REAL-TIME DETECTION OF ACCIDENTAL PATHOLOGIC CARDIAC EVENTS IN THE ELECTROCARDIOGRAM

Ivo Tsvetanov Iliev[1], Vessela Tzvetanova Krasteva[2], Serafim Dimitrov Tabakov[1]

[1] Department of Electronics - Technical University of Sofia
8 Kl. Ohridski str, 1000, Sofia, Bulgaria, e-mail: izi@tu-sofia.bg
[2] Centre of Biomedical Engineering "Prof. Ivan Daskalov" - Bulgarian Academy of Sciences
Acad.G.Bonchev str. Bl.105, 1113, Sofia, Bulgaria, e-mail: vessika@clbme.bas.bg

The major efforts for improving the automated cardiac diagnostics are directed towards developments of innovative hardware and software solutions for computer-assisted electrocardiogram (ECG) monitoring systems. The presented work describes a method for fast detection of pathologic cardiac events by real-time ECG analysis. It is convenient for embedding in microcontroller-based autonomous system for monitoring of high-risk cardiac patients. The algorithm involved on-line operating procedures, including preprocessing filtration, threshold-based QRS detection, interbeat RR-intervals analysis and QRS pattern waveform analysis. Aiming at a simple solution, we adopted specific strategies for signal processing acceleration and for reduction of the operational memory size, such as the resolution reduction of the QRS pattern waveform. Moreover we implemented simplified techniques for rating of the similarity between the QRS pattern of the tested beat and the accumulated QRS pattern of the preceding heartbeats. The repetition of similar QRS pattern waveforms combined with small variances of the RR-intervals, was interpreted as a normal rhythm. However, the appearance of a number of deviations either from the mean RR interval, or from the cumulative QRS pattern waveform, was detected as a sustained pathologic event. The developed algorithm was implemented in Matlab environment. It was tested with internationally recognized ECG databases. Several examples are presented and discussed.

Keywords: ECG monitoring, high-risk cardiac patients, real-time ECG analysis

1. INTRODUCTION

The major efforts for improving the automated cardiac diagnostics are directed towards developments of innovative hardware and software solutions for computer-assisted electrocardiogram (ECG) monitoring systems. The main task to identify patients at risk of arrhythmias, both with and without sustained symptoms is managed for example by the systems for long-term (24 h) heart activity registration, i.e. ECG holters. The bedside ambulatory systems are also very important for monitoring of the vital characteristics of inbed hospitalized patients for a long period of time (reanimation, intensive care rooms, nursing home) [1]. Frequently, critical conditions happen just after disconnection from the ambulatory monitors, in the phase of starting moving, rehabilitation, self-service, etc., i.e. in circumstances without attendance on the patient condition when the nurse/personal care for the patient is recommendable.

Thanks to the fast developments of novel wireless communication technologies, such as Bluetooth, Zigbee, 802.11, etc. [2-4], the implementation of portable autonomous systems for continuous ECG monitoring becomes possible. The build-in algorithm for real-time ECG analysis must guarantee reliable and accurate detection of pathologic cardiac events. The instantaneous wireless alarm transfer to the central

processing unit would allow the immediate ECG inspection by the cardiologists for adequate prompt emergency support to the patient. Thus the chance for survival of high-risk cardiac patients will be increased.

The problem for detection of abnormal ventricular beats is widely discussed in the literature, since they disturb the blood pumping function of the ventricles and their appearance during the vulnerable period increase the risk for initiation of ventricular tachycardia/fibrillation, leading to sudden cardiac death. Although the performance of a number of methods has been extensively studied and highly optimized, their application in portable autonomous systems is restricted because of their off-line operation and/or the limited computation resources available. A recent study [5,6] estimated the applicability of personal digital assistants (PDAs) to perform in real-time a complete electrocardiogram beat and rhythm classifier with competitive accuracy. Although the PDAs are portable devices, they are in the class of minicomputers that can execute rather complex tasks with relative high-consumption and limited time for continuous operation. Taking into account the increasing number of people with cardiovascular diseases, it remains a challenge the development of a very simple autonomous device and a method for fast real-time recognition of pathologic abnormalities in ECG.

The present work describes a simplified software method for fast detection of cardiac events by on-line operating procedures, including QRS detection, interbeat RR-intervals analysis and QRS pattern waveform analysis. In order to provide a simple solution, specific strategies for signal processing acceleration and for reduction of the operational memory size are adopted. The pilot version of the method is developed and tested in Matlab environment but it is applicable for low computational cost systems in portable ECG processing units (intelligent holters, loop recorders, event/alarm recorders or personal devices with wireless data transfer to a central terminal).

2. METHOD

The developed software module for real-time signal processing of single lead ECG is realized according to the flowchart in fig.1. It implements: (i) preprocessing filtration (monitor-type pass-band filtering (1-30) Hz and notch filtering at 50 Hz); (ii) threshold-based QRS detector; (iii) QRS pattern matrix analysis; (iv) RR-intervals analysis; (v) logic rules for pathologic event detection.

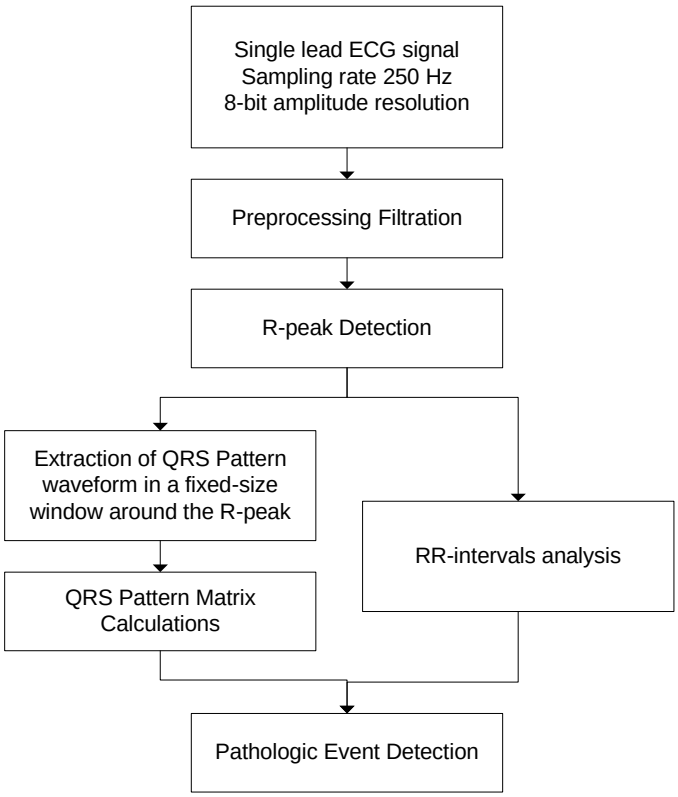


Fig.1. General flowchart of the algorithm

Aiming at a simple solution, we adopted the following main strategies for signal processing acceleration and for reduction of the operational memory size:

2.1. Single lead ECG analysis. The one channel ECG signal is sampled at low rate of 250 Hz and small amplitude resolution of 8-bit.

2.2. Threshold-based QRS Detector. A modified version of the on-line QRS detector [7,8] was implemented, which relies on simple calculations of amplitudes and slopes, and relevant evaluation of adequate dynamic threshold criteria. The proper operation of the presented method requires the correct localization of a reference point within the QRS complex. We assumed that the most deterministic point of the QRS is the maximal amplitude R-peak, which is distinguishable by its sharp peak with steep edges. Examples of the properly recognized R-peaks are presented by 'o' marks in fig.2, fig.4-7.

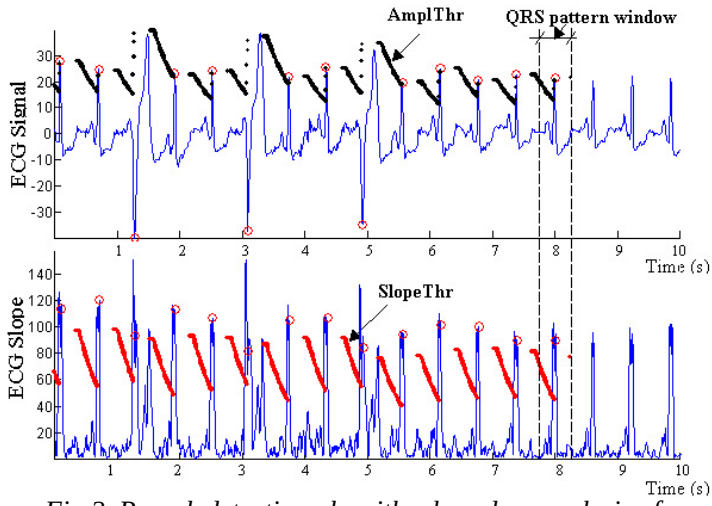


Fig.2. R-peak detection algorithm based on analysis of dynamic thresholds of the ECG amplitude (upper trace) and the ECG slope (bottom trace). The detected R-peaks are marked with (o). The window for extraction of the current QRS pattern is enclosed by vertical dotted lines.

2.3. QRS Pattern waveform (PW). The *PW* was represented by a limited number of samples with reduced amplitude resolution which were selected around the detected R-peak. Our practical application involved a number of 128 samples (500 ms window) with 5-bit resolution. The length of the QRS pattern was chosen to include of the complete QRS, even in the worst case of prolonged ventricular extrasystole or bundle branch blocks. It can be helpful to view such signals on an oscilloscope, where the trigger can be adjusted so that the QRS waveforms are superimposed. An example is presented for the in signal in fig.2 with overlapping QRS patterns of 8-bit and 5-bit resolution (see fig.3).

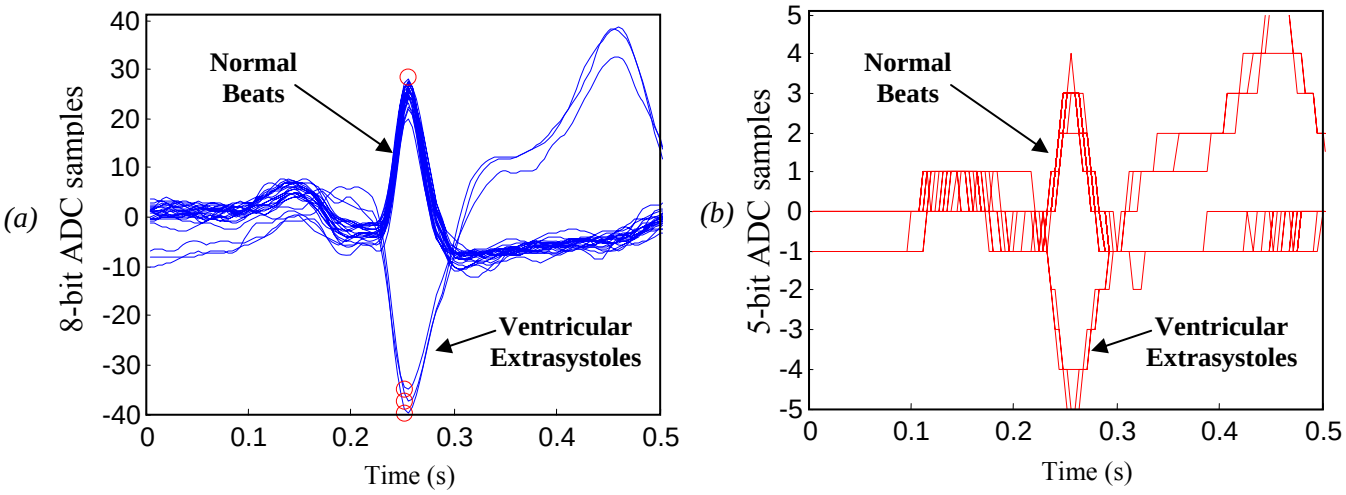


Fig. 3. Superimpozed QRS pattern waveforms, all aligned by the maximal amplitude R-peak at 63th sample - marked with (o) in (a). (a) 8-bit QRS pattern waveforms (b) approximated 5-bit QRS pattern waveforms.

2.4. QRS Pattern matrix. A reduced-size QRS pattern matrix (*PM* – size 128 x 5 bit) accumulates the QRS pattern waveform history. Virtually, the *PM* columns correspond to the position of the samples in time, and the *PM* rows correspond to the samples' amplitude. The main idea is that the repetition of the identical ECG pattern waveforms of the predominant beats is accumulated into a dense area of superimposing waveforms (fig. 4c – the dark trace). In contrast, the waveform of an abnormal ventricular contraction deviates from the expected area of the periodic waveforms (fig. 4c – the light trace). The *PM* elements are dynamically updated by each consecutive QRS pattern waveform, following simple procedures for accumulation and erasing, as follows:

- **Initialization**: At the beginning of analysis all *PM* elements are set to zero. $PM(i,j) = 0$, where the column index *i*=1,2,…,128 and the row index *j*=1,2,…,32.
- **Accumulation**: On R-peak detection, the 5-bit QRS pattern waveform *PW* is accumulated into the QRS pattern matrix *PM*, according to:
  - If $PM(i, PW(i)+16) \le 10 \quad \Rightarrow PM(i, PW(i)+16) = PM(i, PW(i)+16)+1$
  - If $PM(i, PW(i)+16) > 10 \quad \Rightarrow PM(i, PW(i)+16) = PM(i, PW(i)+16)$,

  where the *PM* elements are indexed by *i*=1,2,…,128. Taking into account that the values of *PW* cover the range of 5-bit signed integers (-15 to +16), the above used shifting with 16 is applied in order to supply correct indexing of the *PM* rows with positive integers (1 to 32).
- **Erasion**: The erasion of *PM* is a kind of adaptive cleaning procedure of the accumulated QRS pattern waveforms within a preset period of time. We define, that for every 10^{-th} QRS, all nonzero *PM* elements have to be incremented:
  - If $PM(i, j) > 0 \quad \Rightarrow PM(i, j) = PM(i, j) - 1$, where *i*=1,2,…,128; *j*=1,2,…,32.
- **Rating**: Every heartbeat is rated according to the content of the *PM* elements using the counter *RatePM* (range 0-128):
  - If $PM(i, PW(i)+16) > 3 \quad \Rightarrow RatePM = RatePM + 1$, where *i*=1,2,…,128

  The *RatePM* value is presented by 'o' mark in fig.4b and fig.5b for each QRS.

2.5. RR-intervals analysis. It is applied for recognition of disturbances in the cardiac rhythm periodicity. Great variation from the mean RR-interval is a sign for abnormal cardiac contraction. The RR interval deviation from the mean RR interval is assessed by *DiffRR* parameter, which is marked by '•' in fig.4b and fig.5b.

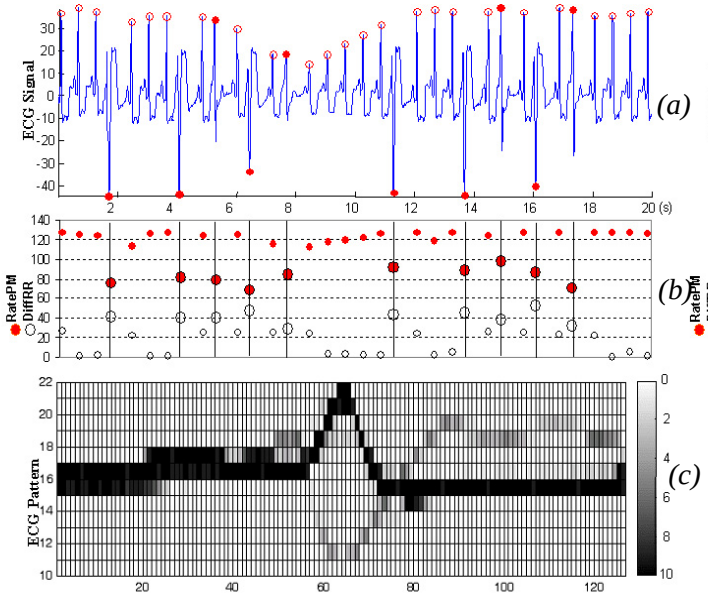
2.6. Pathologic event detection. We implemented a simple triggering algorithm for recognition of single cardiac events when one of the following conditions is satisfied:

- *(RatePM<100) & (DiffRR>20)* - relatively low rating of the QRS pattern waveform, which is combined with moderate RR-interval variation;
- *RatePM<50* - extremely low rating of the QRS pattern waveform;
- *DiffRR>50* - extremely high RR-interval variation;
- Pathologic pause with RR-interval > 2 s.

Single pathologic events are neglected, but their triple appearance within 10s is considered to be life imminent and an alarm is generated.

3. Results and Discussion

The algorithm was initially implemented in Matlab. Its development and testing involved adjusting of the thresholds with the internationally recognized ECG databases (AHA, MIH-BIH), that contain a wide variety of arrhythmias. Several examples are presented, which illustrate the performance of the algorithm.



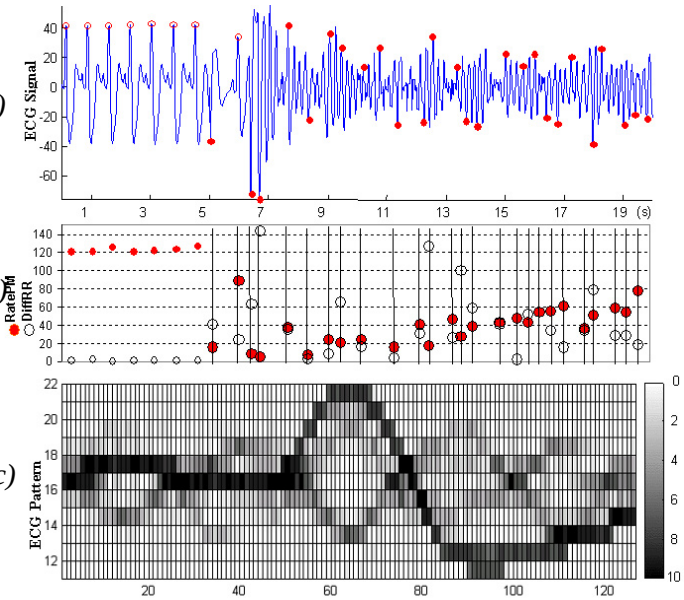
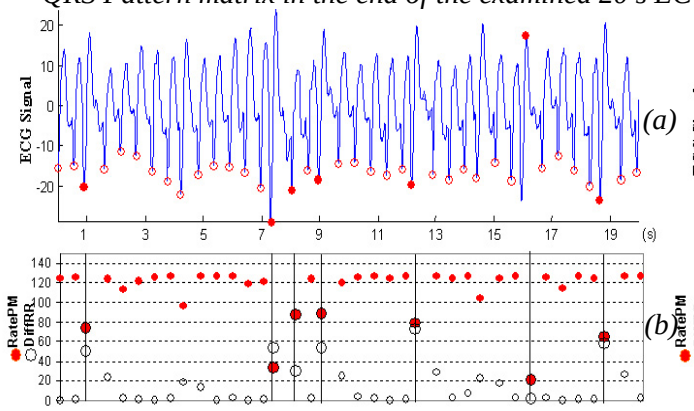


Fig.4. Normal rhythm with extrasystoles *Fig.5. Transient rhythm: block - ventricular fibrillation*

(a) The detected R-peaks are marked with (o) when they are normals and with (•) when pathologic events are recognized; (b) The measured values of RatePM and DiffRR for every beat. The vertical lines correspond to the measurements, which are indicative for abnormal cardiac contractions; The small dots indicate the position of normal beats, while the large dots mark the pathologic events; (c) Visual representation of the QRS Pattern matrix in the end of the examined 20 s ECG epoch.



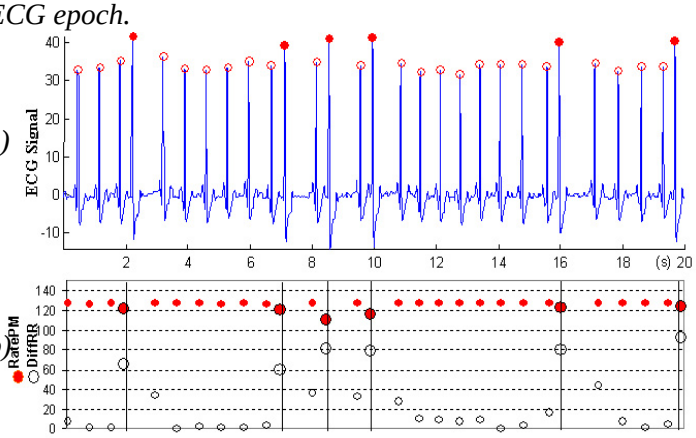


Fig.6. Slow ventricular tachycardia with premature foci activation;Fig.7. Sinus rhythm with premature beats

The example in fig.4a represents high-risk patient with ECG indicative for recent acute myocardial infarction (visible ST-elevation). The normal rhythm is disturbed by several ventricular extrasistoles (two-focal). Despite of their changeable shapes, all of them are correctly detected as pathologic events, accounting for both the drop of *RatePM* bellow and the increase of *DiffRR* above the defined thresholds (fig.4b). The ECG Pattern matrix (fig.4c) shows two well visible traces - the darker trace is formed by the normal beats, the lighter trace represents the casual extrasystoles.

The example in fig.5a was chosen to represent a high-risk patient with left bundle branch block and R-on-T extrasystole, which initiated rapid ventricular tachycardia/fibrillation. This situation requires immediate pathologic event alarm, since the prompt defibrillation is required for restoration of the circulation. The transition of the rhythm from block to ventricular fibrillation is detected immediately, as seen by the great difference between *RatePM* and *DiffRR* values, measured before and after the initiation of spontaneous fibrillation (fig.5b). The QRS Pattern matrix (Fig.5c) stores the regular waveform of the QRS block rhythm (dark trace) and the irregular fibrillation waves, which appear with different polarities, amplitudes and widths (visible by the chaotically distributed grey rectangles).

The high sensitivity of the method for recognition of pathologic beats with waveshape resembling the wave of the primary beats is also demonstrated. Such are the extrasystoles in fig.4 (see the 3^{-th}, 5^{-th}, 8^{-th}, 10^{-th} extrasystoles), the casual rapid ventricular tachycardia beats in fig.6 which resemble the primary slow ventricular tachycardia beats, the narrow extrasystoles in fig.7 which have the same polarity and similar waveshape like the normal beats. The method recognizes correctly all of these pathologic activations, according to both high *RatePM* and/or low *DiffRR* values. We should note that even some of the beats of the primary rhythm appear with amplitude modulation, none of them was misclassified as pathology.

During the development phase of the algorithm, we considered the qualified opinion of an experienced cardiologist, who defined the conditions, which require secure alarm, e.g. three exclusive beat contractions appearing in a time interval of 10 s, pathologic RR-interval pause, significant RR-interval variability, etc. The algorithm could be easily modified and adapted for recognition of unforeseen critical conditions, which might appear in the next phase of experimental testing and verification of the real device in clinical conditions.

5. ACKNOWLEDGMENT

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