Remote Continuous Cardiac Arrhythmias Detection and Monitoring

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Abstract. The current techniques used to diagnose cardiac arrhythmias such as Holter, Rtest and telemetry system are partially efficient because they are limited either in time or in space. In this paper, a platform dedicated to the real-time remote continuous cardiac arrhythmias detection and monitoring is proposed. Such a platform permits to improve the accuracy and the efficiency of the diagnostic of ventricular tachycardia among the high risk of death patients and enables to propose the implantation of ICD to prevent sudden death. The new method allows the patient to lead a normal life while being remotely monitored in real-time by an ambulatory wireless ECG sensor. When a cardiac arrhythmia is detected a message including a sequence of ECG signal and the patient images (indoors only) are sent to the remote surveillance server. According to the gravity of the symptom the cardiologist can intervene in real-time or lately. The system is evaluated on about ten patients: heart beat and cardiac rhythm disturbance. The real-time results are similar to the HP telemetry system ones.

Keywords: Telemedicine, real-time remote continuous cardiac arrhythmias detection, wireless ECG sensor network, remote monitoring server.

1. Introduction

Thanks to the rapid developments of pathological research and clinical technologies, most of heart diseases can be effectively treated and prevented in today's society. Nevertheless, it can't change the fact that heart disease is still the world's number one killer. It is responsible for one in every three deaths, which is an estimated seven million deaths in the world each year [15].

Most of them are sudden cardiac death after heart attack. The sudden death is defined as a death arising less than one hour after the first symptoms felt by the patient. It concerns about 50,000 persons per year in France. 90% of the sudden deaths are due essentially to the cardiac arrhythmias: 20% are caused by heart block or pause (bradycardia) and 80% are caused by the ventricular fibrillation (VF), frequently initiated by the ventricular tachycardia (VT). The principal aetiology of sudden death for adults is due to myocardial infarction. For the group of population having a coronary pathology and chronic ischemia, the risk of death is particularly high.

This "massive heart attack" is generally considered as an unpredictable and unpreventable event. In spite of the effectiveness of the post-heart-attack treatment, the patients die because heart attack usually occurs suddenly, without a shred of warning.

Recent studies have shown that there are common significant cardiovascular abnormal symptoms such as palpitations, faints, chest pain, shortness of breath etc, before the sudden appearance of a lethal heart arrhythmia. If these symptoms can be early detected and diagnosed, time is won to prevent the occurrence of heart attack. Therefore, to reduce the number of disabilities and deaths caused by heart attack, it is necessary to have an effective method for early detection and early treatment.

The most effective preventive therapy of sudden death due to cardiac arrhythmias is the implantation of an implantable cardioverter-defibrillator (ICD). ICD is used to apply a strong electrical shock to the heart. By adjusting cardiac rhythm to orderly and effective status, this device helps to treat cardiac disorders such as ventricular fibrillation, ventricular tachycardia, atrial fibrillation, and atrial flutter. Unfortunately, its high cost is a main factor that impedes ICD to be widely applied. Moreover, it is an invasive technique requiring a major surgery with potential complications. The complications that a physician may encounter during surgery are the venous access, lead placement, intravascular thrombosis/fibrosis, and the generator [16].

Currently, ICD is mainly applied to the high risk death patients who have cardiac arrhythmia especially VT or VF, when the risk is accurately identified. Nevertheless, recent surveys discover sudden cardiac death not only occurs in people who have had heart attacks (myocardial infarction) in the past, but also can occur in young people who were entirely well until they died [17]. Therefore, we need an effective personal diagnosis system which can continuously monitor cardiac status. This system should be cost-effective, risk-free and easy to use in daily life.

The ECG (Electrocardiograph) is the most commonly performed cardiac test, because it is a useful screening tool for a variety of cardiac abnormalities; the test is simple to perform, risk-free and inexpensive. From the ECG tracing, the following information can be determined [18]:

- the heart rate
- the heart rhythm
- the conduction abnormalities: abnormalities in the way the electrical impulse spreads across the heart
- the coronary artery disease
- the heart muscle abnormality etc.

The HOLTER technique is no doubt frequently used to record 24h or 48h of 2 leads ECG signals. The recorded ECG signals will be analysed by a dedicated software and a report is produced to be interpreted by the cardiologist, but it is proved largely insufficient for a long term prediction because the critical cardiac arrhythmias do not necessarily occur during the 24h or 48h [19]. Another technique called RTEST allows the patient to monitor the record of a sequence of the ECG signals [11]. The recorded ECG signals may be sent to a remote server or analyzed later. One of the drawbacks of the RTEST technique is that most of the time the patient does not feel the palpitation or the VT. In fact, some cardiac rhythm disturbances are just asymptomatic. The new generation of RTEST may be configured by the physician to record automatically the ECG signals. Thus, these two techniques are limited in time (4 weeks for the RTEST) and are proved insufficient and partially efficient. Furthermore, the telemetry cardiac arrhythmia detection system (for example Agilent) is expensive and limited in space because in general, it is only installed at the cardiology department of a hospital.

Therefore, it is very important to propose a new method permitting to improve the efficiency and the accuracy of the cardiac arrhythmia diagnostic which is not limited in time and in space like the previous ones. Furthermore, the comfort of the patient has to be taken into account by allowing the patient to live normally and stay at home. All cardiac rhythm disturbances will be recorded and analysed continuously and automatically in real-time and, according to the gravity of the symptom, an emergency message may be sent to a remote server. The cardiologist can confirm or reject the emergency message by analysing the sequence of ECG signals included in the emergency message. If necessary, he can also remotely analyse in real-time the patient ECG signals.

In fact, we believe that such a platform is able to improve the result of the prediction and the diagnostic for the patient having cardiac arrhythmias, because it is not limited in time and in space. Moreover, the patient feels easy and more secure at home. When a high risk of death patient is definitely identified an ICD will be proposed. Finally, the platform is able to monitor a large number of patients at home.

This paper is organized as follows. In section II the system elements and operation modes of the platform are described. Section III presents the key techniques of the platform. Finally in section IV, performance test and evolution, the conclusion and the ongoing work are presented.

2. Overview of Platform

Our main objective is the development of a platform adapted to telemedicine applications especially to real-time remote continuous cardiac arrhythmias detection and monitoring. The platform integrates the advanced wireless telecommunication technology such as WiFi, Bluetooth, GSM and UMTS and the distributed embedded real-time intelligent sensors communicating over Internet.

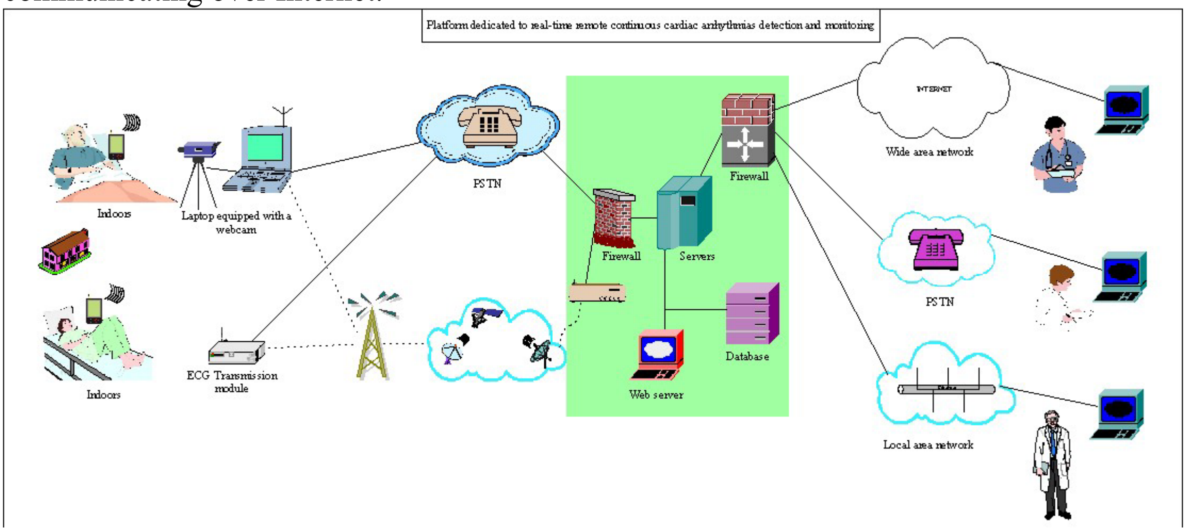

Figure 1 - Platform dedicated to real-time remote continuous cardiac arrhythmias detection and monitoring

2.1 Platform elements

The platform structure shown in figure 1 comprises two parts: a local system and a remote system, which contains 4 main configurable elements. The local system has a wireless ECG sensor (WES) and a local server, and the remote system includes a remote server and a remote surveillance system (Diagnosis and visualization).

Figure 2.a - Wireless ECG Sensor

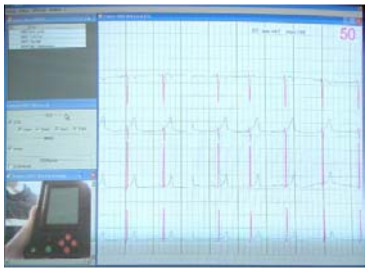

Figure 2.b - Remote surveillance server

2.1.1 WES

To realise a low cost, low energy consuming and compact wireless ECG sensor (WES) responding to the last AHA recommendations [6], the embedded basic technologies such as distributed real-time fault tolerant micro kernel [3, 4], dedicated hardware and firmware [12] and real-time TCP/IP protocol stack [1, 4] are implemented in the WES.

The wireless ECG sensor prototype (figure 2-a) is a real-time wireless embedded portable sensor (size=70*100mm) based on the Texas Instruments ultra low power micro-controller MSP430 [13] corresponding to the recommendations of AHA [6]. The sensor without wireless adapter consumes only 10mA. The key features of the WES are:

- Gain: 1000
- CMMR(min): 120dB
- Bandwidth: 0.05Hz to 125Hz
- Programmable sample frequency more than 500Hz
- Analogue to digital converter: 12 bits
- Leakage current: 10µA.

The WES enables to capture 4 leads ECG signals sampled at 500Hz in real-time (The sample frequency is reprogrammable). These sample signals are sent simultaneously to the local server over wireless medium such as WiFi or Bluetooth. In off-line mode, ECG signals will be stored into a flash memory of the WES. The duration of the ECG records depends on the capacity of the flash memory card, the sample frequency and the number of ECG leads. The two latter parameters may be configured by the user. For example, 128M flash memory card can store 24h continuously 4 leads ECG signals sampled at 500Hz. In this way, the WES works as a HOLTER or a RTEST.

2.1.2 Local server

The local access server that may be implemented by a standard PC or a mobile phone or a dedicated network access medium, provides two network medium access services: wireless connection with the WES by wireless medium (WiFi or Bluetooth), and network connection with the remote system by multi-support network access mediums.

The different access mediums that patients can use are: Modem, broadband, wireless and satellite connections. The network bandwidth of the access mediums is fluctuated in time because it is affected by various disturbance factors [20]. Therefore, the remote system must be adaptable to meet various network access medium bandwidths and local server performance. So, in accordance with the network access medium and local server resources, local peer can be configured to provide real-time ECG signals and patient‘s image transmission and diagnosis. Otherwise, if the local server is a mobile phone, only short high level alarm message is sent to the remote server. Thus, the local server may be configured to support 4 different operation modes (section 3).

For 4 leads ECG signals sampled at 500Hz, a 5 seconds frame contains 20,000 bytes of ECG signal data (4 leads x 500Hz x 5s x 2 bytes). The fluctuation of 56Kbps MODEM bandwidth does not allow real-time continuous transmission of ECG data. So, it is important to minimize the amount of transmission data to reduce network traffic load. A no loss ECG signal compression algorithm is implemented by taking into account the resolution of ADC 'Analogue to Digital Converter' of the WES and the type of ECG signals. The compression ratio can attain 50~60%, so only 8000~10,000 bytes of data are transmitted. Furthermore, if ECG signals diagnosis is performed by the local server, only 25% of ECG signals raw data (2000~2500 bytes per frame of 5s) are really transmitted to the remote server for its display. In fact, the ECG signals sampled at 125Hz are acceptable for its visualisation.

Depending on the network traffic, the patient's images captured from a webcam connected to the local server are used to confirm the emergency state and remote diagnosis. In fact, in spite of the advance of the techniques used to detect cardiac arrhythmias, currently the accuracy of the results is around 90% [5, 7, 8, 9, 10]. Consequently, 10% of emergency messages are false and it will be hard to manage the first aid. Therefore, for real-time remote assistance and surveillance, the patient images are absolutely essential.

2.1.3 Remote server

The remote server provides network connection and patient database management. Thus the remote server is composed of three servers: PPP server, WAP server and database server. The PPP server allows the patient to connect to the remote server through a traditional Public Switched Telephone Network (PSTN). The PPP server supports different PSTN medium bandwidth: 56Kbps (standard Modem), 512Kbps and 1Mbps (ADSL). The WAP provides seamless network connection over wireless mobile communication network and it tunes automatically to the available medium bandwidth: GSM (9,6Kbps) and GPRS (115Kbps). Moreover, in case of limited area such as a department of a hospital, the local servers and the remote server may be configured to operate with the Ethernet LAN.

The database server stores patients' ECG signals sequence, patient' ECG diagnostic reports, patients' images, and patients' profile and account information. Thus, at all times, the physician can visualize the status of a patient and he can remotely reconfigure the function mode of the local system.

2.1.4 Remote surveillance system

The remote surveillance system contains a visualization surveillance platform and a background real-time communication system.

In order to improve the efficiency of data transmission, an adaptive communication protocol with acknowledgment is implemented over UDP protocol (User Datagram Protocol offering non-guaranteed datagram delivery) to deliver ECG signals. As we state previously, ECG signals are compressed before sending to the remote system (each frame is a window of 5 seconds ECG signals). So, the received ECG signals will be decompressed and stored into data frame list and be displayed after 25~30 seconds delay (5~6 data frames). The data buffering and delay are necessary to guaranty the real-time continuous display of ECG signals.

Furthermore, compared with image data used to confirm diagnosis results, ECG data is higher priority level of transmission. Thus, if the network traffic is heavy, the remote server will request the patient peer (local server) to stop or reduce image transmission. Finally, in order to guarantee the security of data transmission, a private key of 64 bits length is used to perform encryption and decryption of all patient's data.

The interactive visualization surveillance platform (fig. 2b) enables to display continuous ECG signals sequence and patients' image, to respond to various alarm messages, and to support real-time or on-line diagnosis. The 4 leads ECG signals and its diagnosis results can be recorded into local data files in the format of WFDB [14]. It is to be noted that the interactive visualization system provides the same GUI as today available commercial devices (Agilent telemetry system, ELA etc.)

2.2 Operation modes

This platform enables 4 operation modes in order to adapt to different application environments and requirements. The operation mode is decided by the physician by taking into account the patient's physical status and network medium access bandwidth. The key features of the 4 operation are as follow:

1. **Level 1:** Real-time *continuous ECG signal*. For the sake of remote real-time displaying and diagnosing, the data including continuous ECG signals acquisition and its detection report will be sent in real-time to remote system. This operation mode is the highest alarm level enables real-time on-line diagnosis. This mode is not appropriated to monitor large number of patients due to the limitations of network bandwidth, system resources and human resources but it is necessary to monitor high risk of sudden death patient. In practice, each physician can survey approximately 4 patients. In this level, to assure reliable cardiac arrhythmias diagnosis, patient's image may be required.
2. **Level 2:** *ECG signal sequence*. In order to satisfy remote real-time multi-patients detection and monitoring, the WES is configured to send automatically a sequence of ECG signals (pre- and post- abnormality) to the remote system when a cardiac arrhythmia event defined by the cardiologist is detected. This operation mode is suitable for long-term multi-patients (lower risk of sudden death than the previous class of patients) cardiac arrhythmias events surveillance.
3. **Level 3**: *textual emergency message.* In this mode, only a short textual emergency message will be sent to physician when a cardiac arrhythmia event is detected. According to the gravity of the symptom the physician can decide to intervene immediately or later. This mode may be operated on any access medium (wire or wireless).
4. **Level 4**: *diagnosis report email*. It's the lowest level operation mode. The local server will send periodically a report (like HOLTER report) attached to an email to the remote server. The period is defined by the physician. This mode is suitable to monitor a large number of patients.

   It is to be noted that, the physician can remotely reconfigure the operation mode to adapt to the evolution of the patient's status.

3. Technological Overview

In terms of software development, the platform contains 4 main configurable modules. The 4 modules are configurable and loaded to implement an application tuning with system resources to meet users' requirements.

ECG acquisition module: The WES enables to capture 4 leads ECG signals sampled at 500Hz in real-time. The sample frequency and the lead numbers are programmable to meet users' requirements. The raw digital input ECG signals are filtered by a band pass (0.05Hz, 125Hz) and a notch (50Hz). Furthermore, in order to satisfy real-time multi-processes operation, an adaptable embedded real-time micro kernel is integrated into the WES.

ECG diagnosis module: Another key feature of this platform is real-time effective ECG detection and diagnosis algorithm. This algorithm can automatically diagnose in real-time tachycardia ventricular (TV), brachycardia ventricular (BV) and fibrillation ventricular (FV) and other anomalies. Moreover, the algorithm is developed to ease its VLSI implementation.

Embedded real-time communication module: The platform provides an embedded real-time TCP/IP stack to supply network function for the WES. This minimization TCP/IP stack contains essential real-time communication elements that support following protocols: TCP, UDP/IP, ICMP and PPP. It also provides remote surveillance functions for system management on SNMP standard and PING service.

Telemedicine communication module: A reliable and effective remote network communication is the main foundation of telemedicine. The telemedicine communication module provides a high layer adaptive communication protocol permitting to overcome network access medium bandwidth fluctuation. Moreover, a compression algorithm is implemented to reduce network traffic. Because of the different priority levels between ECG and image data, a competition algorithm is designed to ensure real-time transmission of ECG signals.

The telemedicine communication module ensures data reliability, network security and peer to peer quality service.

4. Conclusion and ongoing work

Currently, the platform dedicated to the real-time remote continuous cardiac arrhythmias detection is evaluated on about 10 patients at the C.H.U. of the Gabriel Montpied hospital in Clermont-Ferrand (France). The detection algorithms were also evaluated by using MIT-BIH data base [14]. Concerning VT and ESV, the detection rate is about 96% on the patients. It is to be noted that, the quality of the ECG signal of our platform is better than the HP telemetry system one.

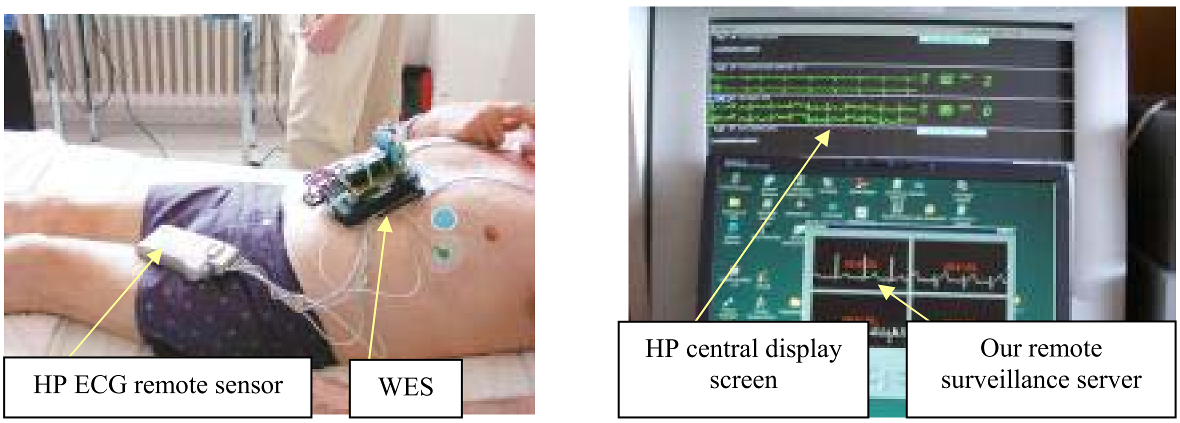

Figure 3 - Test and evaluation at the Gabriel Montpied's hospital in Clermont-Ferrand

Our platform allows continuous remote cardiac arrhythmias monitoring and permits the patient to lead a normal life indoors and outdoors thus it is more efficient to diagnose cardiac arrhythmias.

The results of the test and evaluation until now are satisfactory. We believe that such a platform enables a new clinical approach to evaluate more accurately a large number of the high risk of sudden death patients. Furthermore, it may be used by the cardiologist to remotely monitor and evaluate the efficiency of the drug or to discuss a difficult cardiac pathology with other colleagues.

We are working on the implementation of Intelligent Wireless ECG Sensor (IWES) by integrating the cardiac arrhythmia detection algorithm on a chip (ICAC). The ICAC is currently under evaluation and test on an FPGA. Thus the new platform contains a set of IWES and a remote server and it will be more reliable and friendly used. With the IWES, when the patient leaves home (outdoors), the wireless communication is out of range so the IWES is automatically disconnected to the remote server. Thus, when the cardiac rhythm disturbances are detected and the ECG signals are recorded locally in the Multimedia flash card. Therefore only the highest emergency short message will be sent to the remote WAP server through mobile phone (SMS). The emergency message may be defined by the cardiologist according to the physical state of the patient. In fact, periodically the IWES tries to connect to the remote server, if the connection is established a cardiac rhythm disturbance report or all the recorded events may be sent to the remote server.

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