Epilepsy Seizure Detection App for Wearable Technologies

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Abstract – For people who are suffering from epilepsy (both diurnal and nocturnal) it is essential to have a system that can detect and alarm seizures in real-time. In this paper, we present a preclinical demonstrator for real-time detection of seizures based on heart rate. The system consists of a body hub (a smart phone having Bluetooth Low Energy and Android Operating System) and a MIO Alpha Watch which are connected via Bluetooth. The seizure detection application running on the body hub is using the output value of the heart rate to classify the data from the MIO Alpha. It can generate a local alarm followed by sending an SMS message when a seizure has been detected. The user has the possibility to set the alarm threshold for the absolute level of the heart rate, the temporal variation in the heart rate and to choose where to send the SMS. In addition, the application detects when the system is disconnected or when the sensor is not in contact with the skin. The preliminary results are encouraging and the application is available for the public.

1 INTRODUCTION

About 65 million people all over the world are suffering from epilepsy which is a group of long-term neurological disorders with an estimated prevalence of 5.8 out of 1000 [1]. Most people can be successfully treated with medication, although this is not possible in 20-40% because of resistance to medication [2], [3], [4], [5]. For a small proportion surgery can successfully be used, but 25% is not seizure-free after the surgery with the current medical technology [6] and suffer from refractory epilepsy. Some of these patients cannot take care of themselves and they have to be nursed at home or need attention of medical personnel.

Despite all medical effort and progress, epilepsy is dramatically affecting the life of patients and their families. Not knowing when the next seizure will occur and how severe it will be is the main source of anxiety for these people. This fact is aggravated by the prospect of SUDEP (Sudden Unexpected Death in Epilepsy) [7] which is a fatal complication of epilepsy. It is the most common cause of death among people with epilepsy. Arrhythmia (tachycardia or bradycardia) [8] is a condition which is observed in most cases of epilepsy and it can lead to SUDEP.

Moreover, the possibility of a seizure to be missed by the caregiver during night is high and people need a system for seizure monitoring in these cases. The most common and used systems for ambulatory monitoring of epilepsy are based on motion and sweat [9], [10]. These devices showed positive results but they have many limitations. They detect seizures with high motor activity and perspiration levels, but seizures without motion go undetected.

On the other hand, the heart rate (HR) can be a better parameter to monitor epilepsy. Seizures typically activate sympathetic nervous activity, increasing the heart rate and blood pressure [11]. Furthermore, tachycardia occurs in more than 80% of seizures [12]. During a seizure, heart rate can increase by 30% compared to baseline [13]. In addition, the heart rate can provide information on eventual complications such as bradycardia (low heart rate, $HR < 60$). Therefore a heart rate monitoring system for epilepsy can have more advantages than traditional ones based on accelerometry.

However, nowadays there are no user friendly devices to monitor the heart rate in ambulatory monitoring for epilepsy. Most of these systems are using electrodes which may not be appropriate for long-term monitoring, because the wires can break, or electrodes can fall off, or cause skin irritation.

Monitoring heart rate in real-time is required in fitness applications as well. Athletes require precise measurement of their heart rate to tune their training regimes [14]. Different heart rate regimes are an indicator of aerobic or anaerobic metabolism. For this purpose many companies developed non-invasive heart rate monitoring devices such as the Polar Heart Rate belt (`www.polar.com`), the MIO Alpha watch (`www.mioglobal.com`), or Basis (`www.mybasis.com`). From these devices, watches are friendlier and more suitable for long-term monitoring than the chest belts.

We combined a heart rate monitoring watch with a specific algorithm in an Android app to detect epileptic seizures which result in tachycardia or bradycardia. The resulting app was made for nocturnal monitoring. This is different than the current technologies which are based on an accelerometry sensor embedded in the phone of the user, such as: EpDetect [15] and Seizure Alert and Recorder [16]. These accelerometry-based apps require that the patient wears the phone continuously at the belt region. In the following section we describe the system, algorithm, and its evaluation.

2 MATERIAL and METHODS

2.1 System architecture

The proposed system is a continuation of the work of Ungureanu et al. [17]. In that work they used an ECG sensor connected to an Android phone with Bluetooth 2.1. Here, we used Android devices with BLE (Bluetooth Low Energy) capability combined with a MIO Alpha watch. The MIO Alpha watch directly provides the heart rate and BLE is more efficient and stable than Bluetooth 2.1. The overview of the system with the Seizure Detection and Alarm Generation is shown in Figure 1.

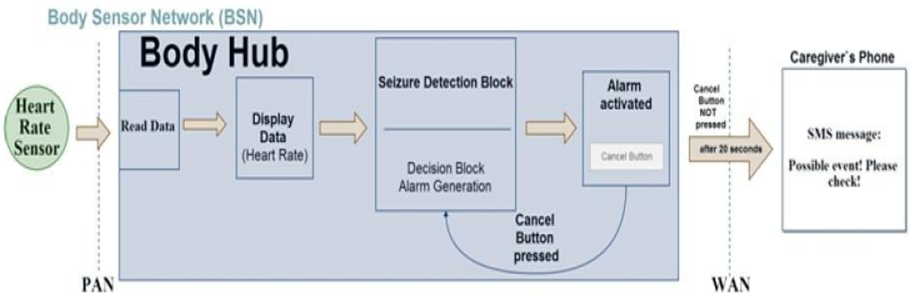

Fig. 1. The system overview with the Seizure Detection and Alarm Generation

The Body Sensor Network (BSN) is composed of a Body Hub (the smart phone) and a Heart Rate Sensor (here the MIO Alpha Watch), which are linked through a Bluetooth (short-range wireless network technology) connection. The heart rate sensor sends the measured heart rate to the Body Hub where it is displayed. In our system, the main purpose is to detect epileptic seizures with tunable parameters on the measured heart rate. The app contains the modules to read and process the incoming HR data as well as to send the alarms via SMS messages.

2.2 MIO Alpha general description

The MIO Alpha is a watch used in fitness applications to measure the heart rate. It uses photoplethysmography to measure the HR (Beats Per Minute (BPM)) via two green LEDs and a photodiode. This device is using BLE which is more energy efficient than the previous Bluetooth versions. The MIO Alpha watch can be attached on the wrist or other locations (forearm or upper arm), see figure 2.

Fig. 2. The MIO ALPHA watch measuring the heart rate, Left, wrist attachment and Right, upper arm.

Electrocardiography (ECG) is the gold standard in HR monitoring. However, photo plethysmography using green light is known to record the heart rate signal as well. During tests made at San Francisco State University in a series of cycling, walking, jogging and running tests, the HR measured with MIO Alpha obtained a 0.99 correlation coefficient with HR obtained from ECG systems [12]. Devices such as the MIO Alpha watch are friendlier

[18] and they can provide comparable accuracies as ECG devices. The sensor does not require sticky electrodes or interfacing substances which can cause skin irritation.

2.3 Seizure detection algorithm

The seizure detection algorithm is simple. It compares the average of the HR in a temporal window with an upper threshold (TH1) and a lower threshold (TH2). The length of the window and TH1 can be set by the user. The standard settings are a temporal window of 10 seconds, an HR upper limit of TH1 = 120 BPM, and an HR lower limit of TH2 = 40 BPM. Each time the phone receives the HR, the value is transferred into a circular buffer of a length set by the user. At every second after the first buffer is filled; the average of the HRs in the buffer is computed and checked against thresholds (TH1 and TH2). The Fig. 3 shows the overview of the seizure detection algorithm.

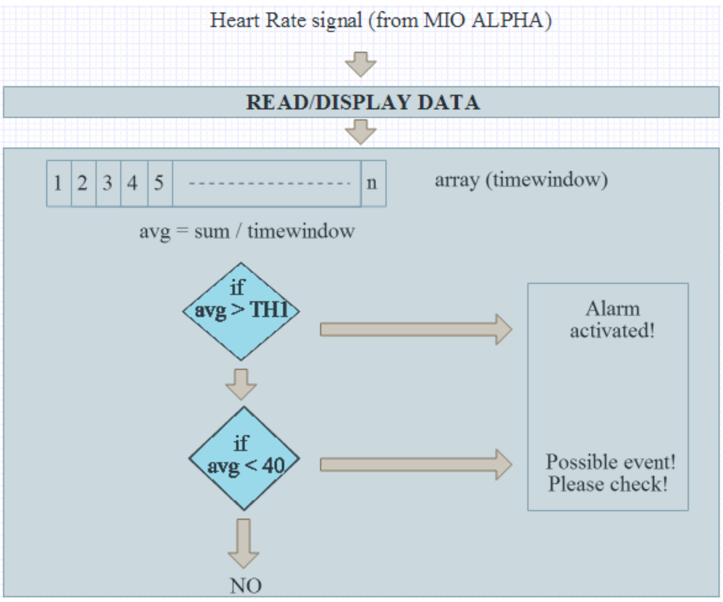

Fig. 3. : Overview of the seizure detection algorithm.

Determining the length of the window and threshold TH1 can be done by consulting a neurologist to maximize the sensitivity and to reduce the number of false positives per patient.

2.4 Correlation between HRs derived from ECG and the MIO Alpha

We tested the accuracy of MiO Alpha by simultaneously recording the HR using the watch connected to a Motorola Moto G phone + Wahoo App and the standard ECG system with electrodes.

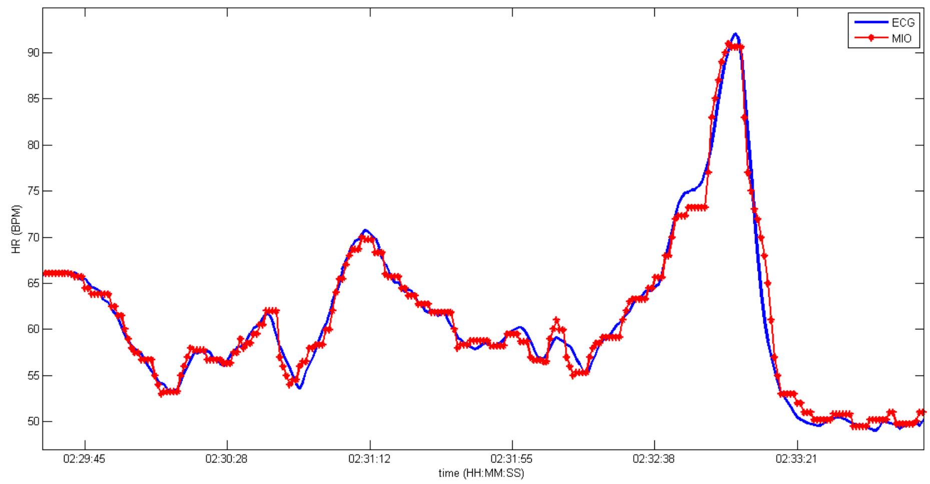

Fig. 4. Comparison between HRs derived from the MIO Alpha watch and ECG.

A volunteer wore the MIO Alpha while his HR was recorded with a standard ECG device (the recordings were performed while the volunteer was asleep). We extracted the heart rate from the ECG using R-peak detection and we plotted it over the HR recorded with the MIO Alpha. Fig. 4 shows both heart rate signals (HR from ECG in blue, and HR from MIO Alpha in red). We can observe a good correlation between them. However, the heart rate from MIO seems to be smoother. This indicates that signals from MIO are smoothed and interpolated. Therefore, they cannot be used for heart rate variability studies.

2.5 Graphical user interface

The design of our application is simple. The main user interfaces (GUIs) of the application running on the smart phone are shown in the Fig. 5.

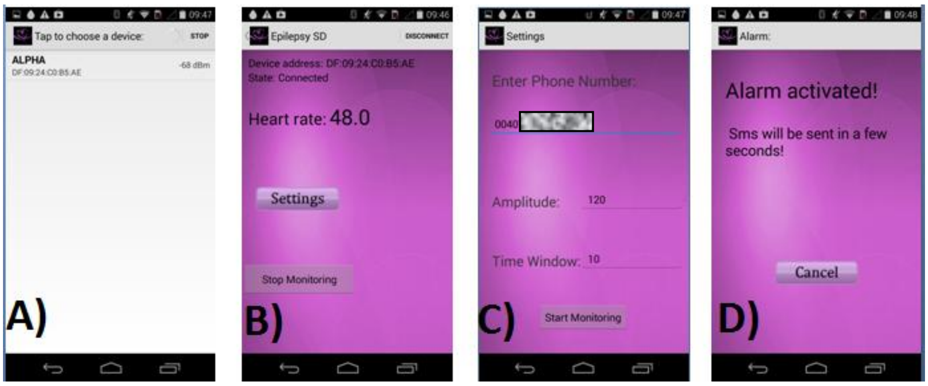

Fig. 5. The GUIs of the application

The operation of the application is as follows: Firstly, the user has to connect to the Alpha device (Fig. 5.A). Secondly, an image field (Fig. 5.B) appears. Here, the system automatically starts monitoring using the previously entered settings. If the application is opened for the first time, it has automatically implemented some values: 120 BPM for the Amplitude, 10 seconds for the Time Window and a fictional Phone Number 0000. The user can press the Settings button and a new screen will appear (Fig. 5.C). We also established a default setting for the amplitude threshold (TH2) at 40 BPM, because if the value of the HR is below it, the patient is in serious danger and should be immediately checked. In this activity, the user can modify the amplitude threshold (TH1), the duration of the time window and the phone number where to send the SMS. Next, the start monitoring button should be pressed. Now, the app will start monitoring with the settings introduced. When an event has been detected, an image will appear on the screen of the smart phone. The user is alerted that an event has been detected using both a vibration pattern and an auditory alarm, and if it is not cancelled within 20 seconds, the alarm SMS message will be sent.

The Body Hub (a smart phone with BLE) generates a local alarm. For this fact the app contains a high priority alarm sound from the ISO/IEC

60601-1-8 medical equipment standard, along with vibrations on a special pattern [17]. In this case the caregiver will know that something happened.

The content of the alarm SMS has different messages for different situations. If the average of the HR is larger than the TH1, the SMS text is: “Possible event! Please check!”. Otherwise, if the heart rate is below 40 BPM the text will be: “Heart rate low! Please check!”.

There are two types of disconnection between the MIO Alpha and the smart phone. One situation occurs when the phone of the user is out of range and the phone does not receive any data from the watch. The second situation occurs when the watch is not in contact with the skin. In both situations the SMS text is “The system is now disconnected or not in contact with the skin! Please check!” which will be immediately sent to the phone of the caregiver. On the monitoring device there will be a vocal alarm which will say the same thing.

3 RESULTS

3.1 Validation of the detection algorithm

The detection algorithm was tested offline on HR measured from patients with epilepsy before embedding it in the application. From the existent data base in Kempenhaeghe, we selected 15 patients which had convulsive seizures (Tonic Clonic (TC), Hypermotor and Tonic (T) seizures) while sleeping. These patients were recorded with a standard ECG system with two supraclavicular ECG-leads (left and right).

Before applying the seizure detection algorithm, the ECG data has been processed as following:

1. The HR was extracted offline from the ECG data using a Matlab implementation of Afonso et al. [19], [20].

2. The outliers (heart rate > $\pm$ 1/3 of previous heart rate) were replaced by the average of the previous two heartbeats.

3. The result was smoothed using a 10-sample moving average, interpolated and sampled again at 1 Hz.

To find the optimum threshold amplitude and temporal window, we developed a Matlab code. We varied the temporal threshold from 2 seconds to 30 seconds in step of 2 seconds and the HR threshold from 70 to 130 in steps of 5 BPM. For each temporal window and amplitude threshold we computed the SEN (Sensitivity) as (TP/(TP+FN))*100 and PPV (Positive Predictive Value) as (TP/(TP+FP)) *100. This calculation was done using the algorithm described above taking into account all night of recording. In an ideal case, the SEN and PPV should be both 100%. The final data is shown as heat maps where on x axis is represented the temporal window and on y axis the HR threshold, while on the z axis is the SEN and PPV value. Fig. 6 shows a typical result for the patient three.

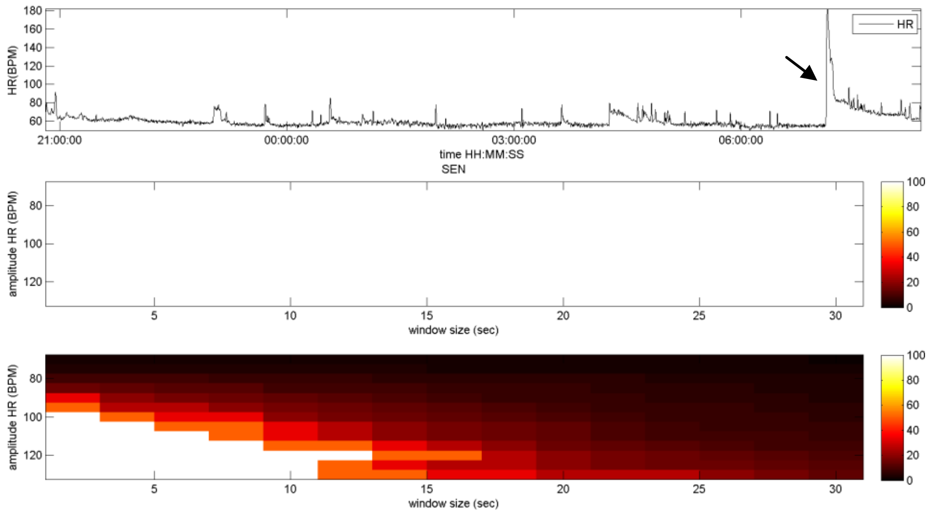

Fig. 6. A typical result of the algorithm validation (patient three).

Upper figure shows the HR signal. With Black arrows is indicated the location of one generalized tonic clonic seizure. We can observe that during the seizure, the HR increased to more than 140 BPM. For the rest of the night, the heart rate did not increase more than 90 BPM. The middle and the bottom figure show the heat map for SEN and PPV. The highest the SEN and PPV, the brightest the colors are. We can observe that for temporal windows having a range of 2-10 seconds and an amplitude threshold of 100 -130, we achieve 100% SEN and PPV.

Another example (patient four) is shown in Fig 7. In this case is a patient with tonic seizures.

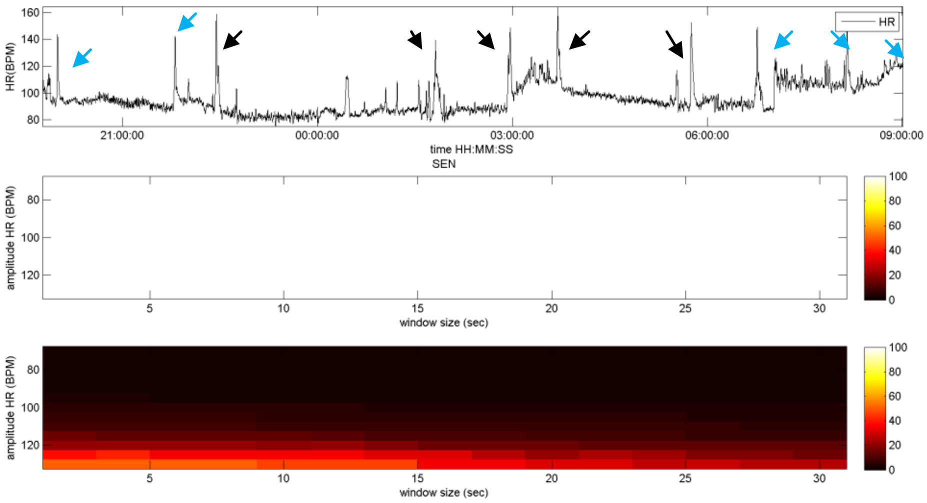

Fig. 7. Validation results from the seizure detection algorithm for patient four.

In this case there are 5 false positives (shown by red/blue arrows), The PPV in this case is 50% for HR range 125-130 BPM and temporal windows of 2-10 seconds.

Arousal and short awakenings are the main sources of false positives on such seizure detection algorithm. If the heart rate growth during a seizure is not high, then the algorithm can still be used but with higher false positive rate. The results from this analysis (shown in table 1) indicate that there is no universal threshold combination to achieve 100 % SEN and PPV.

Pat	Seizure type	Max SEN (%)	Max PPV (%)	TH1 (sec)	TH2 (BPM)
1	Hypermotor	100	25	2-8	130
2	GTC and Tonic	100	16	2-6	115
3	TC	100	100	2-10	100-130
4	TC and Tonic	100	50	2-8	125-130

5	T and Hypermotor	100	50	12	120
6	Tonic	100	100	2-10	115-130
7	TC and Tonic	100	50	2-12	95
8	Hypermotor	100	44	2-18	115
9	Tonic	100	18	2-8	105
10	TC and Tonic	100	25	2-10	80

Table 1. Optimum TH1 and HR amplitude to achieve 100% SEN in 10 patients.

We can observe from Table 1 that for some patients the algorithm provided good values for both SEN and PPV while for others had a poor performance. This can be explained by the type of the seizure and inter-patient variation. Each patient has to be addressed independent. However, in case of patients with generalize tonic-clonic (GTC) and Hypermotor seizures, the HR exceeded 120 BPM. These values are rarely achieved during a normal sleep. In the case of patients having different type of seizures, the algorithm detects only if the heart rate increase will be high, while the others will not. The user can decide which seizures are important to detect.

3.2 Testing the app

The app was tested on 5 healthy volunteers (5 nights in total). The amplitude threshold was set at 120 BPM and the time window at 20 seconds for all volunteers. During all recordings, the system disconnected twice because the connection between the MIO and the phone was lost. The watch was reconnected to the mobile phone and the connection was maintained till the next day. No other alarms were generated in this period of over 50 hours of testing. Since its release, the app was downloaded by more than 100 people. Some of them reported that indeed the app helped detecting the seizures but they also reported the false positives.

3.3 Limitations of the system

The system of the MIO Alpha watch combined with the Epilepsy Seizure Detection App has several limitations. This is due to intrinsic limitations from both MIO Alpha and the smart phone as well as seizure types. The watch is not a medical device. The purpose of it is to provide average values of HR and therefore the signals are smoothed and interpolated. The main consequence is that MIO Alpha cannot detect asystole. We tested this behavior using an inflating cuff and a commercial pulse oximeter as in Fig.8. At the forearm level we attached the MIO Alpha and we started the HR measurements. At the upper arm we stopped the blood flow towards the hand using an inflating cuff (inflated at 120 mmHg). We used a pulse oximeter attached to a finger to check when the pulsations stopped due to the cuff-pressure. While the oximeter indicated no pulse at finger level, the MIO Alpha showed HR for at least one minute. The watch was trying to provide a HR while there was no blood flow. Eventually the MIO will provide higher and higher values because of interpolation procedures. These erroneous values eventually will be high enough to generate an alarm in the phone. However, this can take a few minutes, which is too long in these situations.

Fig. 8. Test for asystole detection

We observed another behavior. If the MIO Alpha is removed from the skin while it is measuring, or the contact is not good enough (the watch is balancing on arm), then it can still indicate HR. MIO Alpha will only generate an alarm when it does not observe a reflecting surface. This is again the consequence of heavy filtering.

The other limitation comes from the instability of BLE devices, which is especially the case in earlier versions of smart phones with BLE. To eliminate the disconnection problem while measuring the heart rate, we set the app to function with its display turned on, but it can work also in the background. Having the display turned on, the battery life could be reduced, but this is optional. However, the system has been tested on the following phones: Motorola Moto G, Samsung Galaxy S3, and the Samsung Galaxy S4. The most stable Bluetooth connection was obtained by using the Samsung S4 because the system is more recent. Using both Motorola Moto G and Samsung S3 we encountered some problems with the Bluetooth connection. The application worked in the background for a few minutes and after that it disconnected.

The last limitation comes from the seizure type and from the baseline heart rate of the patient. If the heart rate increase during a seizure is not high (>20% from the minute before the seizure) then the seizure can be missed using a higher threshold. The arousals, short awakenings are the main sources of false positives.

4 CONCLUSION

Patients with epilepsy need seizure monitoring in ambulatory settings. The current systems are not sufficiently user friendly and precise for long-term monitoring. We have presented a unique combination of a device used in fitness to monitor heart rate with a simple algorithm for detecting epileptic seizures. The system allows modification of the main alarm settings to adapt the alarms to the specific patient. Moreover we added alarm functionalities to detect when the MIO Alpha is losing connection with the smart phone, or when the MIO Alpha is not in contact with the skin. We showed on volunteers that no false alarms were generated during the night. Only two alarms were generated, both caused by loss of connection between the MIO Alpha and the smart phone, due to BLE instability. However, this app was made for nocturnal monitoring. For daily use, the system can be improved by increasing the complexity of the seizure detection algorithm. This will be done also to make it more adaptable to different seizure types.

For future work, we will port this app to IOS to increase the number of people who can access it, and also because Apple devices have more comparable operating systems. Therefore the stability should increase. We could add GPS tracking in order to obtain user coordinates each time an alarm is triggered. The settings could also be expanded to allow for editing of the content of the SMS or adding a list of people who would receive the SMS.

Such apps which use existent wearable devices can be developed to monitor other medical conditions. These can be used for elderly monitoring. This app is available for download and test free of charge. We are not liable for any damage that may occur from the use of this app. By scanning the Fig.9 you will be redirected to the link where the app is published and you can download it from there.

Fig. 9. The QR Code of Epilepsy Seizure Detect

5 ACKNOLEDGEMENT

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