Continuous Monitoring of Children with Suspected Cardiac Arrhythmias*

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Abstract. Advances in wireless communications and networking technologies as well as computer and medical technologies, enable the development of small size, power efficient and more reliable medical multi-parameter recording systems, which can be used for continuous monitoring of patients. Through this paper we present the design and development of an m-health system platform that will be used in order to monitor children with suspected cardiac arrhythmias. The proposed system is based on sensor networks, in order to monitor a subject while being in a predefined area like his/her house; while another module based on PDAs and wearable ECG recorders will be used in order to extent the coverage outside the patient's house. Furthermore the system will be based on a variable sampling rate to conserve power for the possible arrhythmia episode. The system design and development has been completed and currently is going through the initial testing phase for the first improvements.

Keywords: Sensor networks, wireless telemedicine, home monitoring, children arrhythmias.

1 Introduction

Telemedicine has been used for many years in order to improve health care provision or for patient monitoring solutions. Several issues such as the computational capability, size of the devices, power efficiency and cost have been limiting the availability of devices and services to a few special cases [1]. Recent advancements in communications and

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computer systems can help us develop general-purpose systems that are more efficient, much smaller and at lower costs.

In this study, we will focus on the continuous monitoring of children with suspected cardiac arrhythmias. In order to evaluate the size and severity of the problem; arrhythmia is one of the most difficult problems in Cardiology both in terms of diagnosis and management. The problem is particularly pronounced in Pediatric Cardiology because of the variety of etiologies and the difficulty that the children are having in trying to communicate their symptoms. For example in the case of hypertrophic cardiomyopathy, it is known that children are at higher risk for arrhythmias and sudden death than adults. In most of the cases an ECG tracing is required and this is sufficient for an accurate diagnosis, whereas in some cases, a more sophisticated modality is required [2], [3].

As an example a relatively recently recognized rare form of cariomyopathy, the Isolated Noncompaction of the Left Ventricle (NCLV), which is a rare form of cardiomyopathy, poses new challenges. A subset of patients with this disease are especially prone to arrhythmia and sudden death. It is not always possible to estimate the risk of each patient with the available test modalities even if we include genetic testing. Current testing with the holter monitor has proved insufficient because it is limited to 24 or 48 hours of recording during which the patient may be asymptomatic. We care for a group of such children, some of whom are at imminent risk of sudden death [2], [3].

In this study, a mobile health (m-Health) system that will be able to monitor children continuously during their daily life activities is proposed. The system will be able to do real-time acquisition and transmission of ECG signals from the patient, and facilitate an alarm scheme able to identify possible arrhythmias so as to notify the on-call doctor and the relatives of the child that an event or something that denotes malfunction is happening. This system is a significant extension over our earlier telemedicine work in real-time ambulatory monitoring systems [4].

2 Example Cases

In order to better appreciate the problem a brief description of two cases is presented:

Case 1: A few years ago we lost one such child, a four-year-old boy that was our first patient to be diagnosed with this disease. He was presented with a near miss episode of sudden death while at the nursery school and he was revived at the hospital where he was brought unconscious. He was then referred to UK for electrophysiological studies that were essentially normal. He had periods of bradycardia on the holter monitor and during his hospitalization. It was believed that the episode of loss of consciousness may have been related to bradycardia and a pacemaker was implanted. A few months later, while at school, he lost consciousness again and was brought to the hospital but he could not be revived this time. Before dying, an ominous form of arrhythmia (torsades de pointe) was recorded. A few weeks before death, his mother reported a very short episode of near loss of consciousness that retrospectively could have been a short episode of arrhythmia but unfortunately there was no record of it.

Case 2: The second case is that of a nine year old girl with a history of several episodes of loss of consciousness and NCLV. In her case, we were lucky to record one such episode on the holter monitor. She had multiple episodes of supravenrticular tachycardia following one of which there was a prolonged pause that coincided with the witnessed episode of loss of consciousness. She was then started on beta blockers and she remains asymptomatic over the last three years.

The description of these two cases highlights the wide range of clinical presentation and the variety of the underlying arrhythmias that these children present. Some of these children are high risk for sudden death and at the same time it is very difficult to decide for the proper treatment, making their ECG monitoring a very important task. The methods available today for ECG monitoring are clearly insufficient for this purpose. We need a noninvasive or minimally invasive way to record the ECG for extended periods of time and at the same time perform automatic analysis continuously or at frequent intervals.

3 Methodology

In general the design problem has been divided into two cases. For the first case, called “In-house case” the subject is located in his/her house. For the second case, called “Moving patient case” the subject may or may not be located in his/her house. In both cases we require continuous 24-hours monitoring.

In house case: During this case, a sensor network installed in the child’s house that will be used in order to continuously monitor ECG signals from the patient [6] – [9]. Several other environmental parameters like light, temperature, sound and acceleration will also

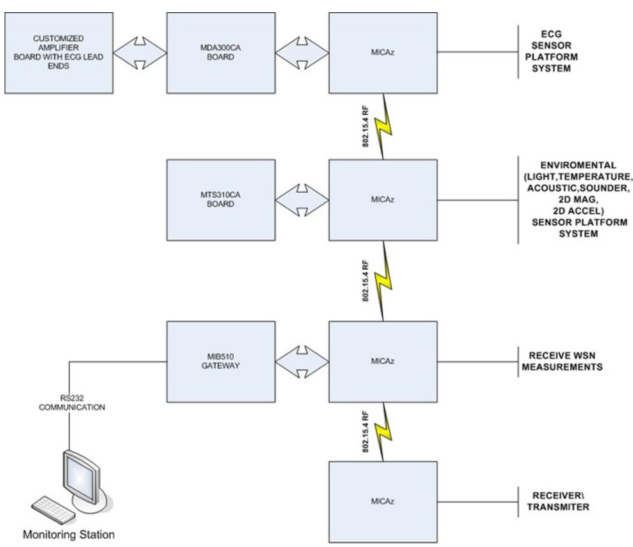

Fig. 1. Block diagram of the in-house wireless sensor network © IEEE 2007 [5]

be monitored so as to continuously check the living conditions. The ECG (3 lead) signal will be recorded by a sensor carried from the child, that will be part of a wireless sensor network (WSN) installed in the house. The ECG sensor has been specially designed & developed by SignalGenerix ltd (http://www.signalgenerix.com) Signal information from the wearable sensor will be propagated to a local monitoring station which will also act as a gateway to the rest of the monitoring network. This case can be described as follows (see also Fig. 1):

a. The cardiac pulse is propagated through the WSN to the local monitoring station with an embedded broadcast algorithm.
b. The local monitoring station is required to collect all environmental measurements (e.g.temperature, 2D accelerometer, sound, light):
   - Sample the ECG signal.
   - Store the sensor data locally.
   - Analyze the ECG signal in order to detect possible cardiac arrhythmias.
c. In the case of a detected arrhythmia:
   - Send an alarm message to the central monitoring station (located in hospital).
   - Send an alarm via an SMS to the supervising doctor and a relative.
d. The central monitoring station is required to:
   - Store data sent from the local monitoring station.
   - Display data transmitted from the local monitoring stations and through a web interface.
   - Analyze the ECG signal further. (send a message (SMS, e-mail etc.) to the doctor).

Moving Patient Case: The second case is more general and will be used in order to complete the coverage of the system. For this case, the child will be monitored using the same ECG recording device but the signals will be transmitted, through a PDA device, directly to the central monitoring system. The transmission will be performed through the use of 2.5G and 3G mobile communication networks (GPRS/UMTS) [1]; depending on the equipment and network.

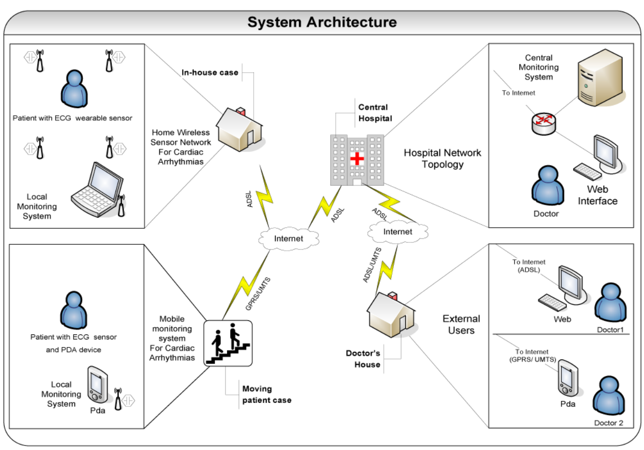

Fig. 2. Overall system Architecture © IEEE 2007 [5]

The information will be stored locally on the PDA and a basic analysis of the signals will be performed locally on the mobile unit (depending on the equipment specification). The central station is required to provide for the storage and analysis and display of information, as well as the notification of the on-call doctor and the relative in case of an alarm. The case can be described as shown in Fig. 2:

a. The cardiac pulse is propagated through the ECG sensors to a PDA carried by the patient. The PDA system is required to:
   - Sample the ECG signal and send it via GPRS/UMTS to the remote monitoring station.
b. The remote monitoring system is required to:
   - Store data for the specific patient.
   - Analyze the ECG signal in order to detect possible cardiac arrhythmias.
   - Send an alarm via an SMS or e-mail to the supervising doctor and a relative.
   - Display data locally and through the web.

Variable rate ECG signal recording: The continuous-time monitoring is limited by the available battery power. In order to achieve better results and more time of transmission we propose the use of a variable-rate signal processing system that will be used to reduce the power requirements by reducing the sampling rate during normal operation, while saving the high sampling-rate and transmission during a possible arrhythmia session. To recognize the power savings, we note that power consumption is directly proportional to the frequency of operation. Thus, we can reduce power consumption by increasing the sampling period T_s. We can show that without changing the anti-aliasing analog filter prior to sampling, using a digital filter of variable bandwidth BW, we can produce a properly sampled ECG signal, sampled at $2(1-1/BW)T_S$. Furthermore, larger sampling periods can be accommodated by varying the analog cutoff frequency of the anti-aliasing analog, lowpass filter. Here, we note that we do require continuous transmission of one lead of ECG signal. For the case of a moving patient, three leads will be acquired and stored on the device, but only one waveform will be transmitted continuously [8]. This will result in power savings due to the reduction in transmission power requirements.

Sensor network: Research on sensor networks is relatively recent and is currently one of the emerging fields of information technology, combining sensing with communications so as to have continuous monitoring and support the mobility of sensors [9]. For our case we have chosen to develop a Mote-based sensor network based on Crossbow® equipment [10]. In general, motes can operate using three types of topologies which are: 1) point to point topology, i.e. transmission between two notes, 2) Ad-Hoc topology which is a dynamic setup of a network structure and 3) Hybrid topology or Mesh which is a combination of both [9], [10].

4 System Architecture

The proposed network that will be used to cover the patient's house is based on motes like MicaZ™ while the acquisition of ECG data is performed through a custom created

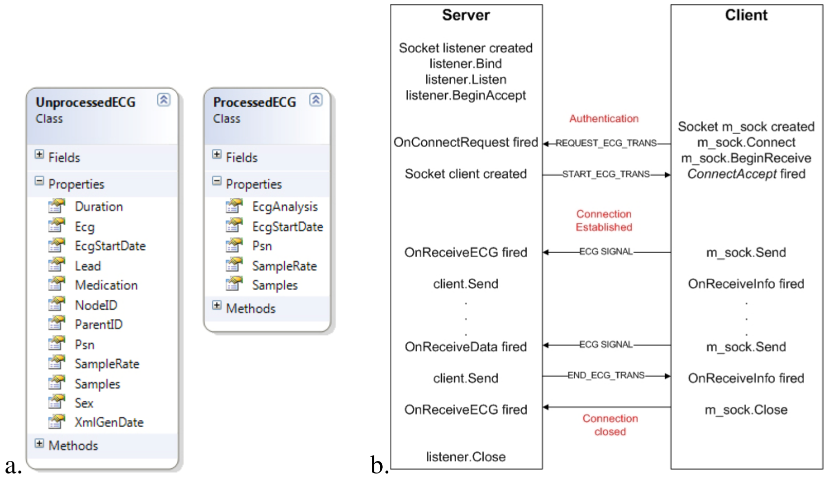

Fig. 3. a. The two classes of the XML communication Scheme Unprocessed-Processed Classes. b. Transmission protocol followed during the connection of the sites to server.

board connected to the MDA300CA™ acquisition board. Additional environmental data will be collected through the MTS310CA™ sensor board. All collected information will be transmitted to a gateway, MIB510™ connected on a Personal Computer; this is going to be the local monitoring system as shown in Fig. 1.

The in-house network will be connected to the remote monitoring system which is going to be responsible for re-evaluating the transmitted signals, local storage of the signals and display on a web interface. It will be also responsible for the notification of the on-call doctor and a relative of the child. A similar scheme will be followed for the moving patient case, where ECG signals will be collected by the same ECG acquisition device and transmitted to the remote station through a mobile communication network. The remote station will perform the same actions as above. The overall system architecture diagram is shown in Fig.2.

ECG Analysis and Transmission: For the ECG analysis needs of our project we use the open source QRS Detection software provided by E.P.Limited online at [10]. The software uses two modules. The first one is the QRS Detection which includes the QRS detection functions and the QRS filter functions. The second is the beat classification module which is used for beat classification and detection.

For the ECG signal transmission between the in-house network and the remote monitoring system an asynchronous xml communication protocol is proposed. The protocol is based on two important classes shown in Fig. 3.a. The first is the Unprocessed ECG class which is responsible to collect all the data related to the recorded ECG. The processed ECG class is responsible to collect all the data related to the analyzed ECG. The Unprocessed ECG class contains the following properties: Psn is patient's identification number, Ecg corresponds to a set of values for the ECG signal ex (200,150,175...), EcgStartDate is the timestamp of the first ECG sample value in Ecg field, SampleRate for our system is 200Hz, Samples is the number of ECG

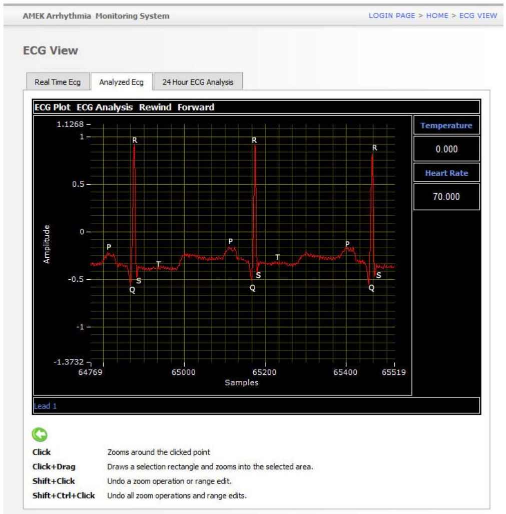

Fig. 4. Snapshot from a sample transmitted ECG signal with the analysis points

samples, XmlGenDate is the timestamp when the xml file is generated, Sex, NodeID and ParentID contain information about the sensor network, Duration is the ECG signal duration, Lead and Medication. Processed ECG class is consisted from the Psn EcgStartDate, SampleRate, Samples and EcgAnalyis properties. In EcgAnalysis field the analysis information (ex P,P,P,Q,R,S) is stored.

Based on the above classes a client in home monitoring and a server in remote motoring system are built so that after the ECG signal is recorder and or analyzed to be transmitted to the remote server. The protocol is based on the TCP/IP protocol suite and asynchronous communications. The sequence of the messages that are exchanged in the cases of Unprocessed ECG and Processed ECG signal is shown in Fig. 3.b. First the client transmits a request message to start sending ECG signal. The server receives the message and transmits a message to the client in order to start the ECG signal transmission. The connection is closed when the client receives a message to stop drop the connection. An example of the transmitted signal after the online analysis is show in Fig. 4.

5 Concluding Remarks

In this study, a prototype m-Health monitoring system for children with possible arrhythmias has been presented. As we have discussed, identification of children with arrhythmias is not an easy task and the treatment is not the same in all cases. Some forms of treatment, as is the case for some antiarrhythmia medications, increase the risk of arrhythmia (proarrhythmia effect) so it would be wrong to start such treatment without prior documentation of the problem. Another form of treatment uses implantable defibrillators. This form of treatment has given some promising results over the last few years. As we noted, it is difficult to decide who needs to be treated, not only because of the enormous cost but also because it entails a major at risk for arrhythmia and to record the type of arrhythmia that is needed before deciding on the proper management.

We hope that through the use of such a system we will be able to help in the identification of the type of problem thus helping the doctors provide the proper treatment. We have provided a basic architecture description of the system that has been developed. The system is currently being technically tested. Soon after this task, we intent to test the system on healthy volunteers. Finally the goal will be the testing of the system on non severe cases.

Acknowledgments

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