A Novel Approach to Continuous Heart Rhythm Monitoring for Arrhythmia Detection

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1 Introduction

Wireless cardiac devices offer a novel method for remote monitoring of cardiac patients. Diagnosing the work of the heart, in the most basic approach, is mainly based on observing the hear rhythm. In the mid-twentieth century, the 12-lead electrocardiogram was developed and standardized by American Heart Association (AHA) [1,20]. Since then, electrocardiography belongs to the first diagnostic steps in evaluating patients presenting with heart complaints. In particular, it plays an essential role as a non-invasive, inexpensive tool for assessing arrhythmias and ischemic heart disease.

A vital concept in electrocardiography is the idea of the Einthoven triangle, which allows the recording of heart rhythm and electrical activity from three limb leads. This idea of recording the voltage difference between electrodes, proposed 100 years ago, underlies all electrocardiogram (ECG) devices to this day and has also been used in our approach, but in a slightly changed form.

One of the frequent complaints of patients is arrhythmia, which can be detected with the help of the ECG device attached to the patient in a supine position. However, to obtain more diagnostic information, the examination should be carried out over an extended period (e.g., 24 h). Maintaining the patient's lying position over such a long period of time is burdensome and impractical. The ECG Holter devices are barely adequate to cope with patient physical activity requirements. Currently Holters allow for the daily recording of the heart activity, while allowing for patients' moderate activity during the recording period.

To increase the likelihood of recording an arrhythmia, a more extended ECG recording is often required [3,9], sometimes even for a couple of weeks. The

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implementation of such a solution creates new challenges. More specifically, the device must work for weeks and its use must be relatively well tolerated by the patient. Emerging technical problems, such as the long-term operation of the device on battery power or the stability of the electrodes, are accompanied by medical problems, such as allergy issues and abrasions to the skin. In addition, an extensive logged data set of 160–200 MB per day needs to be analyzed to detect potential heart rhythm abnormalities over a longer period of time. The volume of one or two weeks of ECG recordings increases sharply to a dozen gigabytes (GB) and, therefore, there is a need to automatically detect arrhythmic episodes in the ECG trace that may indicate pathologies. However, this requires the development of new algorithms for the initial analysis of ECG recordings. which will leads to the reduction of the analysis area from several GB to several hundred megabytes (MB) as is the case of a Holter monitor.

The device for continuous heart monitoring for arrhythmia detection should provide a reliable and convenient way of recording the ECG signal while maintaining daily activity. In addition, patients would benefit from a non-intrusive device, would not require active interventions such as closing the circuit with a finger, as in a needed in a smartwatch. It should also alert to the occurrence of different kinds of arrhythmias and conductance disorders.

2 Background and Objective

Atrial fibrillation (AF) is the most common type of cardiac arrhythmia [11]. It is estimated that AF occur in one in three, at index age of 55 years, people during their lifetime. The prevalence of AF in the adult population is between 2% and 4%, and due to the aging population, these numbers are expected to increase. AF is a risk factor for death and variety of cardiovascular diseases. It may lead to thromboembolic complications including stroke, heart failure and decompensation, myocardial ischaemia mainly due to excessive tachycardia [2]. Thromboembolic complications of AF can be prevented by anticoagulation therapy. However, antithrombotic treatment imposes the risk of bleeding complications. Therefore, this treatment is indicated if the presence of AF is confirmed by ECG recording. The most important factor that impedes the initiation of anticoagulant therapy is a delayed recognition of AF due to its paroxysmal nature and often asymptomatic occurrence. The most crucial component of preventing AF complications is early detection.

Another issue is the invasive approach to the treatment of AF, i.e., different ablation strategies [4]. The decision to use those methods can only be made in the case of an ECG-documented episode of AF. The obvious difficulty is that episodes of AF occur in various patients with different burdens, and even a few episodes in a year still increase the risk of thromboembolic complications.

Many strategies have been proposed to screen patients for AF. Education of the general population based on pulse regularity checking to select patients in whom ECG should be performed are the cheapest but also the least reliable means of recognizing existing arrhythmia [5]. The other approach is to determine the patient population at-risk of AF, based on the risk factor occurrence in whom prolonged ECG monitoring may reveal an illness. Awareness of the patients from the general population results in increased use of commonly available methods of ECG monitoring (standard 12-leads ECG, 24-h Holter monitoring) and the usage of wearables like hand watches with the function of the ECG recording. However, the watches or wristbands do not allow for continuous control of the heart rhythm. The existing medical devices for continuous rhythm recording can be classified based on the position of the electrodes: on or under the skin. The later system called an implantable loop recorder is the gold standard, however, its use is limited by the cost and the risk of the complications, including bleeding, bruising, and infections of this invasive procedure. Furthermore, a skin scar is an unavoidable remainder of the device insertion.

In turn, the external electrodes are not well tolerated when used for a prolonged period of time. The main problem is to obtain a stable position of the electrodes on the skin. Electrodes attached to the torso record best signals. This position's disadvantage is the need to use adhesive materials to attach them to the skin. This leads to dropping out of the electrodes, skin allergy issues and motion artefacts with prolonged registration. Localizing the electrodes on the limbs for continuous rhythm recording may simplify the procedure and increase their stability. The received ECG signal is a one bipolar lead and most frequently corresponds to the first limb lead of the Einthoven triangle. Nevertheless, the problem of motion and muscle artefacts remains to be resolved. The recording of ECG signals in a single-arm setting was proved to be feasible [10,17,19]. So far, there is no commercially available system using this method of ECG registration.

3 Proposed Solutions

As mentioned in the previous chapter, the 12-lead ECG as a standard test performed in the hospital and laboratory setting (recorded in a supine position) cannot be used for continuous, long-term recording of heart activity.

There are portable devices usable for monitoring ECG heart activity, which extend the recording time and are helpful for observing rare cardiac arrhythmias [13]. An excellent example of such devices may be a Holter monitor, a portable ambulatory device for cardiac 3–5–12 leads monitoring for 24 to 72 h. Nevertheless, the Holter recorder is limited by the constraints of the electrode placement and measurement time.

For patients with more transient symptoms (episodes), a cardiac event monitor worn for a month or more, should be used [3]. A more extended measuring period requires a device less restrictive of the patient's physical activity, and from this perspective, some smartwatch models capable of recording an ECG, seem like an exciting solution. These devices can be worn freely on the wrist for an extended period, but the recording is performed only with the measuring circuit closure by placing a finger from the other hand on the smartwatch. Thus, we obtain a measurement of the ECG potential difference between the upper limbs, which corresponds to *lead I* in a standard 12-lead ECG. Smartwatches can be worn for a long time. However, the timing of ECG recordings depends on the user's decision. Therefore, it does not meet the continuous monitoring requirements - it is an ECG recording based on the patient's request (usually of 30 s or so). Thus, a smartwatch is inappropriate because it requires the continuous closure of the measuring circuit through constant contact of the two hands with the device. As mentioned above, such devices are not good enough because they can provide only a snapshot in time of the patient's heart rhythm.

3.1 Proposed Wearable Device

The current state of the available electronics and IT technologies allows for the implementation of a wearable device. Moreover, as mentioned in the previous section, recording ECG signals in a single-arm setting proved to be feasible [10,17,19]. Therefore, our proposal focuses in on this direction of research and development. We designed the POLIBAND ECG armband for the detection of atrial fibrillation episodes. Technical details of the implementation of this wearable device can be found in [14], while in Fig. 1, its functional diagram is presented.

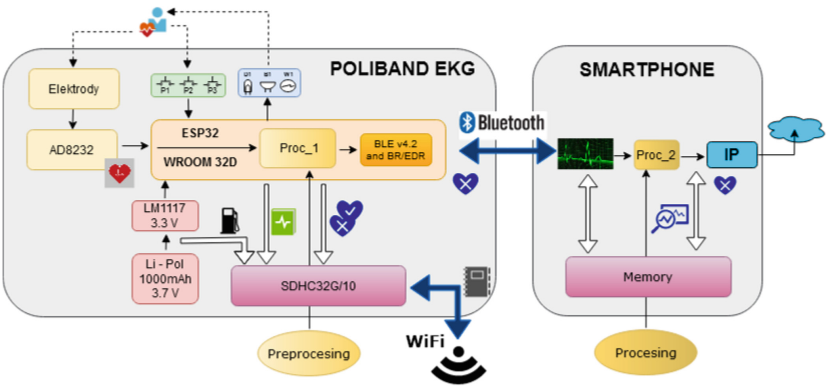

Fig. 1. Functional diagram of POLIBAND ECG communicating with a smartphone via Bluetooth.

The material technology (constantly being improved and tested) used to make the electrodes, in conjunction with the electronic input circuit, adjusts the impedance of the skin-electrode-device connections, ensuring the proper ECG signal conditioning and reduction of analog tract contamination. The two main aspects on which these activities focus are the fluctuation of electrode potential polarization and electrode-skin impedance fluctuation. Signal conditioning activities cannot be exaggerated, especially in terms of the use of filters. We are aware of avoiding the over-conditioning of the ECG signal because we are especially interested in the shape and periodicity of the signal, therefore, it does not need to be smoothed out too much.

3.2 ECG Signal Preprocessing

After conditioning, the electrodes' voltage signal is processed in a AC/DC converter (*AD 8232* chip) into a sequence of 12-bit digital samples. Then, it is recorded in the *SDHC32/10* memory card and preprocessed by *Proc_1*.

The preprocessing *Proc_1* routine consists of several sequential steps designed to cope with:

- baseline wandering,
- power line interferences (50/60 Hz, EU/USA),
- electromyogram noise,
  * day activity artefacts as changes in impedance electrode-skin, ESD discharges, patient mobility muscles potentials
  * physiological artefacts as spontaneous myographic activity of peripheral muscles,

The first three (*dashed*) steps which provide adequate filtrations are based on the selected digital filter implementations of recursive filters: high-pass, narrow pass-band and low-pass, respectively. This filtering is realized with software procedures that were designed to preserve the most significant ECG frequency components but at the same time suppress the noise frequencies [16]. These filters were conformed and implemented to the requirement for real-time SoC microprocessor operation. The results of their action are presented in Fig. 2.

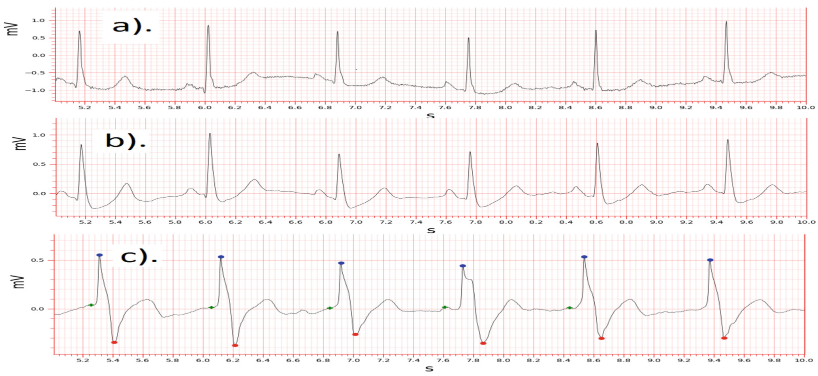

Fig. 2. ECG signals: a) original, b) without baseline wandering, c) without power line interferences but with fiducial points *R, S, P*.

The other two (*asterisked*) steps are more sophisticated, even for specialists who want to catch artefacts on the ECG. We worked on a relatively simple (implementable in a SoC microprocessor) binary classifier (artefact/non-artefact), but the results obtained were not satisfactory. Therefore, we use a dissimilar method in the last two steps when searching for artefacts and eliminate them from the ECG signal. Now, we search for QRS complexes and eliminate everything else (also artefacts) that is not useful for further ECG signal analysis.

We do not filter out what is wrong/unnecessary, i.e. artefacts from the signal because it is very difficult to define the concept of an artefact in the algorithm. In the provided ECG signal, we annotate the R-wave as a fiducial point (see Fig. 2c), then determine the Q-wave and S-wave, and as a result, we obtain the QRS-complex. We take out what is essential from the provided record, i.e., those fragments of the record, which are continuous sequences of many QRS complexes. We give up the remaining pieces of the record, however, within continuous sequences of many QRS complexes, we do not lose the PQ-segment, PQ-interval, ST-segment, and QT-interval records, which will used for further analysis.

4 Conclusion and Future Directions

The ECG signals obtained after the *Proc_1* preprocessing are filtered, thus distortions and noise are reduced. Next, only those parts of the ECG are selected that correspond to the morphology (QRS complex) of the ECG signal. Final waveforms are wirelessly transferred (Bluetooth) to the smartphone, where they will be further analyzed/classified, first in smartphone, second in cloud (Fig. 1).

Using the computing power of the smartphone, we plan the next stage of processing (*Proc_2* in Fig. 1). It will base on ECG signal classification in the scope of the occurrence of different kinds of arrhythmias. For this purpose, we plan to use spectral signatures, creating them for each form of arrhythmia, such as bradycardia, tachycardia, asystole, etc.

Spectral signatures will be created using methods as feature extraction as well as different transforms such as Fast Fourier, Discrete Wavelet or Stockwell [12,18]. These methods have been proven many times, both in the case of simple waveforms (capnography [15]) and more complex signals (audio signals). Hence, we expect that using them in the classification of the ECG signal will bring excellent results.

Having developed algorithms, we will work on digital signatures for selected abnormal states such as different kinds of bradycardias, tachycardia, asystole etc. In these studies, we will use the well-known [6–8] databases as well as the results collected on the basis of the POLIBAND ECG armband. Well-known [6–8] databases were created in hospital and laboratory conditions. Hence, using POLIBAND ECG data is crucial because this device works in much more demanding conditions than those that considered when creating previous devices.

The feasibility of collecting electrocardiograms from the arm described in the literature [17,19], was confirmed by experiments performed by us. It should be noted however, that in this approach the location of the electrodes drastically differs from the Einthoven triangle. We have not found any theoretical framework to explain this situation in the literature. Therefore, this should also be the subject of further research.

During our research, we were also unable to find a reasonable answer to the questions: how does the number of leads reduction affects the diagnostic information contained in the signal? We reduce the recording ECG signal from twelve to one bipolar lead. Is there such a considerable redundancy of information in 12-leads ECG recording that we really do not lose anything essential in this way? Of course, we do realize that there will be some losses. But it will be important to find out how widely and how crucially we will narrow the possibilities of a correct diagnosis.

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