A Health Monitoring System Using Smart Phones and Wearable Sensors

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Abstract— This paper describes work in progress regarding personalized heart monitoring using smart phones. Our research combines ubiquitous computing with mobile health technology. We use wireless sensors and smart phones to monitor the wellbeing of high risk cardiac patients. The smart phone analyses in real-time the ECG data and determines whether the person needs external help. Depending on the situation the smart phone can automatically alert pre assigned caregivers or call the ambulance. It is also used to give advice (e.g. exercise more) or to reassure the patient based on the sensors and environmental data.

1. INTRODUCTION

The estimated direct and indirect cost of cardiovascular diseases in the United States alone is $393.5 billion for 2005 according to [1]. Statistics indicate that approximately $4 billion of unnecessary medical costs are spent each year on the assessment of non-cardiac cases in hospital emergency departments.

To reduce these costs and the anxiety of people with known cardiovascular problems we propose a portable monitoring system that monitors the heart and notifies the person or external party in case of abnormalities. Our monitoring system is meant for patients that have a known cardiovascular disease and need to be monitored around the clock.

Traditional heart monitoring solutions exist for many years such as the Holter device which records the patient's ECG for 24 to 48 hours and is then analysed afterwards by the cardiologist. The patient can 'wear' the device and go home and resume his/her normal activities. The main drawback of these solutions is when a major incident occurs during the monitoring phase. It is recorded but no immediate action is taken to help the user. Other solutions have been introduced that address this problem and J. Rodriguez et al have classified these solutions in two groups [2]:

The first group uses smart phones (or PDAs) equipped with biosensors that record the heart signals and transmit them to a healthcare center or hospital for analysis. Some solutions can store the signals locally as well. Examples include Alive technology [3], Vitaphone [4], Ventracor pocketview [5] or Welch Allyn Micropaq [6]. Most are capable of recording, viewing and storing ECGs directly on the smart phone. Some solutions transmit the stored ECG to the healthcare center using wireless technologies (e.g. GPRS).

The second group aims at building platforms for real-time remote health monitoring. Examples are Mobihealth [7], Telemedicare[8], Osiris-SE[9] and PhMon[10]. These solutions use (wearable) wireless sensors to monitor patient's vital signs (e.g. ECG, oximeter, blood pressure). The European project Myheart [11] develops such a platform and focuses on heart patients. Myheart aims at designing intelligent biomedical clothes for monitoring, diagnosing and treatment. The platform developed by this second group collects the bio data and sends it to a care center or a hospital for processing and analysis. None of these solutions process the ECG data locally on the smart phone, and the ECG signals need to be continuously transferred to a health center if the patient needs to be monitored 24/7. This can be costly when GPRS is used for transmitting the data. To deal with this issue several research projects consider processing the ECG data on a local device. Example projects are Amon, Epimedic and Molec.

AMON [12] is a wrist-worn medical monitoring and alert system targeting high-risk cardiac and respiratory patients. The system includes continuous collection and evaluation of several vital signs, smart medical emergency detection, and is connected to a medical center. For heart monitoring, they are technically limited by the fact the device is worn on the wrist and therefore the ECG signal is very noisy and not suitable to diagnose cardiac abnormalities.

The Epi-medics project [13] defines an intelligent ECG monitor which can record, analyse ECG signals and other sensor information and can generate alarms. It can also be personalized but it is not a device meant to monitor the patient 24/7. The patient connects to the 12 lead monitor periodically as directed by the heart specialist or when he/she doesn't feel well.

MOLEC [2] provides a solution that analyses the ECG locally on a PDA. It generates alarms to the hospital in case of high risk arrhythmias.

Our objective is to investigate and develop an application whereby a heart patient is monitored using various types of sensors (ECG, accelerometer, oximeter, weight scale, blood pressure monitor). The sensor information is collected and transferred wirelessly to a smart phone. Our solution analyses the ECG and other sensor data on the local device. One distinction of our solution compared to the others is that we can personalise the monitoring and we have mechanisms in place to locate the user in case of emergency whether the patient is indoors or outdoors. We detect life threatening arrhythmias and give the patient general information about their health when they are not in a dangerous situation. We can also store extra information for further use by the health providers.

This paper is organised as follows: section 2 discusses the overall architecture whereas section 3 focuses on the implementation of our personalized heart monitoring system. Finally, section 4 concludes this paper.

2. ARCHITECTURE

Figure 1 shows an overview of our heart monitoring architecture.

The heart patient has one or more sensors (e.g. ECG and accelerometer) attached to his/her body. External devices are used, such as a blood pressure monitor or weight scale, to collect periodically additional health data. We use off the shelf sensors enabling us to incorporate the best technology as they appear on

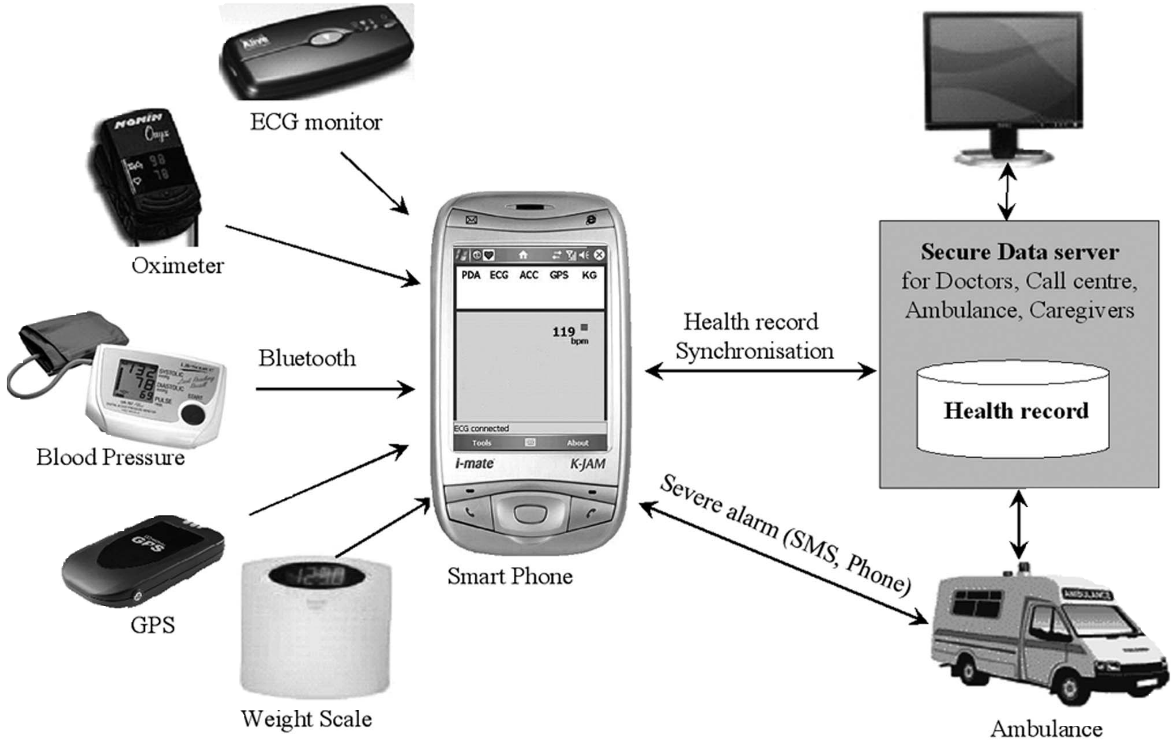


Fig. 1 –Personalized Heart monitoring architecture

the market. The sensors are Bluetooth enabled or integrated into the smart phone (e.g. GPS). The smart phone processes the sensor data and monitors the patient's wellbeing, and in case of an emergency, it automatically calls an ambulance to the location of the patient. It can also warn caregivers or family members via SMS or phone when the patient is in difficulty.

The data collected by the smart phone can be transmitted to the health care Data server via the internet. A patient can upload the data whenever the smart phone is connected to the internet via the desktop cradle/charger or wirelessly. This is a cost efficient way to upload data which is not time critical. However, in case of an emergency, updates are immediately transferred to the Data server using the best available connection (e.g. GPRS). The specialist can access the Data server via a secure internet connection to remotely monitor the patient and if necessary update the threshold levels for the sensors. Relevant sensor data is stored in the patient's health record and can be used for further analysis.

2.1. Sensors

Data from each sensor is collected and processed in the smart phone to establish a diagnosis. For high risk cardiac patients the ECG signal is the obvious data that needs to be collected continuously and should be given priority over all other sensor data. It is also important to store the ECG signal for further analysis by the cardiologist.

Detecting falls using an accelerometer is another important indication that something is wrong with the patient. Using an accelerometer and other contextual information, we can also evaluate the level of activity of the heart patient. We assess this against the heart specialist's personalized guideline and either congratulate the patient for reaching his/her goal or encourage them to exercise a bit more. The level of physical activity recommended for a heart patient depends on his/her condition and health history. National Heart Foundation of Australia [14] says that physical exercise improves the live expectancy of heart patients and they set guidelines to help heart specialists in setting a personalized level of activity for their patients.

We use an integrated Bluetooth ECG/Accelerometer sensor from Alive Technologies [3]. We selected this sensor since it has been demonstrated that it provides reasonably good signals for detecting normal or abnormal rhythms (arrhythmias). The Alive accelerometer has been used during a study of stroke patients at the Prince Charles Hospital (Australia) and can successfully detect falls [15]. The sensor is small (match box size) and can be easily worn without being noticed by other people.

Fig. 2 A&D blood pressure monitor and Alive ECG/Accelerometer monitor

We also use a Bluetooth enabled blood pressure monitor and weight scale from A&D Medical [16]. High blood pressure is another important risk factor for developing cardiovascular diseases [1] and regular monitoring is essential. Being overweight or obese can contribute to developing cardiovascular diseases and for some heart patients monitoring their weight is important.

Finally to accurately obtain the location of a patient in case of an emergency a GPS sensor is used. However, GPS does not work indoors and we need to complement it with other location sensors such as the GSM Cell ID or WiFi access point locations. With GSM Cell IDs and WiFi access points we are able to provide a rough indication of the location of the patient as described in [17].

2.2. Smart phone functionalities

The application in the smart phone receives the results from the sensors and determines whether an alarm should be raised. The results of the sensors can be inaccurate due to noise and inaccurate readings. The monitoring system is only useful if we know the quality of the data we receive from the various sensors and the quality of the diagnosis based on that data. Knowing the quality level we can put mechanisms in place to compensate for the lack of accuracy of certain sensors or get feedback from the patient to confirm a diagnosis.

The application will therefore access the results of the sensors and if a threshold level has been reached the application needs to crosscheck whether the patient is in danger to avoid raising false alarms. In the current implementation we collect additional data from the sensor(s) and if we still measure a life threatening situation the application will seek confirmation from the user. The user can disable the alarm in case of a false alarm. If the user does not react within a certain time (currently 30 seconds) an emergency call is automatically placed. This feature is included since many patients black out or experience speech and swallowing difficulties at the time of a heart attack [1].

Since our target group will be mainly elderly people, the interaction with the monitoring application needs to be simple, personalised and adapted to the user's health condition. For example we need voice interaction in case the patient has bad eyesight or vibration and flashing lights for hearing impaired patients.

Furthermore, it is important to provide accurate but yet non-overwhelming information to the patient since we do not want to cause extra anxiety which would make the situation worse. For this reason we do not show an ECG diagram to a patient since we learned from discussions with cardiologists that this is a major source of anxiety for cardiac patients.

The smart phone application stores configuration data and sensor readings in a local database. Depending on the patient, the specialist can configure one or more sensors to be used to monitor the patient. The configuration section is password protected and is only accessible by a medical specialist. The specialist determines which sensors should be used and configures the monitoring frequency and threshold levels for each sensor. For example some cardiac patients need to monitor their glucose level, whereas others need to monitor their weight and blood pressure. Also threshold levels for raising an alarm differ depending on the patient's age and condition.

3. PROTOTYPE

We developed the application on Microsoft's Windows Mobile 5.0 Pocket PC platform using Microsoft Visual Studio 2005. We selected this platform due to easy access to lower level APIs which are needed for the sensor modules. Also the tight integration with the operating system allows easier access to other applications running on the smart phone such as the calendar application, WiFi and obtaining the GSM Cell ID. We used the .Net Compact Framework 2.0 extended with OpenNETCF [18] modules to develop the application. Data is stored in an SQL CE Server which is a compact database for mobile devices. For the smart phone we use the i-mate® K-JAM manufactured by HTC.

3.1. Heart monitoring

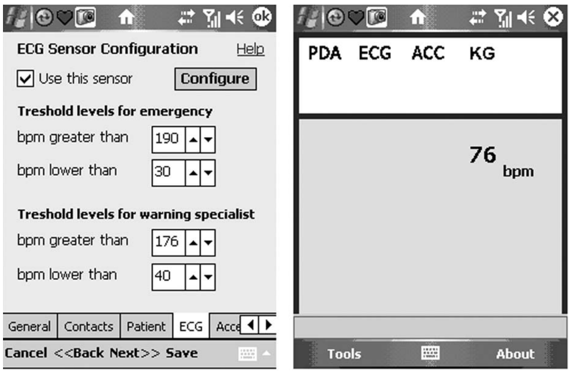
The ECG sensor is the most crucial component of our architecture. ECG signals can be a source of errors which makes it hard to interpret arrhythmia correctly. In our prototype we work with a single channel, two electrodes ECG sensor. Noise, interference and non-rest conditions of the patient can contaminate the signal. This implies that we focus on extreme ECG signals.

In the first stage of the prototype we focus on two life threatening arrhythmias: Ventricular Fibrillation (VF) and Ventricular Tachycardia (VT). VF is a lethal arrhythmia characterized by rapid, chaotic movements of the heart muscle that causes the heart to stop functioning and leads quickly to cardiac arrest. VT is an abnormal heart beat usually to a rate of 150-200 beats per minute. VT may result in fainting, low blood pressure, shock, or even sudden death. To detect these arrhythmias we have implemented a beat detection and classifier algorithm as well as a VT/VF detection algorithm for the smart phone.

For the patient to have a chance to survive VT/VF, a defibrillator should be applied within 5 minutes. Our system detects a VT/VF onset and alerts emergency services/caregivers/bystanders within 30 seconds. It therefore increases the chance that help can be given in time.

We used the open source heart beat detector and classifier developed by Hamilton [19], which is based on the algorithms developed by Pan & Tompkins [20]. The original open source implementation is in C and we ported it to C# for easy integration with the other C# software modules.

The heart beat detector and classifier is able to detect and classify a heartbeat as Normal, PVC (Premature Ventricular Complexes - extra heartbeats) or Unknown. PVCs are often harmless, but when they occur very often or repetitively, they can lead to more serious rhythm disturbances [21]. We also calculate the heartbeat rate which will be checked against the threshold levels set by the cardiologist for the patient. If the rate is too slow or too fast, the application will inform the user. If we deal with a PVC or unknown beat we record the ECG and check it for a VT/VF rhythm. We used the algorithm as detailed in [22]. If the algorithm detects either a VT or VF signal the emergency procedure is started.


ECG Sensor Configuration

☑ Use this sensor

Treshold levels for emergency

bpm greater than 190

bpm lower than 30

Treshold levels for warning specialist

bpm greater than 176

bpm lower than 40

PDA ECG ACC KG

76 bpm

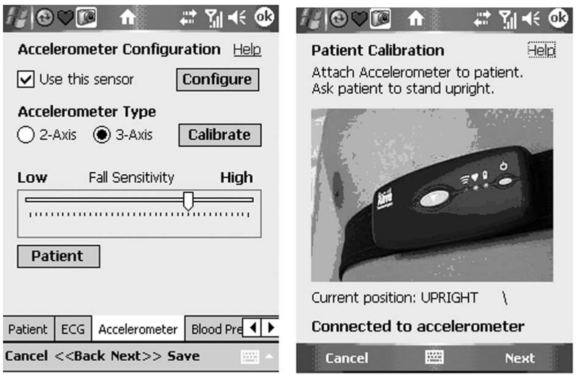
Fig. 3 ECG configuration and real-time monitoring

The heart beat detector and classifier has a sensitivity value of 99.42% and a positive predictive value of 99.51% when tested against the MIT/BIH Arrhythmia records [23]. This is a high level of accuracy and the algorithm is also capable of processing the live ECG data in real-time on the smart phone. Detailed description of the performance of the heart beat detector and classifier can be found in [24].

Figure 3 shows how the ECG sensor can be configured and a normal screen showing only the beats per minute.

3.2. Fall detection

Accelerometers are widely used to monitor human body activity. We implemented an algorithm developed by Brown [25]. This algorithm uses a state-machine that analyses data from a 3-axis accelerometer worn on a waist belt.


Accelerometer Configuration

☑ Use this sensor

Accelerometer Type

○ 2-Axis ● 3-Axis

Patient Calibration

Attach Accelerometer to patient.
Ask patient to stand upright.

Current position: UPRIGHT

Connected to accelerometer

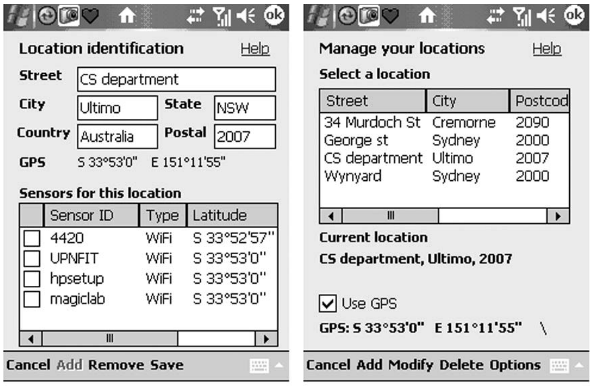
Fig. 4 Accelerometer configuration and calibration

The algorithm focuses on large accelerations and the user's upper body position. After a large acceleration the user's position is analysed. A fall is detected when the user's position is horizontal or not upright after some period of inactivity. An acceleration is not classified as a fall when the position is upright or the accelerometer detects activity. Based on Brown's testing (123 falls and 36 non falls), the algorithm is able to detect around 90% of all the falls along with 5% of false positives. The accelerometer sensitivity can be adjusted to the person's movement characteristics (Figure 4). High fall sensitivity implies that the algorithm classifies an acceleration faster as a fall compared to a low sensitivity level.

In order to accurately detect a fall we need to calibrate the accelerometer. When a patient has attached the monitor to the body he/she will be asked to stand upright. This will set the accelerometer to the upright position and after an acceleration the algorithm can determine whether a fall has occurred based on the current position of the patient (e.g. horizontal, bent down).

3.3. Location detection

We can use GPS to determine the location of a patient in case of an emergency. However GPS is only useful outdoors and in clear sight of GPS satellites. Many heart patients will spend most of their time indoors and in order to automatically determine the location we use WiFi and GSM as a means to determine the location. Since GSM Cell id and WiFi access points are not automatically related to a location, the user has to 'relate' a particular location with the WiFi/GSM Cell data.


Location identification

Street CS department

City Ultimo State NSW

Country Australia Postal 2007

GPS S 33°53'0" E 151°11'55"

Sensors for this location

	Sensor ID	Type	Latitude
☐	4420	WiFi	S 33°52'57"
☐	UPNFIT	WiFi	S 33°53'0"
☐	hpsetup	WiFi	S 33°53'0"
☐	magiclab	WiFi	S 33°53'0"

Manage your locations

Select a location

Street	City	Postcod
34 Murdoch St	Cremorne	2090
George st	Sydney	2000
CS department	Ultimo	2007
Wynyard	Sydney	2000

Current location

CS department, Ultimo, 2007

☑ Use GPS

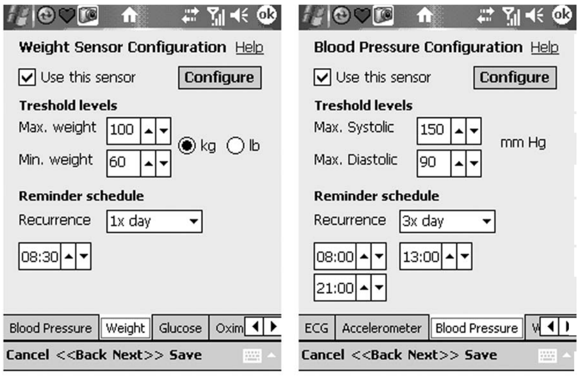
GPS: S 33°53'0" E 151°11'55"

Fig. 5 Location identification

Figure 5 shows how a user can automatically spot WiFi access points and GSM Cells and assign these to a particular address. If GPS is available the longitude/latitude coordinates are also assigned to the address. When an alarm is raised the application will automatically start sensing the environment for WiFi access points and GSM Cells. If a match is found, the related address will be used as the current location of a patient. For this scenario to work, the user needs to sense and input the addresses where he/she is normally staying.

3.4. Personalisation

The specialist can activate one or more sensors for a particular patient. Figure 6 shows how the weight and blood pressure can be configured. The specialist determines how often a patient should take a particular measurement which can vary from once a week to several times a day.

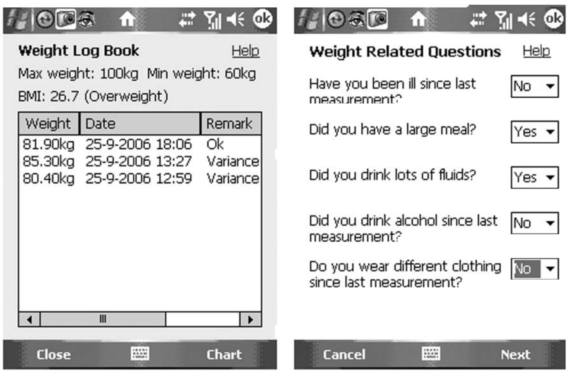


Weight Sensor Configuration
☑ Use this sensor
Treshold levels
Max. weight 100
Min. weight 60
● kg ○ lb
Reminder schedule
Recurrence 1x day
08:30

Blood Pressure Configuration
☑ Use this sensor
Treshold levels
Max. Systolic 150
Max. Diastolic 90
mm Hg
Reminder schedule
Recurrence 3x day
08:00
13:00
21:00

Fig. 6 Weight and blood pressure configuration

A patient will automatically be reminded by the smart phone to take a measurement and a monitor application is activated automatically to collect the data from the weight scale or blood pressure monitor. The patient can also track all the measurements in a weight or blood pressure log book (Figure 7).



Weight Log Book
Max weight: 100kg Min weight: 60kg
BMI: 26.7 (Overweight)

Weight	Date	Remark
81.90kg	25-9-2006 18:06	Ok
85.30kg	25-9-2006 13:27	Variance
80.40kg	25-9-2006 12:59	Variance

Weight Related Questions

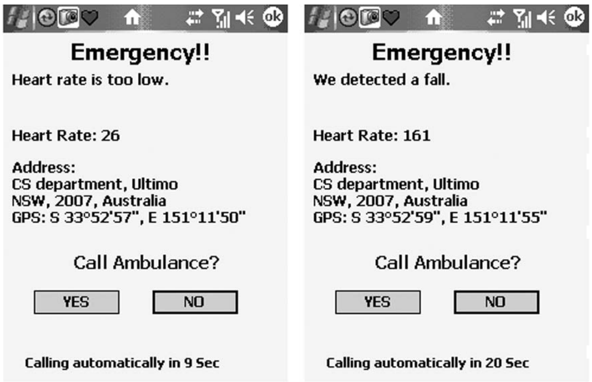
Have you been ill since last measurement?	No
Did you have a large meal?	Yes
Did you drink lots of fluids?	Yes
Did you drink alcohol since last measurement?	No
Do you wear different clothing since last measurement?	No

Fig. 7 Weight log book and weight related questions

Based on the threshold levels set by the specialist the patient can monitor his or her progress. If a measurement differs too much from a previous measurement the application will ask the user to redo the measurement. The application will ask the user to answer several questions in case the second measurement still varies too much (Figure 7). The answers will help the specialist to analyse why the measurement varies too much.

3.5. Emergency procedure

In case of an emergency the application shows the alarm screen and plays a loud recorded message notifying the user. The user can disable the alarm in case of a false alarm (Figure 8). Otherwise a first aid message is played continuously on the smart phone instructing (potential) bystanders what to do in case the patient is unable to speak. Simultaneously an emergency call is placed automatically by the application.



Emergency!!
Heart rate is too low.

Heart Rate: 26

Address:
CS department, Ultimo
NSW, 2007, Australia
GPS: S 33°52'57", E 151°11'50"

Call Ambulance?

Calling automatically in 9 Sec

Emergency!!
We detected a fall.

Heart Rate: 161

Address:
CS department, Ultimo
NSW, 2007, Australia
GPS: S 33°52'59", E 151°11'55"

Call Ambulance?

Calling automatically in 20 Sec

Fig. 8 Emergency

3.6. Current status

The components described in this section are fully functional. For the heart monitoring, we are now focussing on improving the VT/VF algorithm to increase the sensitivity and specificity levels as well as developing smarter algorithms to detect early signs leading to a heart attack. For fall detection, we are investigating the use of two-way audio webcams to confirm the fall and being able to interact with the patient while at home.

4. CONCLUSION

This paper described a personalized health monitoring application using a smart phone and wireless (wearable) sensors. We are able to detect life threatening arrhythmias locally on the smart phone and, if the patient is in danger, we can contact an ambulance automatically. In normal situations, our system monitors and records the sensor data for inclusion in the patient health record which is used for further analysis by a specialist.

Our system is designed with personalisation in mind. The heart specialist can select one or more sensors to be used for a particular patient and configure the corresponding threshold levels for that patient. Our application generates alarms or warnings when thresholds have been reached.

We process ECG and other sensor data locally on the smart phone, therefore we are able to supervise a patient without being continuously connected to a health-centre. This reduces the workload of medical staff, communication costs and motivates the patient's self-care.

Our solution is meant to monitor the patient continuously and an issue is the battery life of the used devices. The ECG sensor battery lasts for approx 60 hours. The smart phone's battery only lasts for approx eight hours when continuously connected to the ECG Bluetooth device which can be an issue if the wearer is not close to the charger (less than 10 meters). However studies show that a lot of heart patients are sedentary and can therefore charge the smart phone while being monitored.

Our target audience is patients that have had a heart attack, or are at high risk. We learned from discussions with cardiologists that these patients are worried that a heart attack will occur again. They are very motivated to wear a device that can monitor and reassure them and intrusiveness seems not to be an issue for these patients.

We believe that our system is a step towards promoting patient's autonomy and by providing personalized monitoring and advice we hope that it will give the patients more confidence and improve their quality of life.

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