Section II introduced the system architecture. Section III introduced the system software design and the abnormal ECG detection algorithm for AF. In Section IV, the performance of dry electrode and the accuracy of our WMEMS system for AF detection were tested. In Section V, the conclusion was drawn.

II. SYSTEM ARCHITECTURE AND DESIGN

Fig. 1 illustrated the basic scheme of our proposed WMEMS system. The system hardware consists of a wearable ECG acquisition device, a mobile phone with Global Positioning System (GPS), and a healthcare server. First, ECG signal obtained by the wearable ECG acquisition device will be transmitted to patients' mobile phone via Bluetooth. The ECG monitoring MIDlet program in the mobile phone will continuously monitor patient's HR, and transmit the averages of one-minute HR every two hours to healthcare server via SMS message anywhere in the globe if they are under the coverage of Global System for Mobile communications (GSM) cellular network. If abnormal HR condition is detected, then the ECG monitoring MIDlet program will send a SMS alert message which contains raw ECG data and GPS information to the healthcare server and physicians to provide emergency treatment. Under long-term ECG monitoring, the occurrence of broken lead, poor electrode-skin contact, or other problems may cause judgment fault of recognition algorithm. By using raw ECG data in the SMS alert message, physicians can understand the actual state of patients to save the cost of telemedicine and reduce the workload of physicians caused by judgment fault.

A. .Design of Novel Dry Foam Electrode

A novel dry foam electrode was proposed and applied for wearable ECG acquisition device. In view of this, the proposed dry foam electrode, as shown in Fig. 2, was designed to contact the skin with an electrically polymer conductive foam with the compression set about 5~10 %, which was made by urethane material. They were covered with a 0.2 mm-thick taffeta material made electrically polymer conductive fabric (conductive about 0.07 ohm/squares) and coating with Ni/Cu on all surfaces to establish an electrical contact similar to that of the dry silver electrodes. A 0.2 mm layer of Au was used as an adhesion layer. The size of our dry foam electrode is 14(L) x 8(W) x 8(H) mm. With the prototypes of our dry foam electrodes fabricated in hands, ECG measurements are conducted on the participant. Our dry foam electrode can adapt to the skin topography, and guarantees small relative motion of the skin to electrode because of its flexibility and cushioning effect.

The following are major advantages of our dry foam electrode for long-term ECG measurement: the skin-electrode contact area and skin properties between each subject are directly related to the skin-electrode impedance. The contact area should be increased to keep lower impedance. When the electrodes are attached on the hairy skin site, the contact area will obviously reduced because the thickness of hairs will increase the gap between the skin and electrode. However, the proposed dry foam electrode, made by the conductive foam, can provide a good softness property to fit the skull shape. On the hairy site, it can fill the spacing between the hairs to increase the skin-electrode contact area. By applied the slight force on the electrode to ensure the prefect contact of dry foam electrode on the skin, the effect approaches to the wet electrode on the hairless skin. Our dry foam electrode can maintain the contact even under motion, and rubbing and sliding of the electrode on the skin, to reduce the motion artifact more effectively.

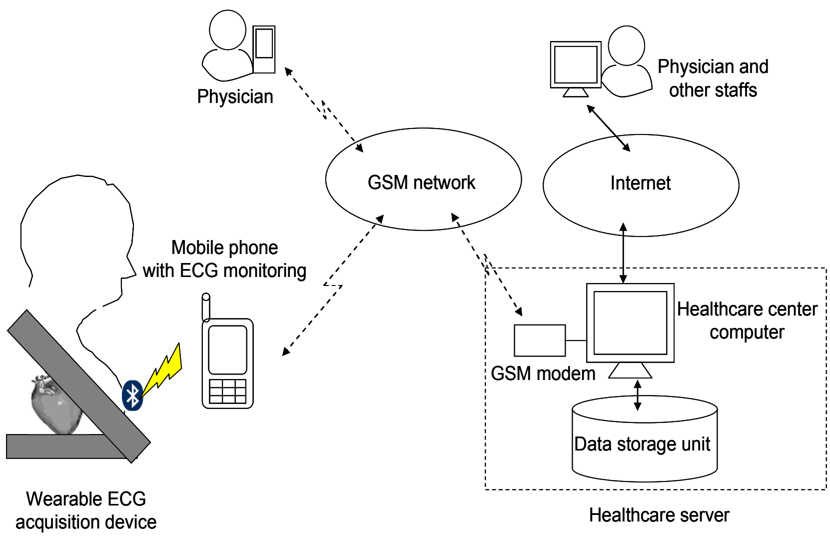

Fig. 1 Basic scheme of our WMEMS system.

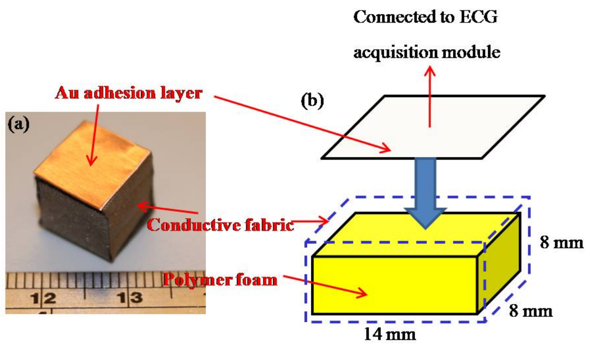

Fig. 2(a) Top view, (b) Exploded view of our proposed dry foam ECG electrode. The foam electrode was covered by the conductive fabric on all surfaces and then paste on a Au layer.

B. ECG Acquisition Module

The ECG acquisition module is a three-lead ECG device, and consists of Front-End Amplifier (FEA) circuit, Analog-to-Digital Converter (ADC), microprocessor, Driven Right Leg circuit (DRL), and wireless transmission circuit, as shown in Fig. 3. Here, FEA circuit, which contains a pre-amplifier and a band-pass filter, was designed to amplify and filter ECG signal. The gain of FEA circuit was set to about 112 times with frequency band of 0.05 - 150 Hz. Microprocessor (TI MSP430) is used to control the ADC to obtain, pre-process and send ECG data to wireless transmission circuit. ECG signal will be digitized by a 12-bit ADC with sampling rate of 512 Hz. Here, the wireless transmission circuit contains a Printed Circuit Board (PCB) antenna and a Bluetooth module which is fully compliant with the Bluetooth v2.0+ EDR specification. The size of the ECG acquisition module is about 4 cm × 2.5 cm × 0.6 cm, and can be embedded into the wearable ECG acquisition device. This module operates at 31 mA with 3.7-V DC power supply, and can continuously operate over 33 hours with a commercial 1100 mAh Li-ion battery.

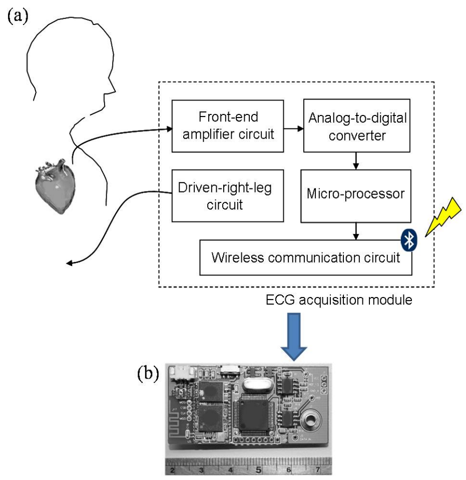

Fig. 3(a) Block diagram and (b) photograph of ECG acquisition module
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C. Mechanical Design of Wearable ECG Vest

This wearable ECG vest is designed to collect ECG signals from the human body continuously in daily life. Fig. 4 shows an overview of the whole medical vest for ECG monitoring, consisting of the following components: three developed dry electrodes, conventional 3-lead standard placements, and the ECG acquisition module. The vest itself is made of very elastic fabric to ensure good contact of the electrodes to the wearer's skin. The developed dry electrodes are placed at specific body Lead II locations and integrated into the vest in manner it makes a good contact with a Velcro strap fixed on the skin surface for long-term ECG monitoring. The ECG acquisition module is integrated into the vest in a small box as indicated in Fig. 4.

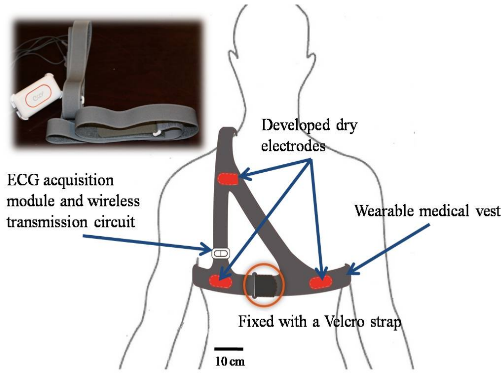

Fig. 4 An overview of the whole medical vest for ECG monitoring.

D. Mobile Phone with ECG Monitoring MIDlet Program

A commercial mobile phone (Nokia N85) built-in GPS module is used as the platform of ECG monitoring. The ECG monitoring MIDlet program developed on Borland JBuilder2005 conjunction with wireless development kit 2.2 was installed on the mobile phone to monitor the user's HR variation. If abnormal HR condition is detected, then the ECG monitoring MIDlet program will send a SMS alert message to the healthcare server and physicians to provide emergency treatment.

E. Healthcare Server

The healthcare server mainly consists of a GSM modem, healthcare center computer, and data storage unit. Here, the GSM modem (SonyEricsson m600i) was used to receive and forward SMS alert messages. In the healthcare center computer, Windows XP was used as the operation system, and the server program developed on J2SE and JDesktop Integration Components (JDIC), was designed to control the GSM modem by using AT-command, and to display raw ECG, HR, and GPS information.

III. SYSTEM SOFTWARE DESIGN

A .ECG Monitoring MIDlet program in Mobile Phone

The flowchart of the ECG Monitoring MIDlet program was shown in Fig. 5. In the beginning, the ECG monitoring MIDlet will call Bluetooth Discovery of BT API to inquiry the Bluetooth device around here. Here, BT API is one of Bluetooth application packages used to set connection between the ECG acquisition module and mobile phone. When the ECG acquisition module is found, DiscoveryAgent of BT API will try to create Serial Port Profile (SPP) to connect mobile phone to ECG acquisition module. Then, received raw ECG data will be sent to BUFFER, and displayed in the screen. Here, BUFFER is a container used to store ECG data. Next, AGLO thread calculates HR from ten-second ECG data every five second. After collecting 120 trials of one-minute HR average, DUL thread will package them into a daily HR message, and send it to healthcare server every two hour. If abnormal condition is detected, the ECG monitoring MIDlet will call GPS API to get GPS information, and then collect abnormal ECG data to SMS API to send an alert message to healthcare server.

B.Abnormal ECG Detection Algorithm in ECG Monitoring MIDlet Program

Atrial fibrillation is the most common cardiac arrhythmia, and affects nearly 1% of the population, and its prevalence increases with age [6]. A typical ECG in AF shows a rapid irregular tachycardia in which recognizable P waves are sometimes absent [7]. The ventricular rate in patients with untreated AF is generally 110 to 180 beats per minute. However, in elderly patients, ventricular rates in untreated AF are typically slower. Since an irregular rhythm of the QRS complexes is the major feature of AF, the R-R Interval (RRI), defined as the interval of neighboring QRS complexes, is an ideal parameter to identify AF. The rule for AF detection was described as follows:

Step 1: QRS detection algorithm marks the R points.

Step 2: Calculates RRI, the duration of adjoined R point.

Step 3: Calculates the variation of consecutive RRI, defined as △RRI.

Step 4: Calculates the standard deviation of RRI (RRIstd) within each 6 seconds of computation.

Step 5: System alarm as twice of △RRI > 150 ms occurred and RRIstd > 60ms within 6 second.

Here, First Derivative (FDI) approach [8] proposed by Friesen et al. was used as the QRS detection algorithm to detect QRS complex wave in this study.

C. Software in Healthcare Server

Fig. 5 is the flowchart of the server program in the healthcare center computer. When the server program starts to operate, it will call GUI and ULIST thread to create graphic user interface, and call STGSM thread to link to GSM modem. STGSM thread will send an AT command to check whether the connection between healthcare center computer and GSM modem is established. If the connection is established, STGSM will create RECV thread to listen and wait new incoming messages. When a new message is coming, RECV thread will call STGSM to handle the new message and go back to listen new incoming messages. Next, the server program starts to extract user phone number, message time, SMSC number, message body and et al. Here, the message body contains raw ECG data and GPS information.

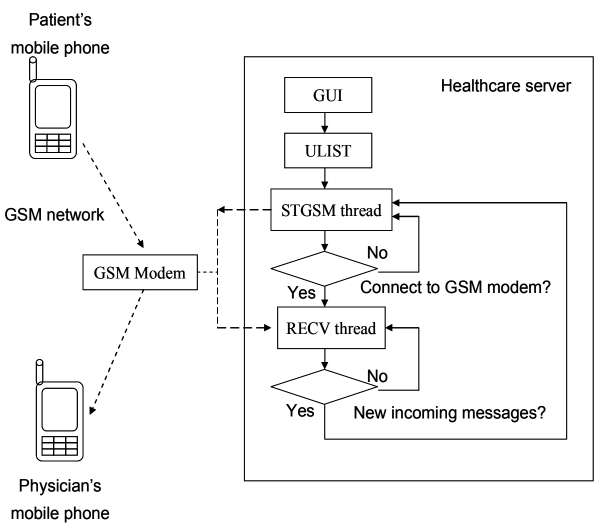

Fig. 5 Flowchart of server program in healthcare server.

IV. Results and Discussions

A. Performance Evaluation of Dry Foam Electrodes

The proposed dry foam electrode was experimentally characterized with respect to (1) the signal quality check, (2) the impedance between electrode–skin interface, (3) the impact of motion artifacts and (4) the comparison of signals qualities between dry/ wet electrodes. In addition, in order to reject power-line interference and other artifacts in ECG signals, the ECG signal was recorded in a shielded room. Note that these investigations are based on engineering, not a clinical approach.

1) Signal-Quality Check

The pre-test experiment for signal-quality check was illustrated in Fig. 6. The aim of this experiment was to understand distortion caused by our dry foam electrode under ECG measurement. First, ECG data was pre-recorded by using standard wet ECG electrodes, and stored in the personal computer. Next, the ECG data was fed into a programmable function generator and passed through a voltage divider to generate the simulated human ECG signal. The simulated ECG signal was further fed to our dry foam electrode, and then amplified by the ECG device. After recording the amplified ECG signal, it was compared with the pre-recorded ECG data. From the high correlation between the pre-recorded ECG and ECG obtained our dry foam electrode, it can present the cleanness of ECG signal recorded by our dry foam electrode. Fig. 9 showed the pre-recorded ECG signal and its counterparts recorded by our proposed dry foam electrode. It showed that the correlation between pre-recorded ECG signal and the signal obtained by our dry foam electrode is high (99.51 %). The result confirms the cleanness of our dry foam electrode from artifacts.

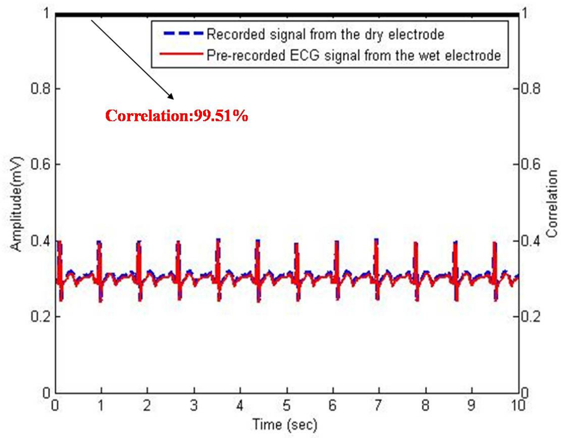

Fig. 6 Pre-recorded ECG signal and its counterparts recorded by our proposed dry foam electrode.

2) Impedance Measurement

The impedance between the electrode–skin contact interfaces was analyzed by impedance spectroscopy (LCR4235, Wayne Kerr Electronics Ltd., UK). The conventional wet electrodes were attached to the skin of the participants using their self-adhesive properties. The dry foam electrodes were attached with a disposable Velcro strap and exchanged carefully between each measurement to avoid any change of the skin surface. The skin of the participant was once cleaned by gently wiping it with a 2-

propanol impregnated cotton pad, which was allowed to evaporate before applying electrodes. In order to guarantee reliable and reproducible results, the test signal of impedance spectroscopy was set to 1 V and the frequency range from 1 Hz to 10 KHz.

Fig. 7(a) showed the impedance measurement on standard Lead II sites. Here, the black line denotes the impedance of our dry foam electrode pair without skin preparation and conducting gel. Blue and red lines denote the impedances of conventional wet electrodes without and with skin preparation respectively. The results showed that the impedance between the skin and our dry foam electrode without skin preparation and conducting gel is similar to that of the conventional wet electrode with skin preparation and conducting gel used. Therefore, the conduction performance of our dry foam electrode outperformed the conventional wet electrode.

In addition, we also traced the impedance changes in the typically Lead II sites over the course of 10 h to monitor the long-term ECG performance of developed dry electrodes. The result is plotted in Fig. 7(b), which showed the impedance variation for wet and developed dry electrodes. The impedance variation of the conventional wet electrode with conduction gel is more obvious lower than that of our dry foam electrode in the first 2 hours. After that point, the impedance of the dry electrodes is significant close to the wet one, even lower. The impedance variation of the developed dry electrode was observed in the range from 14 to 24 k ohm, and is in the acceptable range for normal ECG measurement. Furthermore, compared to the conventional wet electrode for long-term ECG monitoring, our dry foam electrode can significantly provide better stability of the skin–electrode impedance. This result can be explained by that our dry foam electrode does not need conduction gel, which is apt to drying.

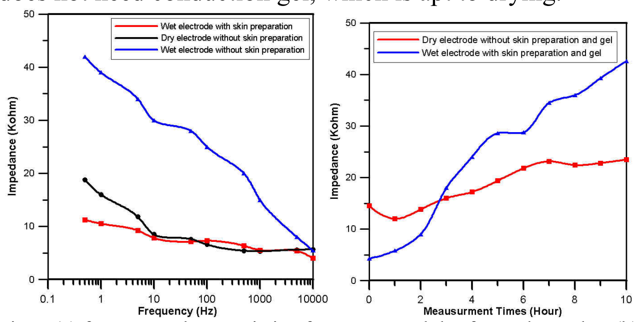

Fig. 7 (a) frequency characteristic of our proposed dry foam electrodes. (b) impedance variation of dry foam electrode and conventional wet electrode under long-term ECG measurement.

3) Comparison of Signals between Dry and Wet Electrodes

Fig. 8 showed the placements and the results of ECG measurement by using our dry foam electrode and wet electrode pairs in the locations of standard Lead II sites. The correlation between signals obtained by our dry foam electrode and conventional wet electrode are typically in excess of 98.21 % in the locations of standard Lead II sites.

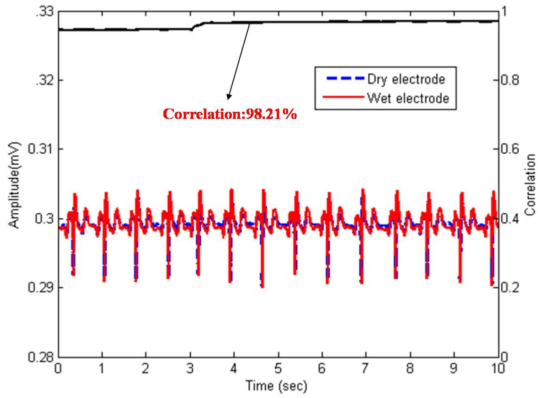

Fig. 8 Placements and results of ECG measurement by using different types of electrodes.

4) Influence of Motion Artifacts

For evaluate the ECG performance of the set of electrodes under test, these electrodes were positioned in a typical Lead II position, and were close to each other respectively. A conventional wet electrode was used as the reference electrode. To evaluate the influence of motion on ECG measurement, the walking motion was performed. The participant was instructed to increase the intensity of the walking motion until the ECG signal measured by the test electrodes was affected. Experiment results showed that the influence of motion artifact for our dry foam electrode is significantly smaller than that of the conventional wet electrode, especially at the 2~4 and 7.6~9.7 sec. This can be explained by that our dry foam electrode can maintain the contact effectively, even under the walking motion. By attaching the dry foam electrode with a little pressure, its elasticity will stabilize the contact both horizontally and vertically. Therefore, even if movement occurs, only parts of the dry foam electrode move and the overall contact area will hardly change. Wet electrodes suffered from moving charge artifact more than dry electrodes [9]. Optimizing the application mechanism will further improve the properties of our dry foam electrode. Embedding foam into a rigid cup with a self-adherent surface and fixed at the medical vest, which is similar to a commercial gel electrode, will enable the application at constant pressure and avoid the friction against the skin completely.

B. Evaluation of Accuracy for QRS Detection and Atrial Fibrillation

First, the accuracy of FDI approach for QRS detection was tested and evaluated. Here, 30-set ECG records in MIT-BIH database [10] was used to test the reliability of QRS detection algorithm. The studied anomalies are arrhythmia and tachycardia atria fibrillation, and the normal cases will be arranged in a third class. We checked if the FDI approach can accurately mark R-point of ECG waveform. Some parameters of binary classification test for R-point detection were first defined. True Positive (TP) indicates R-point of ECG correctly detected as R-point. False Positive (FP) indicates not R-point wrongly identified as R-point. True Negative (TN) indicates not R-point correctly identified as nothing. And False Negative (FN) indicates R-point wrongly identified as nothing. In information retrieval, accuracy and recall mean positive predictive value (PPV) and sensitivity respectively. Experiments results showed that the average accuracy and sensitivity of the FDI approach for 30-trial ECG records are 98.14% 97.32% respectively. This indicated that the FDI approach can effectively detect R-point for arrhythmia and tachycardia atria fibrillation cases.

Next, a total of 20 normal subjects (from 26 to 39 years old) and 25 AF patients (from 26 to 39 years old) participated the clinical study. All the procedures and measurements were approved by the Institutional Review Board (IRB) of CMUH, Taiwan. Comparison and calculation was performed according to the recommendations of the American National Standard for ambulatory ECG analyzers (ANSI/AAMI EC38-1994). Some parameters of binary classification test for AF detection were defined as follows: True Positive (TP) indicates AF condition correctly detected as AF condition. False Positive (FP) indicates not AF condition wrongly identified as AF condition. True Negative (TN) indicates not AF condition correctly identified as nothing. And False Negative (FN) indicates AF condition wrongly identified as nothing. The diagnostic result was recorded every 15 seconds for a total of 5 minutes. Thus, there were a total of 400 detection trials for the 20 control subjects. The sensitivity and positive predictive value were both 100%, suggesting that the detection worked normally on normal subjects. For AF patients, the diagnostic result was recorded every 5 seconds for a total of 5 minutes. Thus, there were a total of 1500 detection trials for the 25 control subjects. The sensitivity and positive predictive value for AF patients were 94.56 %, and 99.22 %. In this case, all the two values were high. This indicated that our system can be useful for abnormal ECG detection in clinical.

V. CONCLUSIONS

In this study, we proposed a wearable mobile electrocardiogram monitoring system for long-term ECG monitoring. The wearable ECG acquisition device integrated with dry foam electrodes and the ECG acquisition module was designed for long-term ECG monitoring in daily life. Moreover, the ECG acquisition module is small-volume, wireless and low-power consumption (long-term ECG monitoring over 33 hours). By using the wearable ECG acquisition device, patients can monitor their ECG states more comfortably in daily life. And based on SMS communication technology, patients can monitor their ECG anywhere in the globe if they are under the coverage of GSM cellular network. Finally, our wearable mobile electrocardiogram monitoring system was also tested for patients of atrial fibrillation in China Medical University Hospital, Taiwan. For 25 AF patients, the sensitivity and positive predictive value of our system were 94.56 % and 99.22 % respectively. Therefore, our WMEMS system can effectively monitor ECG, and really provides a good system prototype for telemedicine applications.

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