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Home-Based Mobile Cardio-Pulmonary Rehabilitation Consultant System

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Abstract— **Cardiovascular diseases are the most popular cause of death in the world recently. For postoperatives, cardiac rehabilitation is still asked to maintain at home (phase II) to improve cardiac function. However, only one third of outpatients do the exercise regularly, reflecting the difficulty for home-based healthcare: lacking of monitoring and motivation. Hence, a cardio-pulmonary rehabilitation system was proposed in this research to improve rehabilitation efficiency for better prognosis. The proposed system was built on mobile phone and receiving electrocardiograph (ECG) signal from a wireless ECG holter via Bluetooth connection. Apart from heart rate (HR) monitor, an ECG derived respiration (EDR) technique is also included to provide respiration rate (RR). Both HR and RR are the most important vital signs during exercise but only used one physiological signal recorder in this system. In clinical test, there were 15 subjects affording Bruce Task (treadmill) to simulate rehabilitation procedure. Correlation between this system and commercial product (Custo-Med) was up to 98% in HR and 81% in RR. Considering the prevention of sudden heart attack, an arrhythmia detection expert system and healthcare server at the backend were also integrated to this system for comprehensive cardio-pulmonary monitoring whenever and wherever doing the exercise.**

I. Introduction

The World Health Organization(WHO) estimated that 17.5 million people died from cardiovascular diseases (CVD) in 2004, representing 29% of all global deaths, which is the number one cause of death globally. Of these deaths, an estimated 12.9 million were due to coronary heart disease and stroke. By 2030 an estimated 23.6 million people will die from CVD and the largest increase in number of deaths will occur in the South-East Asia Region [1]. Clinical research evidences also show that for CVD patients, including postoperatives of cardiac surgery, heart failure patients and even the patients who received heart transplant, cardiac rehabilitation treatment was suggested to have positive effects on disease symptoms, quality of life, cardiopulmonary capability, prevention of disease recurrence and reduction of mortality [2, 3, 4].

However, only one third of CVD patients attends and completes the cardiac rehabilitation program [5]. A number of practical factors, such as insufficient of medical institutions with rehabilitation treatment service, work or time constraints, difficulties with transportation and dislike of hospitals, influence utilization of cardiac rehabilitation [6]. Therefore, home-based cardiac rehabilitations are considered as a feasible alternative to avoid various barriers. Clinical researches had also provided evidences that the result of home-based cardiac rehabilitation treatment was as good as hospital-based cardiac rehabilitation program which was under the supervision of doctors and therapists [7].

For a clinical-valid cardiac rehabilitation program, training task needs to reach certain intensity to strengthen rehabilitants' cardio-pulmonary function. Patients were generally asked to maintain the heart rate during exercise in a specific interval. The training may be too intense to increase the risk when the HR was exceeded the interval; on the contrary, the training became inadequate and ineffective when HR was below the interval. Therefore, the major challenges of home-based cardio-pulmonary rehabilitation can be listed as 1. appropriate time control and intensity maintenance; 2. alarm system to prevent sudden heart attack such as tachycardia or arrhythmias during exercise and 3. instantaneous and successive communication with mentors or physiologists.

General home rehabilitation are usually conducted by the degree of difficulty for the patient self assessment of exercise intensity, the formation of objective indicators cannot be effective. However, with advances in technology, patients have been able to buy a basic heart rate monitor in the market for recording heart rate and other information during rehabilitation. However, most of these devices do not have a real time analysis algorithm so that can't give patients personalized feedback. Besides, data storage and healthcare server, which supported for further evaluation, were also unavailable in the present [8].

In this study, a mobile cardio-pulmonary rehabilitation system with wireless ECG holter was proposed to give real-time feedback during exercise in home-based environments. In addition to ECG plot and heart rate, ECG derived respiration calculation was also applied to derive respiration rate. By means of continuous monitoring of HR and RR allow users to achieve more accurate and effective training intensity. Furthermore, a cardiac arrhythmia detection expert system [9] was also integrated to the system to insure the safety during exercise. The system was developed under Matlab and transplanted to JAVA for

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reducing the computation load and increasing the capability to mobile phone OS. A healthcare server in the backend was also applied for further analysis, monitoring and storage.

II. SYSTEM ARCHITECTURE

The basic scheme of the proposed home-based mobile cardio-pulmonary rehabilitation system was shown in figure 1. Three kernel technologies, including wireless ECG holter, mobile platform with consultant system and remote monitoring server, were developed to offer more reliable and efficient rehabilitation for outpatients. Whenever the patient do the exercise anytime and anywhere, a lightweight ECG holter can be set up using disposable button electrodes affixed to body area. Lead-II ECG signal was transmitted to portable device wirelessly and processed in a period of time. Heart rate and respiration rate were shown instantaneously and refreshed every six seconds. Moreover, a JAVA based intelligent expert system alarms as long as an abnormal ECG signal was detected, such as Bradycardia, Tachycardia and Arrhythmias [9]. The acquired ECG signal was uploaded to remote healthcare server for clinical evaluation. After the rehabilitation session a brief report was displayed to the patient for consultation.

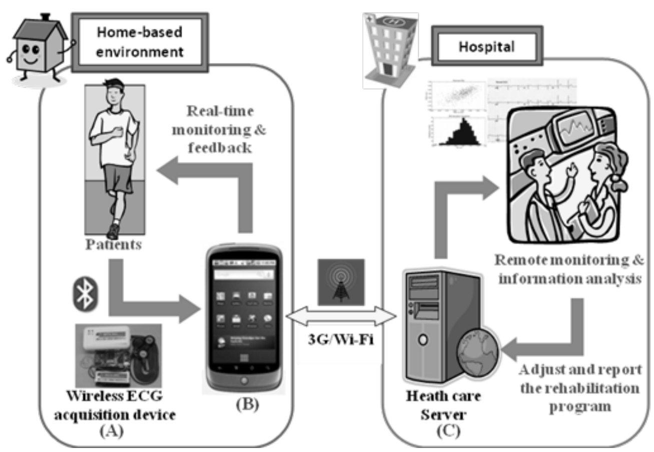

Figure 1. Proposed mobile cardio-pulmonary rehabilitation system, including (A) wireless ECG holter, (B) a mobile platform and (C) remote server.

A. Wireless ECG acquisition device

A lightweight and power-saving wireless ECG device (*A+Care iHeart, NCTU*) used in this research was proposed before [9]. Lead-II ECG signal was measured and transmitted to mobile phone via Bluetooth. The ECG signal was obtained by attaching three electrodes to patient's body. Although 12-lead ECG provides more precise and useful information in clinical diagnosis, it is not conveniently and easily used at home or outdoor. Moreover, the attachment of 10 electrodes on the body not only causes inconvenience of movement but also induces more noise to the signal.

B. Mobile platform

The system proposed is built on Android™ mobile platform (Motorola Milestone™, Motorola Mobility Inc.). It provides with sufficient computing power and communication capabilities. Data was transmitted from ECG acquisition device through Bluetooth module to the portable device. Including QRS feature extraction, heart diseases (Bradycardia, Tachycardia, Atrial Arrhythmias and Ventricular arrhythmias) detection [9] and EDR were applied to process the signal and the information was displayed on the screen instantaneously. Heart rate and respiration rate refreshed every six seconds. In the meanwhile, heart diseases detection consultant system saved abnormal ECG plot and generated a report afterward automatically. At the end of each exercise session, either 3G or WiFi is utilized to upload the data to the heathcare web server.

C. Healthcare server

A Servlet is used to receive the raw data from the mobile phone via HTTP protocol on the healthcare server. When patients login to the server, they need to provide correct username and password to ensure the data security. The server also utilize Java Data Base Connectivity (JDBC) library to connect with MySQL which is used to manage and store the data from the patients.

III. METHOD OF EDR

The fluctuation of chest changes the impedance between the heart and ECG patch sensors during respiration. This change was applied to EDR calculation to decide inspiration or expiration. Assumed that ECG source generated inside the heart was given by $s(t)$, leads to an ECG recorded signal $\mathrm{u}(t)$ at instant *t*. Impedance between the heart and sensors denotes by $I(t)$ and $n(t)$ indicates an additive noise of sensors. An underlying signal $v(t)$ is also considered to give a complete ECG signal $\mathrm{u}(t)$ [10].

$$\mathrm{u(t)} = I(t) \times s(t) + v(t) + n(t) \quad (1)$$

Apparently the respiratory signal is related to $I(t)$ and how to extract and correlate the respiration signal from $\mathrm{u}(t)$ was the main purpose of this method. Once the ECG signal was received the underlying signal and noise were removed first. Following by ECG features extraction and increasing the weight of R-peak rather than others to significant R-peak and insignificant noise for further computation.

Kurtosis computation was applied to adjacent R peaks to get the impedance value $I(t)$ using equation (2) where $K(k) = E(x(t)^4) - 3E(x(t)^2)^2$ and $E\big(x(t)\big)$ denotes the expectation operation on the samples.

$$I = \frac{((\gamma^4 - 3(\sigma^2)^2)K(k))^{\frac{1}{4}}}{(\gamma^4 - 3(\sigma^2)^2)^{\frac{1}{2}}} \quad (2)$$
$$\gamma^4 = E(s(t)^4), \sigma^2 = E(s(t)^2)$$

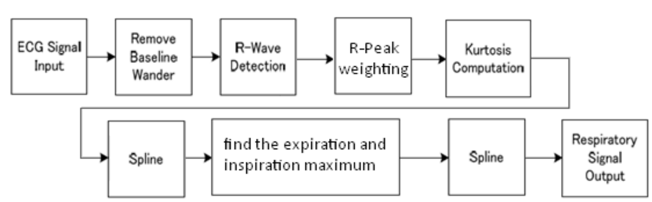

Figure 2. Flow chart for deriving respiration from ECG (EDR).

In a total of N's R-peaks gives (N-1) values of $I(t)$ such that the respiratory signal was obtained by computing cubic spline of $I(t)$. EDR processing flow chart was shown in figure 2.

After first cubic spline process, the signal still contains noise generated by body movement. Such that in the next finding out all of local maximum and local minimum, and grouped a local maximum with two neighboring local minimum as a wave. Comparing between the waves and setting threshold leads to filter out the noise. The filtered signal was processed by cubic spline again and finally receives more appropriate respiratory pattern.

IV. RESULTS

A. Clinical test

Comparison of HR and RR signal between derived ECG and commercialized clinical physiological recorder (Custo-Med) was shown in this section. The testing bed was in Division of Rehabilitation Medicine, Taipei Mackay Memorial Hospital, Taiwan. Totally 15 normal subjects, aged from 20 y/o to 27 y/o, were asked to have treadmill exercise following Bruce test protocol for 30 minutes, pushing the subjects to achieve the maximum heart rate (180-220 bpm). Two recording systems, including wireless ECG holter and clinical physiological recorder, were equipped on subjects during the experiment. The Institutional Review Board (IRB) of MMH approved all the procedures and measurements.

Calculated respiration rate was obtained from both systems and the correlated result was shown in figure 3. The solid line is the RR computed from air flow meter and the dotted line is derived from ECG. Different exercise states from rest to recovery were labeled above by each. The statistical result of all 15 subjects was shown in Table 1. On the aspect of HR, the averaged correlation was 98.5%, compared to clinical recording of commercialized system. On the other hand, ECG

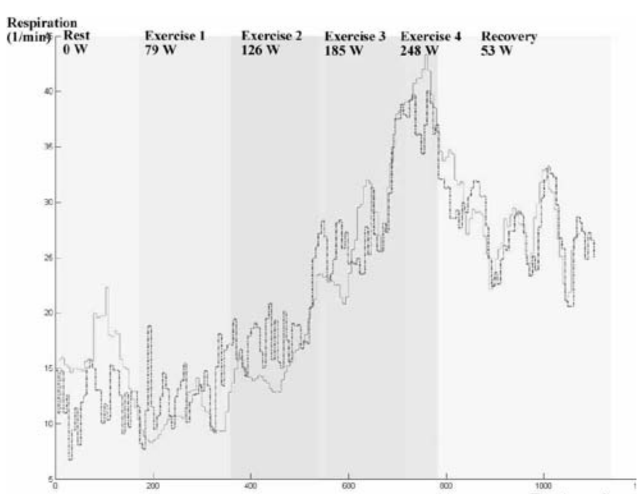

Figure 3. The respiration rate obtained from derived ECG signal (dotted line) and air flow meter (solid line). Different exercise states including rest and recovery state were labeled above the plot.

TABLE 1
CORRELATION OF 15 SUBJECTS

subject	Age	Heart rate correlation	RR corr. In Matlab	RR corr. In JAVA
1	23	0.9967	0.9183	0.8178
2	23	0.9982	0.7879	0.7598
3	27	0.9762	0.6496	0.7944
4	22	0.9938	0.9136	0.8739
5	22	0.9837	0.7441	0.6958
6	22	0.9866	0.8766	0.8899
7	26	0.9940	0.6526	0.8062
8	24	0.9852	0.7432	0.7017
9	23	0.9924	0.8904	0.9154
10	23	0.9973	0.8929	0.8841
11	22	0.9030	0.8034	0.8337
12	25	0.9890	0.8849	0.8469
13	20	0.9916	0.7610	0.8748
14	25	0.9927	0.8696	0.8524
15	22	0.9951	0.6939	0.6626
average	**23.3**	**0.9850**	**0.8055**	**0.8140**

derived respiration rate had up to 80.55% of correlation to air flow meter.

The EDR algorithm programmed in Matlab was also applied to JAVA platform on the mobile. Accordingly, the correlation between JAVA program and air flow meter was 81.4% (table 1), indicates that this EDR algorithm performed stably and reliably in different operated environments.

B. Mobile Application

In the mobile application, user friendly interface and data security were the first consideration. Rehabilitants were received a mobile phone with account, password and training intensity (target heart rate) set and fixed in advance (Figure 4a). Users can increase the training intensity according to circumstances, but cannot make changes to the account and password. This mechanism not only simplifies the operation for patients, but also prevents false information or account validation error. A guest mode was also programmed for testing purpose and cannot upload features to backend server.

Before the application start, user was asked to pair the ECG acquisition device with Android phone via Bluetooth. ECG was displayed immediately on the screen as long as the

(a) (b) (c) (d)

Figure 4. Operation screenshots were shown in sequence. (a) Login and target heart rate setting before start up. (b) Real-time display of HR, RR, exercise elapsed time, target HR achieved elapsed time and ECG signal. (c) Brief report after an exercise. (d) A report for abnormal ECG signals.

connection was established. After six seconds (for HR) or thirty seconds (for RR, overlapping 24 seconds) of baseline calculation, HR and RR result were displayed and refreshed every six seconds. In the meanwhile, the abnormal ECG detection expert system was applied at the same time. When patients began to exercise, they can simply click on the screen starting the recording application and automatically computed not only duration time but also target achieved percentage (Figure 4b).

Click again on the screen stopped the recording and had a rehabilitation report generated, including HR and RR time-elapsed curve, exercise elapsed time, the percentage of reaching the training intensity and the number of suspected diseases (Figure 4c). Data was also send to the server in the background. Moreover, user can check the suspected disease history which involves the time of disease occurrence, six-second plot of ECG waveform and suspect symptoms any time during the application was in use from menu (Figure 4d).

C. *Application performance*

The testing platform was Android 2.1 on mobile with 550 MHz MCU. Power consumption test was measured by a free software available on Android Market called PowerTutor[11]. The results suggested that system consumed 225~270 joule or 62~75 mWatt per hour over all four hours of test (table 2). However, the most important factor affecting the power consumption was the LCD monitor. Up to 5 hours of using time was performed as the LCD always on as the cardio-pulmonary program was running simultaneously when considering a 1400 mAh Li-ion battery. Yet nearly double of time was performed as the LCD was turn off during system running. Accordingly, this system could satisfy most users who doing the exercise or rehabilitation procedure, generally not over an hour.

In order to verify the performance of the system, we measured the computational time as the algorithm was fully loaded. Algorithms for computing six-second ECG signal of heart rate and respiration rate last about 0.3 to 0.4 second on execution, which caused no delay to the platform. The result suggested that this rehabilitation program can performed in a low-end mobile system at the same time given a long term monitoring to the patients.

TABLE 2
POWER CONSUMPTIONS OF SYSTEM

Time (minutes)	Accumulate Energy (J)	Power (mWatt)
60	225	62.5
60	225	62.5
60	255	70.83
60	271	75.28
average	244	67.78

V. CONCLUSION & DISCUSSION

The cardio-pulmonary rehabilitation system proposed in this paper gave a solution for those CVD patients to have a convenient and easily operated ECG holter with multiple services. This system can not only used for rehabilitation but also provides a total solution for telehealthcare or personal health management. However, user friendly wireless environment is the key for applying these systems. In conclusion, a more power saving and miniature system with precise HR, RR and CVD analysis algorithm is the trend to rehabilitation or telehealthcare in the near future.

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