An Intelligent Telecardiology System Using a Wearable and Wireless ECG to Detect Atrial Fibrillation

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***Abstract*—This study presents a novel wireless, ambulatory, real-time, and autoalarm intelligent telecardiology system to improve healthcare for cardiovascular disease, which is one of the most prevalent and costly health problems in the world. This system consists of a lightweight and power-saving wireless ECG device equipped with a built-in automatic warning expert system. This device is connected to a mobile and ubiquitous real-time display platform. The acquired ECG signals are instantaneously transmitted to mobile devices, such as netbooks or mobile phones through Bluetooth, and then, processed by the expert system. An alert signal is sent to the remote database server, which can be accessed by an Internet browser, once an abnormal ECG is detected. The current version of the expert system can identify five types of abnormal cardiac rhythms in real-time, including sinus tachycardia, sinus bradycardia, wide QRS complex, atrial fibrillation (AF), and cardiac asystole, which is very important for both the subjects who are being monitored and the healthcare personnel tracking cardiac-rhythm disorders. The proposed system also activates an emergency medical alarm system when problems occur. Clinical testing reveals that the proposed system is approximately 94% accurate, with high sensitivity, specificity, and positive prediction rates for ten normal subjects and 20 AF patients. We believe that in the future a business-card-like ECG device, accompanied with a mobile phone, can make universal cardiac protection service possible.**

***Index Terms*—Atrial fibrillation (AF), ECG, expert systems, mobile, wireless.**

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I. Introduction

CARDIOVASCULAR disease (CVD) is one of the most prevalent and serious health problems in the world. An estimated 17.5 million people died from CVD in 2005, representing 30% of all deaths worldwide. Based on current trends, over 20 million people will die from CVD by 2015. In 2000, 56% of CVD deaths occurred before the age of 75. However, CVD is becoming more common in younger people, with most of the people affected now aged between 34 and 65 years [1]. In addition to the fatal cases, at least 20 million people experience nonfatal heart attacks and strokes every year; many requiring continuing costly medical care.

Developed countries around the world continue to experience significant problems in providing healthcare services, which are as follows:

1) the increasing proportion of elderly, whose lifestyle changes are increasing the demand for chronic disease healthcare services;
2) demand for increased accessibility to hospitals and mobile healthcare services, as well as in-home care;
3) financial constraints in efficiently improving personalized and quality-oriented healthcare [2].

Though the current trend of centralizing specialized clinics can certainly reduce clinical costs, decentralized healthcare allows the alternatives of in-hospital and out-hospital care, and even further, home healthcare [3]. Rapid developments in information and communication technologies have made it possible to overcome the challenges mentioned earlier and to provide a changing society with an improved quality of life and medical services.

Atrial fibrillation (AF) is the most common cardiac arrhythmia, affecting nearly 1% of the population. Its prevalence increases with age; although relatively infrequent in those under 40 years old, it occurs in up to 5% of those over 80.

Most people with a normal sinus rhythm have a resting heart rate of between 60 and 100 beats per minute. In AF patients, the atria contract rapidly and irregularly at rates between 400 to 800 beat per minute. Fortunately, the atrioventricular node compensates for this activity; only about one or two out of three atrial beats pass to the ventricles [4].

A typical ECG in AF shows a rapid irregular tachycardia in which recognizable P waves are sometimes absent [5]. The ventricular rate in patients with untreated AF is generally 110

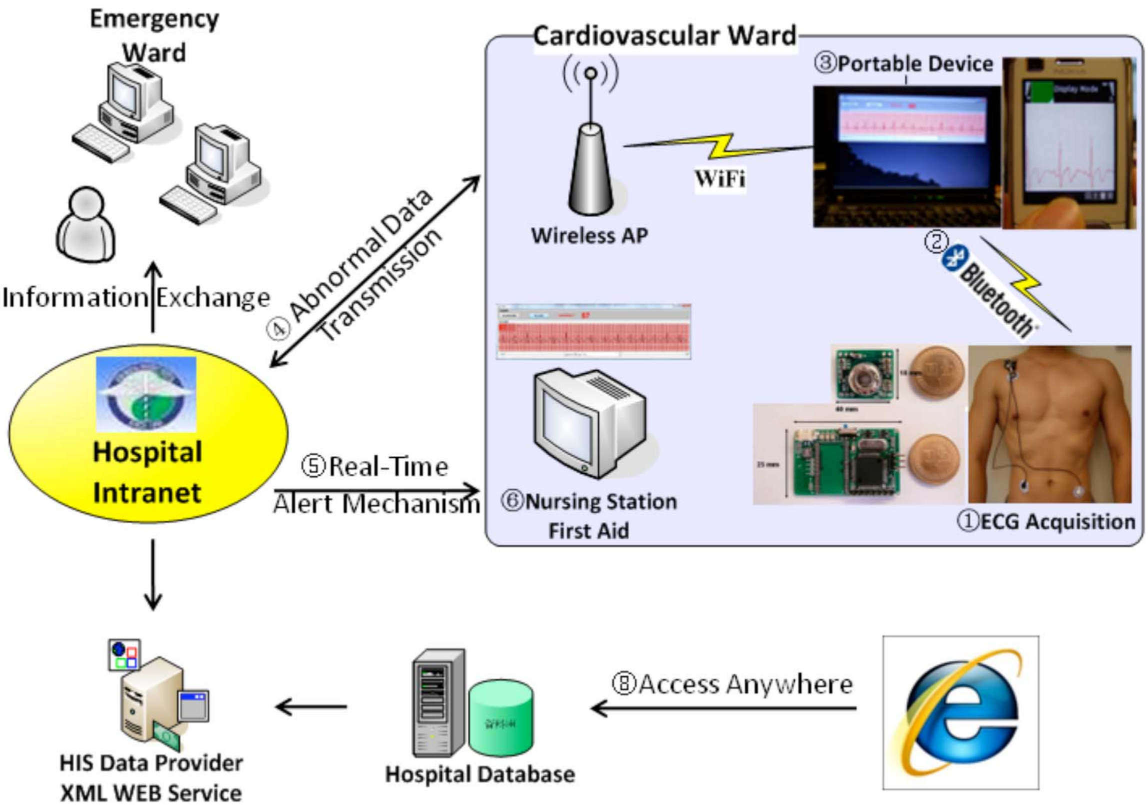

Fig. 1. System flowchart of the proposed intelligent telecardiology healthcare system The system covers a three-lead wireless ECG acquisition device, a Java-based expert system in the portable device and a Web-based monitoring window allowing access to the data server and plot in real time by using an IE browser. Step ①: Attach the device on body by disposable electrodes and acquire data. Step ②: Bluetooth connects between the ECG and the portable device. Step ③: Java-based application shows a real-time plot and computes data every 6 s. Step ④: Abnormal data is detected by the expert system and transmitted through WiFi/3G/2G. Step ⑤: Nondelayed alert message is sent to a nursing station in a cardiovascular ward. Step ⑥: Emergency treatment can be administered. Step ⑦: Information is exchanged through the intranet from other departments. Step ⑧: Web-based monitoring system gives universal telehealth care.

to 180 beats per minute. However, slower ventricular rates may occur in elderly patients with untreated AF.

Data from the Framingham study [6] demonstrates that chronic heart failure is associated with a 4.5-fold increase in risk of AF in men and a 5.9-fold increase in women. Apart from the epidemiological data, most evidence on the prevalence of AF in heart failure patients stems from analysis of a number of clinical trials conducted within the last 10–15 years on populations with heart failure.

AF might have no detectable CVD. Hemodynamic impairment and thromboembolic events related to AF patients included in these trials were selected for different purposes, which are reflected in the varying prevalence of AF. In addition, AF, often associated with structural heart disease, causes significant morbidity, mortality, and healthcare cost in a substantial proportion of patients, thus making it a major global healthcare challenge [7]. In this study, we attempted to develop an intelligent expert system with a built-in abnormal ECG-detection mechanism in the telecardiology healthcare service to facilitate diagnosis and management of patients with AF and other rhythm disorders. Simplicity, reliability, and universality are the main concepts behind this service. Therefore, this study constructs a ubiquitous and intelligent telecardiology healthcare network consisting of a miniature wireless ECG device embedded with an alert expert system for the early detection of cardiac disorders.

II. Intelligent Telecardiology System

Telecardiology applications can be categorized in pre-hospital, in-hospital, and post-hospital stages. The pre-hospital stage detects CVD and transmits the information to emergency service providers before the patient arrives at the hospital. An in-hospital healthcare system helps medical staff to supervise the inpatients and provide suitable treatments at the right time. Finally, the main purpose of the post-hospital stage is outpatient follow-up monitoring and treatment to assure a favorable prognosis [8]. All these stages of diseases management can be assisted by a ubiquitous wireless sensor network (WSN) telehealth system, avoiding unnecessary hospitalization, rationalizing healthcare life costs, and providing a safe and effective way to improve life quality. The main objectives in constructing an integrated intelligent telecardiology system include easy manipulation, reliable results, and rapid communication. The system proposed in this study uses a three-lead wireless ECG device, a Java-based expert system application, and a Web-based monitoring platform to meet these objectives. A small, three-lead ECG device is first set up using disposable button electrodes (Medi-Trace 200, Kendall) affixed to areas on the user's body (see Fig. 1, Step ①). This lightweight ECG can be connected to portable devices, such as a notebook or mobile phone, using Bluetooth (see Fig. 1, Step ②). A Java-based GUI application installed on a notebook or mobile phone can then initiate data recording and data transmission.

Successive data are transmitted to a portable device and processed in a period of 6 s by an expert system built in the Java application (see Fig. 1, Step ③). A lead II signal, coordinated with the direction of cardiac conduction pathway from top right to bottom left, is extracted for signal analysis. As long as an abnormal ECG signal was detected, the system automatically transmitted data over a WiFi/3G/2G networks to a remote data server (see Fig. 1, Step ④). At the same time, the system will send out an alert message to a nursing station in the cardiovascular ward for further examination (see Fig. 1, Steps ⑤ and ⑥). If necessary, the emergency ward or other departments can also access this data through an intranet (see Fig. 1, Step ⑦). With the convenience of the world-wide Web protocol, anyone, including physicians, nurses, and family members, can access the data server and monitor real-time ECG plots using a Web browser, such as Internet Explorer (IE) (see Fig. 1, Step ⑧).

For patients admitted to a cardiovascular ward or intensive care unit (ICU), the proposed cardio-healthcare system provides greater freedom of movement than products currently on the market. Paring lightweight wireless ECG devices with mobile phones offers continuous and reliable patient monitoring. A warning system is also activated when unstable ECGs appear.

The integration of real-time transmission and the expert system allows this telecardiology system to not only be applied to inpatients, but also to normal subjects as a health monitor. This system might also be able to replace the 24-h Holter monitor for longer monitoring and real-time detection.

III. Wireless ECG Device

The proposed three-lead ECG device contains two main parts: the data acquisition (DAQ) unit and the wireless-transmission unit. This study is based on our previous research on a wearable and wireless brain–computer interface [9]. The whole system size measures about 90 × 35 × 15 mm and looks similar to a business card. An additional feature of the proposed portable device is its tunable gain and bandwidths.

A. DAQ Unit

The DAQ unit integrates an analog preamplifier, filter, and an AD converter (ADC) into a small (20 × 18 mm^2), lightweight, and battery-powered DAQ system [see Fig. 2(b)]. The ECG signal is sampled at 512 Hz with 12-bit resolution, amplified by 100 times, and bandpass filtered between 1 to 150 Hz [see Fig. 2(a)]. To reduce the number of wires for high-density recordings, the power, clocks, and measured signals are daisy-chained from one node to another with bit-serial output. Therefore, adjacent nodes (electrodes) are connected together to 1) share the power, reference voltage, and ADC clocks and 2) daisy chain the digital signal outputs.

B. Wireless-Transmission Unit

The wireless-transmission unit consists of a wireless module and a microcontroller. This unit uses a Bluetooth module to send the acquired ECG signals to a custom real-time DSP unit or a Bluetooth-enable mobile phone serving as a real-time signal-processing unit. The wireless transmission circuit [as shown in Fig. 2(c)] measures 40 × 25 mm^2. Fig. 2(d) shows a picture of the integrated three- limb lead wireless ECG system. A reference and a ground channel were also included in the system (not shown). The minimal power consumption of the device enables a usage time of up to 33 h on a single 1100 mA·h Li-ion battery.

All modules included one wireless-transmission unit and three DAQs, weighing less than 100 g in total. Since the overall power consumption of the whole system is about 29.5 mA, the theoretical maximum running time is estimated at about 33 h when using an 1100 mA·h Li-ion battery. However, when we applied the system to patients, the total running time decreased to slightly more than 10 h with continuous acquisition and transmission of the physiological signal to the expert system. According to cardiologists' suggestions, the system's current performance is useful for long-term telemonitoring of certain patients with chronic CVD.

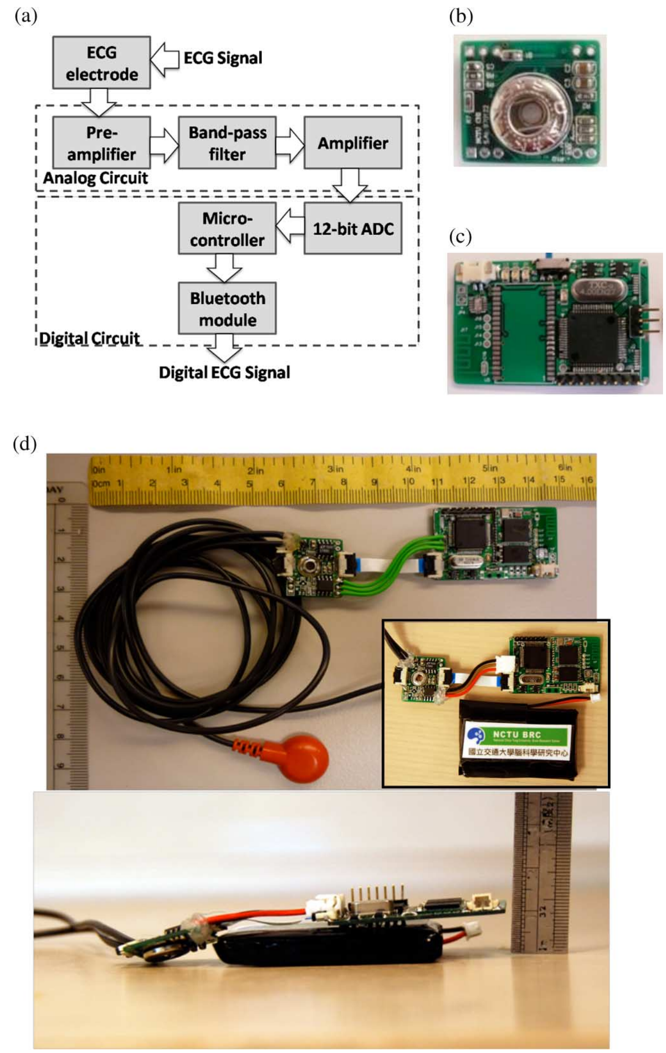

Fig. 2. (a) Block diagram of the wireless ECG device. (b) 12 × 18 mm^2 DAQ unit for each electrode. (c) 40 × 25 mm^2 wireless-transmission unit. (d) Integrated circuits of the NCTU three-limb lead ECG acquisition device.

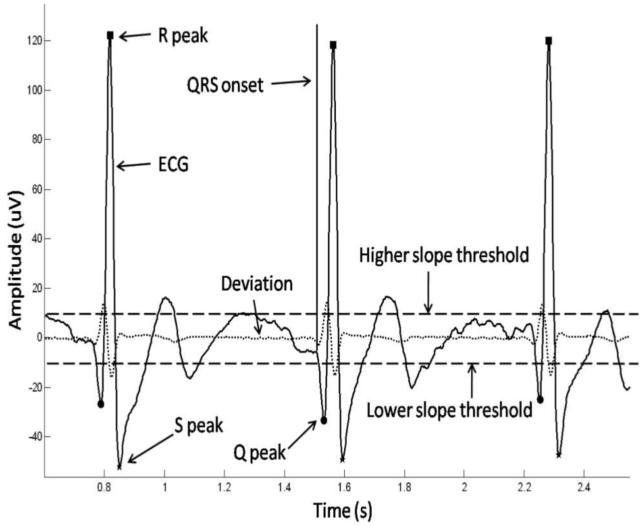

Fig. 3. QRS detection in the normal ECG waves. The black curve means the normal ECG signal which contains three waves. The dotted line shows the first deviation of the normal ECG signal. Results show that full squares mark the R wave peaks, full circles mark the Q wave peaks, and full star mark the S wave peak. QRS onset is defined by the vertical line.

IV. Java-Based Software in a Mobile System

A. QRS-Wave-Detection Algorithm

The ECG signals are amplified and recorded with a sampling rate of 512 Hz and bandpass filtered between 1 and 150 Hz. Artifacts were removed before R peak detection. A 50 Hz notch filter is used to eliminate the power line interference, producing high-frequency, noise-free, smooth data. Two segments of the baseline signal are extracted to compute mean and standard deviation (SD). Besides, the QRS detector requires the first- and second-order derivative of the preprocessed ECG signal. The latter gives spikes at the fiducial points. There are also false spikes, but their relative magnitudes are lower than those of the spikes at the fiducial points. Accordingly, the R peak is clipped by higher magnitude negative peaks and high positive peaks in the first derivative plot (see Fig. 3). The procedure of defining the QRS complex [4] onset is as follows: after 256 ms of flat segment in the ECG, the first sample, where the slope becomes steeper (high positive peaks) than the higher slope threshold, is defined as the QRS onset. The lower slope threshold is used to detect the higher magnitude negative peaks. Both thresholds are updated to search for missing beats. After identifying the QRS onset, the R peak is labeled by searching for the maximal value of the ECG samples in the 36 ms following the QRS onset [4].

When R peak is determined, the QRS detector searches forward and backward to identify the two most negative points on the ECG plot and labels them as the Q wave peak and the S wave peak, respectively. The QRS complex duration is set from QRS onset time to 20 ms after the S wave peak [10].

B. Expert System on Abnormal ECG Detection

After defining the QRS complex and the Q, R, and S wave peak, we then sought to detect common and important rhythm disorders, including *sinus tachycardia, sinus bradycardia, cardiac asystole*, *AF,* and *wide QRS complex*. Sinus tachycardia is detected by the condition of the heart rate >100 beats per minute, whereas sinus bradycardia refers to a heart rate <60 beats per minute. An asystole indicates the situation of no heart rate. Wide QRS complex occurred as the duration of QRS complex was greater than or equal to 120 ms.

C. AF Detection

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. This study uses two different algorithms for AF detection.

Algorithm I:

Step 1: Detection of R waves and marking of R peaks.
Step 2: Calculation of RRI (the duration of adjoined R peaks).
Step 3: Calculation of the variation of consecutive RRI (ΔRRI).
Step 4: Activation of the alarm system when ΔRRI $>$ 150 ms occurs twice within each 6 s of computation.

Algorithm II:

Step 1: Detection of *R* waves and marking of *R* peaks.
Step 2: Calculation of RRI (the duration of adjoined *R* peaks).
Step 3: Calculation of the variation of consecutive RRI (ΔRRI).
Step 4: Calculation of the SD of RRI (RRIstd) in each 6-s recording.
Step 5: Activation of the alarm system when ΔRRI $>$ 150 ms occurs twice and RRIstd $>$ 60 ms within 6 s of computation.

Theoretically, Algorithm I is very sensitive in detecting an irregular ventricular rhythm, yet in the uncommon situation of recording frequent premature beats, the power to differentiate AF from premature beats is impaired. To overcome this potential drawback, we formulated Algorithm II, which uses a cutoff value of RRIstd $>$ 60 ms for AF detection. This criterion reflects the SD of six-seconds' total RRIs greater than 60 ms, when it alerts. The cutoff value of 60 ms was based on comparing 50 normal subjects' and 50 AF patients' RRI measurements in the 12-lead ECGs stored in the MUSE ECG system (GE healthcare, USA) in China Medical University Hospital's (CMUH) database. Fig. 4 demonstrates statistical results of the differences between normal and AF patients regarding ΔRRI and RRIstd. Accordingly, the thresholds of ΔRRI and RRIstd were given as 150 and 60 ms, respectively.

V. Clinical Testing Results

In order to evaluate system performance and sensitivity for AF patient detection, cardiology outpatients were recruited to participate in this study. The diagnosis of AF patients was based on the 12-lead ECG findings of the cardiologists at CMUH.

A. Data Collection

The proposed wireless ECG device was first attached to fixed points on the body. Patients were asked to refrain from body movement or speaking and maintain regular breathing during

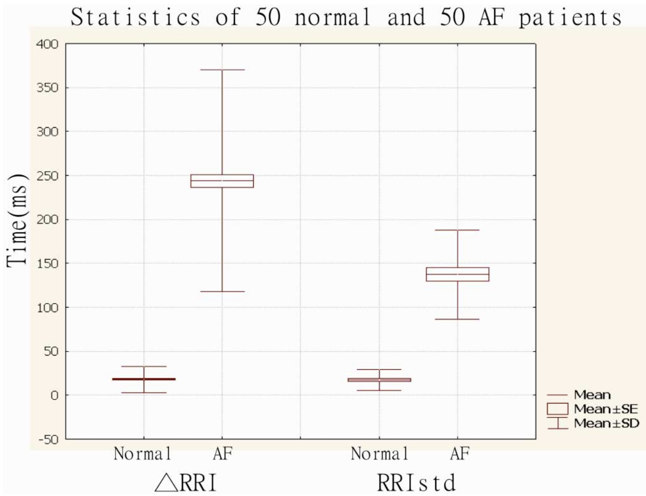

Fig. 4. Statistics of 50 normal and 50 AF patients in (a) ΔRRI and (b) RRIstd.

the 6 min of recording. Raw data were recorded by the Java-based GUI program installed in a netbook, and then, saved to the hard disk in a TXT format. At the same time, heart rate and the detection results of AF were manually recorded every 6 s for AF patients and every 15 s for normal subjects.

Patients were divided into two groups according to AF-determined algorithms. A total of ten normal subjects (average age: 71.6 years old, ranging from 57 to 88 years old) and 20 AF patients (average age: 71.4 years old, ranging from 50 to 89 years old) participated in the clinical study. Nursing staff and patient's family members were allowed to stay with the participants during the recording. The Institutional Review Board (IRB) of CMUH approved all the procedures and measurements.

B. Evaluation of Measurement Accuracy

Comparison and calculation was performed according to the recommendations of the American National Standard for ambulatory ECG analyzers (ANSI/AAMI EC38–1994) [11]. A true positive (TP) indicates that the algorithm successfully detected a true AF episode during every 6 s of computation. On the contrary, a false negative (FN) indicates a failed detection of AF ECG. Finally, false positive (FP) represents a false AF detection, whereas true negative (TN) means normal subjects have nothing detected.

Accuracy, sensitivity and positive predictive values were used for further analysis. The recorded data were shown in Table I for normal people and Tables II and III for AF patients under different algorithm testing.

Table I shows the testing performance in the ten normal subjects. Normal subjects are as the control group in this study. Each diagnostic result was recorded and computed real time per 15 s. Totally recording time was 5 min. Thus, there were a total of 200 detection trials from the ten control subjects. We can clearly see that the detecting accuracy is 100%, which shows that our detection algorithm works normally on normal subjects and the threshold was set at a reasonable level. It will not occur to the FP detection.

TABLE I
TESTING RESULTS OF AF DETECTION IN NORMAL SUBJECTS (CONTROL GROUP)

Normal (n=10)		Testing		
		AF(+)	Normal(-)	Total
Truth	AF(+)	0	0	0
	Normal(-)	0	200	200
	Total	0	200	200*

*Each subject was tested 20 times (every 15 s for a total of 300 s). A total of 200 tests were done in ten subjects.

TABLE II
TESTING RESULTS OF AF DETECTION IN PATIENT GROUP USING ALGORITHM I

Patients (n=20)		Test		
		Positive	Negative	Total
Truth	Positive	1114	78	1192
	Negative	8	0	8
	Total	1122	78	1200*

*Each subject was tested 60 times (every 6 s for a total of 360 s). A total of 1200 tests were done in 20 subjects.

TABLE III
TESTING RESULTS OF AF DETECTION IN PATIENT GROUP USING ALGORITHM II

Patients (n=20)		Test		
		Positive	Negative	Total
Truth	Positive	1135	58	1193
	Negative	7	0	7
	Total	1142	58	1200

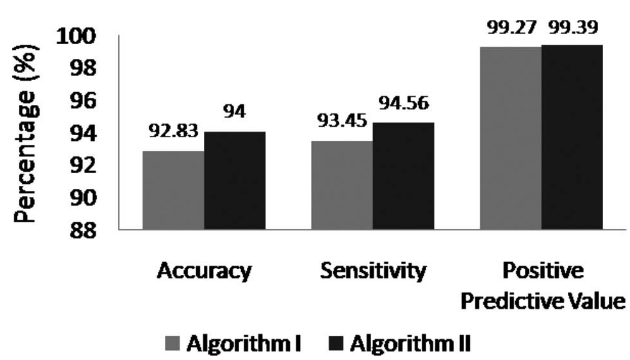

Fig. 5. Average performance between the two detection algorithms.

Twenty patients were tested using Algorithm I, and the experimental results are shown in Table II and Fig. 5. As shown in Fig. 5, the average accuracy was 92.83%, its sensitivity performance is 93.45%, and the positive predictive value is 99.27%.

The same 20 patients were also tested using Algorithm II, in which AF is detected only when two conditions were met. The average accuracy, sensitivity, and positive predictive performance were 94%, 94.56%, and 99.39%, respectively, as shown in Fig. 5. In comparison with the performance of using Algorithms I and II, the performance in Algorithm II was all better than those tested using Algorithm I. These results showed that combining the two conditions, as the detection criteria in

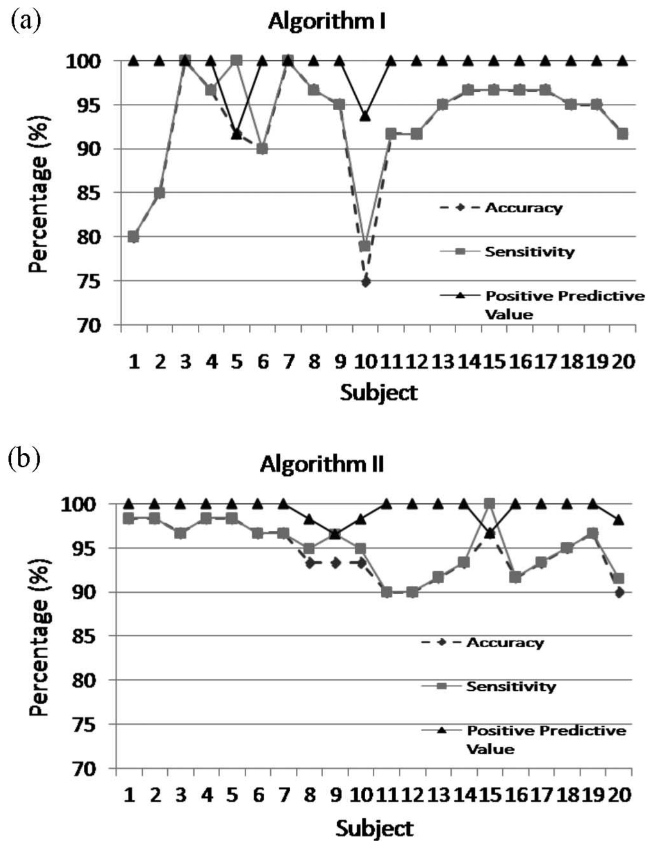

Fig. 6. AF-detection performance between patients when using (a) Algorithm I and (b) Algorithm II.

Algorithm II, will improve the AF-detection performance, especially in terms of accuracy and sensitivity performance.

High positive predictive value indicates that ΔRRI $>$ 150 ms and RRIstd $>$ 60 ms can be the principal parameters for AF detection. On the other hand, single-patient-detection performances are also shown in Fig. 6. Among a total of 20 patients, Algorithm II displays the stable and high impact results across subjects. The results suggest that our system can provide a reliable AF-detection function in telecardiology healthcare services.

VI. Discussion and Conclusion

AF, the most common sustained cardiac arrhythmia, causes significant mortality and morbidity, and remains a major healthcare challenge. Early detection is very important for providing appropriate therapeutic interventions and managing disease-related complications, such as congestive heart failure and stroke. This study demonstrates that the proposed intelligent telecardiology system is capable of accurately detecting AF episodes and instantaneously alerting both the user and the healthcare personnel, facilitating early medical intervention. Furthermore, this intelligent telecardiology system is superior to conventional healthcare devices because it integrates all the key elements in one system. The following list describes the most important features of the proposed system.

1) *Wireless*: Communications between devices are all wireless (Bluetooth/WiFi/3G/2G), reducing wire stock usage and allowing convenient operation.
2) *Ambulatory*: The miniature ECG device is very lightweight, can easily be applied to the body, and can operate for a considerable length of time. The system can be run anywhere with a notebook or mobile phone, eliminating the problems of limited power or restricted areas.
3) *Real time*: ECG signals can be transmitted to nearby mobile devices instantly and there is only a few seconds lag when the signals are transmitted to a remote database server, depending on network capacity.
4) *Self-alarm*: The built-in expert system automatically detects abnormal ECG signals and alerts both the user and healthcare personnel using a mobile phone, or by sending a message to a remote database server installed in the hospital computer system and the emergency service system.

This novel system cannot only be used for inpatients and outpatients, but also provides a long-lasting health monitor to normal people. Patients wearing the lightweight three-limb lead wireless ECG device can hardly feel its presence, but still enjoy a sense of protection.

However, there are several limitations for the expert system. First, AF detection is based on the RRI variation, when the user has frequent atrial or ventricular premature beats, which can be misdiagnosed as AF. Second, in patients with AF and markedly impaired AV nodal conduction, RRI variations may become too small for the system to diagnose AF accurately. Lastly, there is still considerable motion noise during the recording, which might impair diagnostic accuracy.

In conclusion, this novel intelligent telecardiology system is capable of early AF detection, and represents a successful first step toward improving efficiency and quality of care in CVD. Further researches aimed at improving both hardware and software designs are necessary to enhance the efficiency and accuracy in future models of this system.

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References

[1] World Health Organization, “The World Health Report 2008,” World Health Organization, Geneva, 2008. Available: http://www.who.int/whr/2008/whr08_en.pdf
[2] S. Koch, “Home telehealth—Current state and future trends,” *Int. J. Med. Inf.*, vol. 75, pp. 565–576, 2006.
[3] R. J. Romanow (2002, Nov.). Building on values: The future of healthcare in Canada—Final report. Commission of the Future of Health Care, Ottawa, Canada [Online]. Available: http://www.cbc.ca/healthcare/final_report.pdf
[4] J. E. P. Waktare, “Atrial fibrillation,” *Circulation*, vol. 106, pp. 14–16, 2002.
[5] J. Hurst, “Naming of the waves in the ECG, with a brief account of their Genesis,” *Circulation*, vol. 98, pp. 1937–1942, 1998.

[6] W. B. Kannel and D. L. McGee, "Diabetes and cardiovascular disease. The framingham study," *J. Amer. Med. Assoc.*, vol. 241, no. 19, pp. 2035–2038, 1979.

[7] "ACC/AHA/ESC 2006 guidelines for the management of patients with atrial fibrillation," *J. Amer. Coll. Cardiol.*, vol. 48, pp. 149–246, 2006.

[8] G. Vanagas, R. Zaliunas, R. Benetis, and R. Slapikas, "Factors affecting relevance of tele-ECG systems application to high risk for future ischemic heart disease events patients group," *Telemed. J. e-Health*, vol. 14, no. 4, pp. 345–349, 2008.

[9] C. T. Lin, L. W. Ko, C. J. Chang, Y. T. Wang, C. H. Chung, F. S. Yang, J. R. Duann, T. P. Jung, and J. C. Chiou, "Wearable and wireless brain-computer interface and its applications," presented at the 13th Int. Conf. Human Comput Interface, San Diego, CA, 2009.

[10] L. Pang, I. Techoudovski, M. Braecklein, K. Egorouchkina, W. Kellermann, and A. Bolz, "Real time ischemia detection in the smart home care system," in *Proc. 27th Annu. Conf. IEEE Eng. Med. Biol.*, Shanghai, China, Sep. 1–4, 2005, pp. 3703–3706.

[11] *American National Standard for Ambulatory Electrocardiographs*, ANSI/AAMI EC38–1994, 1994.

[12] C. Papaloukas, D. I. Fotiadis, A. Likas, C. S. Stroumbis, and L. K. Michalis, "Use of a novel rule-based expert system in the detection of changes in the ST segment and the T wave in long duration ECG," *J. Electrocardiol.*, vol. 35, no. 1, pp. 27–34, 2002.

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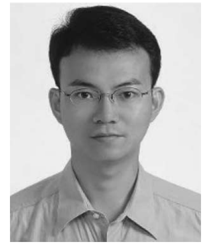

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