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Development of a remote handheld cardiac arrhythmia monitor

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Abstract—
In this paper we present the design and development of a real-time remote handheld cardiac arrhythmic monitoring system (RCAM). A client-server model based on Internet protocols was used. ECG data was transmitted from the remote handheld client to a centralized server, where the QRS and premature ventricular contraction detection algorithms were implemented and graded depending on the number and pattern of PVCs present. The QRS sensitivity and specificity on ECG records from Physionet archives in absence of arrhythmia was 100% and 99.62%, while in presence of arrhythmia was 99.34% and 99.31%. The average 'negative time' measured on ventricular tachyarrhythmia records was 92 seconds. The RCAM can provide remote detection of cardiac abnormalities and give specific diagnosis and recommendations of actions to be taken immediately. The limitation due to the inability of the PDA to perform complex computations was overcome by the use of the remote server.

I. Introduction

Cardiovascular diseases are the No. 1 killer of women and men in the United States. About 340,000 people a year die of coronary heart disease in the Emergency Room or before reaching a hospital[1]. Most of the sudden deaths are caused by cardiac arrest, usually resulting from ventricular arrhythmia. Studies have shown that rapid response time in pre-hospital setting results in reduced mortality and dramatically improved patient outcomes.

Electrocardiogram (ECG) is the most important noninvasive diagnostic tool used for assessing the probability of cardiac event, for stratifying its degree (stable, unstable angina, risk of out-hospital or in-hospital death) and for guiding therapy. Premature ventricular contractions (PVCs) are one of the most common arrhythmias and can occur in patients with or without heart disease. Of patients with prior myocardial infarction (MI), more than 80% show evidence of PVCs on Holter monitoring. Exercise can increase or decrease the PVC rate[2]. PVCs with frequency greater than 10/hour, runs of PVCs, multiple ventricular morphologies, and PVCs occurring early in the cardiac cycle (R-on-T phenomenon) are associated with increased mortality rates and subsequent arrhythmic events.

Studies[3] have shown that remote ECG monitoring from pre-hospital setting results in reduced response time, improving patient outcome. It was also used to assess the probability of cardiac event, stratify risk and to guide therapy. The primary attributes of remote monitoring systems[4] are: (a) Record key information at the point of care, eliminating errors and duplication of effort and providing completeness of data (b) Automate processes and information sharing (c). Provision for clinical decision support (d) Ensure secure acquisition and storage of patient data. (e). Provide reliable performance (f) Assist patients in management of their own health.

ECG signal recording in a non-hospital setting can be classified as (a) Short-term and (b) Long-term. Short-term measurements (5-15 min) are usually made at the doctor's office or at small clinics. Long term measurements (24-96 hours) are usually made at patient's home by ambulatory monitors (Holter). The disadvantage of the short-term recordings is that it is not possible to have a complete diagnosis, and the shortcomings of long-term recordings is that it is not possible to intervene immediately, which sometimes could lead to serious conditions. Holters with DSP chips[5] for ECG analysis can detect cardiac events in real-time and send cardiac report to a monitoring station using standard telephone lines. However such monitoring Holters are expensive, and they do not provide any feedback to the patient about his/her medical condition. Remote ECG monitoring has also been shown to be effective when done from a commercial aircraft[6] or an ambulance[7].

ECG data is usually transmitted incorporating Internet Protocols (TCP/IP). TCP (Transmission Control Protocol) is chosen because it offers permanent connection channels, data packet checking to assure all data is transmitted and error checking within packets to assure data integrity[8]. TCP/IP encapsulated ECG data is sent over PSTN (Public Switched Telephone Network)[5], Cellular (GPS[9], TDMA) or broadband networks (DSL / Cable) from the remote patient location to the hospital. PSTN is the most commonly used medium for ECG transmission due to its ubiquitous presence. However data sent over PSTN has a high error rate causing frequent delays. Real- time ECG monitoring systems incorporating GSM data networks[9] have an advantage of being wireless, but its limited bandwidth caused significant data loss. Remote web servers are also

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used to store and display real-time ECG data. Java embedded systems[10] (e.g. Dallas Semiconductor Tiny Internet Interface) are cost effective and provide real-time web-based monitoring. However, these systems do not provide any mechanisms to analyze ECG data or provide feedback to the patients.

Handheld devices like PDAs (Personal Desktop Assistants) are small, light, and easy to use and have powerful computing capabilities. New generation models have features like built-in networking using Wireless LAN and its integration into the cellular phone has made it possible for the remote monitor to access hospital services. PDAs have been used in medical community for accessing online medical databases[11], to record patient and clinical training data[12] and to send ECG data from the ambulance directly to the hospital. However, at the present time, PDAs do not posses computing capability required to perform real-time ECG analysis. Computer based analysis of ECG for detection of cardiac arrhythmias has been used with considerable success. Implementation of innovative signal-processing and analysis techniques have been assisted by the availability of web based remote processing servers in small sized hospitals[13].

The PDA-based remote monitor was designed to monitor ECG and provide real-time feedback. Detection of anomalies in ECG was performed in real-time by a remote processing server. The server also records and stores ECG for immediate or future medical consultation. The effectiveness of the RCAM was quantified by 'negative time to alarm' (time before onset of ventricular fibrillation) measurements on data from CU Ventricular Tachyarrhythmia database.

II. METHODS

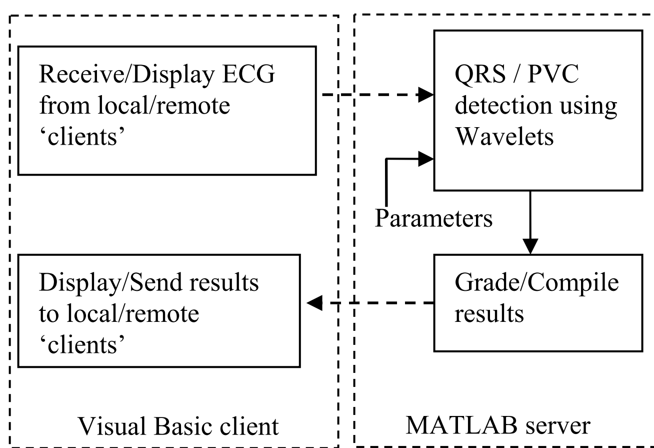
In order for the remote cardiac arrhythmia monitor (RCAM) to be reliable, it must not miss a life threatening arrhythmia, causing the patient a lost chance of treatment, minimize false-positive detection, which may lead to improper therapeutic intervention. In addition to reliability, speed of transmission is also critical to early detection of arrhythmia.

(a) *Remote Client*

ECG data was transmitted from remote clients (computers/PDA) to a central server for analysis and storage. The analyzed results were sent back to the remote client in real-time to monitor current condition, to aid in diagnosis and to provide early warning/alarm in case of abnormality. The results were also made available to other remote clients (physicians) to aid in diagnosis. In our study, the data used to study the effectiveness of the RCAM was obtained from Physionet archives. The details of the data used are explained in section (d). No additional filtering of ECG data was performed. The ECG data was displayed on the remote client and transmitted to central server. Windows sockets incorporating TCP/IP protocols were used to establish a connection between the remote client and central server. A wireless connection was established across the Internet between the remote client - Sony Clie TH-55 PDA (Palm 5.0 and built-in WiFi) and a central server - Compaq Presario R3000 laptop (Windows XP SP2 with built-in WiFi). The server was designed to handle multiple local/remote clients at the same time. Microsoft Visual Basic 6.0 and Mobile Visual Basic 4.0 software was used to develop the graphical user interface (GUI) and communication (TCP/IP) modules for the remote client. Data received from client applications was stored on the server for a more comprehensive off line analysis at a later time.

(b) *Central Computation Server*

Availability of built-in digital signal processing and statistical algorithms has made Matlab the software of choice for development of the software. Since Matlab is launched and controlled by Visual Basic, Visual Basic acts as an 'Application Client' and Matlab acts as an 'Application Server' (Fig 2). The Matlab server was run in shared mode (multiple client applications) on the local system. Matlab automation server capabilities include the ability to execute commands in the Matlab workspace and to get and put ECG data as matrices directly to and from the workspace. The QRS/PVC detection and classification algorithms are implemented in Matlab workspace. The results of the analysis were transferred to Visual Basic for display and transmission to remote clients.



Fi Fig 1. 'Client-Server' model at the central computation server

(c) *QRS Detection/Classification algorithm*

The automated detection of QRS complexes is important to cardiac disease diagnosis. A good performance of an automatic ECG analyzing system depends heavily upon the accurate and reliable detection of QRS complexes.

Wavelet transforms was used to detect QRS complexes. Biorthogonal wavelets enable detection of peak of a wave as an extrema and have minimum number of sign changes, simplifying QRS detection algorithm. Local maxima of dyadic wavelet transform at various orders (4, 5, 6 and 7) are used to locate the QRS/PVC transition points in the ECG signals.

The sensitivity and specificity of the detection algorithms were given by:

Sensitivity = 100 * (TB – FN) / TB (1)

Specificity = 100 * (TB – FP) / TB (2)

where, TB – total QRS complexes detected, FN – False negative and FP- False positive.

A parameter file was created for each dataset to aid in an accurate detection of cardiac events. The parameters were created based on the QRS peak characteristics. Parameters include thresholds at different wavelet orders, average QT interval, and QRS search interval. The algorithm grades the occurrence of abnormal cardiac arrhythmia based on Lown grading scheme[14] (Table I). The alarm is triggered with the onset of Grade 4 and elevated heart rate (>120 beats/min).

Grade 0	No PVCs present
Grade 1	Occasional PVCs (< 30/h)
Grade 2	Frequent PVCs (> 30/h)
Grade 3	Repetitive PVCs (A -Couplets, B -Salvos)
Grade 4	> 3 PVCs in a row

Table I. Lown Grading Scheme

(d) *Data*

Ten ECG records from MIT Normal Sinus Rhythm Database [16] were used to test the QRS detection algorithm. The subjects in the datasets had no significant arrhythmia. The records were of one minute duration and were sampled at 250Hz. Seven records of 10 minute duration sampled at 360 Hz were chosen of subjects with monomorphic PVC were chosen from MIT-BIH Arrhythmia Database [16]. Four records containing PVCs leading to ventricular tachycardia were chosen from Creighton University Ventricular Tachyarrhythmia Database[15]. The ECG data in the records was of 8 minute duration and was sampled at 250Hz. In each record, the 'time to alarm' (predict the onset the ventricular tachycardia based on the presence of PVCs) was measured. ECG data from Lead II was selected from all the records. The records used were accompanied by an annotations made by cardiologists, who have manually identified the time of occurrence and classified the type of QRS complex, making it suitable for this study.

III. Results

The sensitivity and specificity measurements for the normal sinus rhythm dataset are shown in Table II.

Data	Detected	FP	FN	Sensitivity	Specificity
1052	65	0	0	100.00	100.00
1177	103	1	0	100.00	99.03
1184	81	2	0	100.00	97.53
1265	89	0	0	100.00	100.00
1272	58	0	0	100.00	100.00
1273	88	0	0	100.00	100.00
1453	77	0	0	100.00	100.00
1483	91	0	0	100.00	100.00
1773	69	0	0	100.00	100.00
1795	61	0	0	100.00	100.00

Table II. Sensitivity and Specificity of QRS detection algorithm using a normal sinus rhythm database.

The sensitivity and specificity measurements for the QRS and PVC detection algorithms on the MIT-Arrhythmia dataset are shown in Table III.

Data	QRS		PVC	
	Sensitivity	Specificity	Sensitivity	Specificity
105	99.64	98.93	50.00	64.29
106	99.85	98.77	54.55	81.82
114	99.82	97.72	97.44	89.74
116	99.75	100.00	64.29	100.00
119	99.55	98.64	98.59	97.18
208	96.81	99.59	87.91	92.19
221	100.00	100.00	88.34	88.96

Table III. Sensitivity and Specificity of QRS / PVC detection algorithms using MIT-Arrhythmia database.

The negative 'time to alarm' measurements using the data from the CU Ventricular Tachyarrhytmia database are shown in Table IV.

Data	Onset of VF (s)	Alarm Time (s)	Negative Time to Alarm (s)
04	155	128	27
05	358	60	298
07	182	148	34
20	245	235	10

Table IV. Measurement of 'negative time to alarm'.

IV. Discussion

In our implementation of PDA based client, we have used only a single channel ECG data (ML II lead). This was done due to limitations in networking and processing speed of the handheld device. Addition of another channel from the data (V1 lead) would increase the sensitivity and specificity of the QRS/PVC detection algorithms. The only non-automated step in the system is creation of parameters. The use of default parameters was found to increase the incidence of false positive and false negatives. In case of PVC detection, the parameters were skewed to reduce the incidence of false positives (false alarm). Table IV shows the effectiveness of the detection algorithm to detect the onset of ventricular fibrillation before it occurs (negative time).

V. Conclusions

The limited computational resources on the handheld PDA led to the development of the remote cardiac monitor. The availability of real-time feedback provides a real-time ECG monitoring before and after medication and exercise. In 'normal' patients, the RCAM would provide the user reassurance in absence of the physician. The PVC sensitivity and specificity rates can be significantly enhanced by an addition of another ECG lead (for example: addition of V1 data from MIT-database). The detection algorithms were optimized for speed and accuracy. At the server, Matlab provides an easy and computationally powerful environment for implementation of faster and more effective algorithms for online and offline analysis. With the availability of faster processing handheld devices, it might be possible to compute part or all of the detection on the handheld device itself.

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