Algorithms for ECG Analysis in Mobile Cardiac Monitoring System

Alexander Kalinichenko, Svetlana Motorina
Saint Petersburg Electrotechnical University,
St. Petersburg, Russian Federation
ank-bs@yandex.ru, motorina_sv@mail.ru

Alexey Uskov
Medical project CardioQVARK
Moscow, Russian Federation
alexei.uskov@cardioqvark.ru

***Abstract*—This work presents algorithms and software for the automated ECG processing and analysis in the mobile cardiac monitoring system based on smartphone. The key component of the system is portable ECG acquisition device realized in the form of smartphone case. The registered ECG is preprocessed by the smartphone software and is transferred further via Internet to the cloud service where additional computer analysis of the signal is implemented and the ECG and its analysis results are stored in the database. The data from the cloud service are available both to the patient and to his doctor. The following main functions of ECG analysis are realized by the algorithms: pacemaker spikes detection, heart rate control, cardiac arrhythmia recognition and heart rate variability analysis. Several modifications of the ECG acquisition device for iPhone series 5/5S, 6/6S are in batch production now in the frames of CardioQVARK project. At the same time the data from the system database are used permanently for the further enhancement of the algorithms.**

I. Introduction

Development of the mobile communication technology makes it possible to create compact and easily available smartphone based devices that provide real-time control of human physiological parameters and also translation of registered data to medical centers where they can be reviewed by doctors. The possibility like this is especially important for the cardiac patients supervision. In case of the mobile based devices use the conditions of physiological signals acquisition (first of all of ECG) differ much from the conditions typical for standard ECG equipment. So the task of special ECG processing algorithms development becomes urgent. This work is devoted to the description of the ECG analysis algorithms complex oriented to the use in mobile cardiac monitoring systems.

The main tasks of the ECG analysis algorithms in mobile cardiac monitoring system are the following [1], [2]:

- current control of heart rate, that represents one of the most important physiological indexes;
- recognition of cardiac arrhythmias, first of all – ventricular and supraventricular premature beats (extrasystoles) indicating presence of pathological changes in the heart automatism and conduction;
- analysis of ECG form pathological changes caused by cardiac ischemia (coronary heart disease);
- heart rate variability (HRV) analysis that provides quantitative measures of vegetative regulation condition in human organism.

Some patients may have implanted cardiac pacemakers. In this case their ECGs have rather specific form that requires use of the special algorithms for the signals processing [3], [4]. The main tasks of these algorithms are recognition of pacemaker spikes and reliable real-time visualization of the spikes, if they are present in the signal.

This paper presents the whole complex of the ECG analysis algorithms used in the software of a mobile cardiac monitoring system based on smartphone.

II. Smartphone based cardiac monitor

The described algorithm was developed for the use in the mobile cardiac monitor CardioQVARK [4], [5], based on iPhone series 5/5S or 6/6S. The iPhone series was selected as one of the most reliable types of smartphones. The ECG registration device represents a portable case into which a smartphone is inserted. On the rear side of the case two electrodes are placed for the ECG acquisition from fingers of both arms that corresponds to the standard ECG lead I. The ultra high impedance ECG sensors PS25251 and the 24-bit stereo audio analog-to-digital converter ADAU1361 are used for the ECG acquisition and sampling that provides frequency range of the signal 0.2-10000 Hz and sampling rate 20000 Hz.

Special version of the device also exists where two external electrodes connected to the device by cable are used for the ECG acquisition. The breast leads are used as a rule in this case. It provides the possibility of ECG lead selection and the obtained signal has significantly better condition comparing to the acquisition from the finger-tips.

The registered signal is first preprocessed in the smartphone and displayed in the real-time mode at the screen. Then the signal is decimated to 1000 Hz and transferred via Internet to the cloud service where additional analysis of the signal is implemented and the ECG and its analysis results are

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saved in the database. The data from the service are available both to the patient and to the doctor with the use of special client application that can be installed at smartphone, clipboard computer, notebook or desktop computer (Fig. 1).

The cloud service represents a distributed system that realizes the following main functions:

- receiving of the data from patients smartphones and transferring the results of the ECG analysis back;
- storing of the obtained data in the common database;
- providing authorized access to the patients data for the doctors who monitor these patients;
- automated processing of the stored data with the use of various program packages realizing different methods of the data analysis;

The used data protection technique provides strict confidentiality of the data access. The whole volume of a patient personal data is available only for the patient himself and for his doctor.

At the same time the service software provides possibility of impersonal access to the ECG recordings and to the diagnostic and anthropological data of patients. Due to this possibility the mass data processing technologies (such as big data and data mining) can be used to reveal some latent regularities, interconnections and trends in the data related to the whole contingent of the patients under control.

III. ECG ANALYSIS ALGORITHMS

A. Common structure of the ECG analysis process

In case of the ECG acquisition from two finger-tips the obtained signal is characterized by some specific features, namely:

- only one ECG lead is available;
- no possibility of the lead selection is available; the used lead corresponds to the standard lead I that for some patients may have very low amplitude;
- the noise level is much higher than in case of some standard ECG electrodes use.

So the used algorithms should demonstrate robustness to the listed above factors.

The ECG processing and analysis algorithms are distributed between the mobile device and the cloud service.

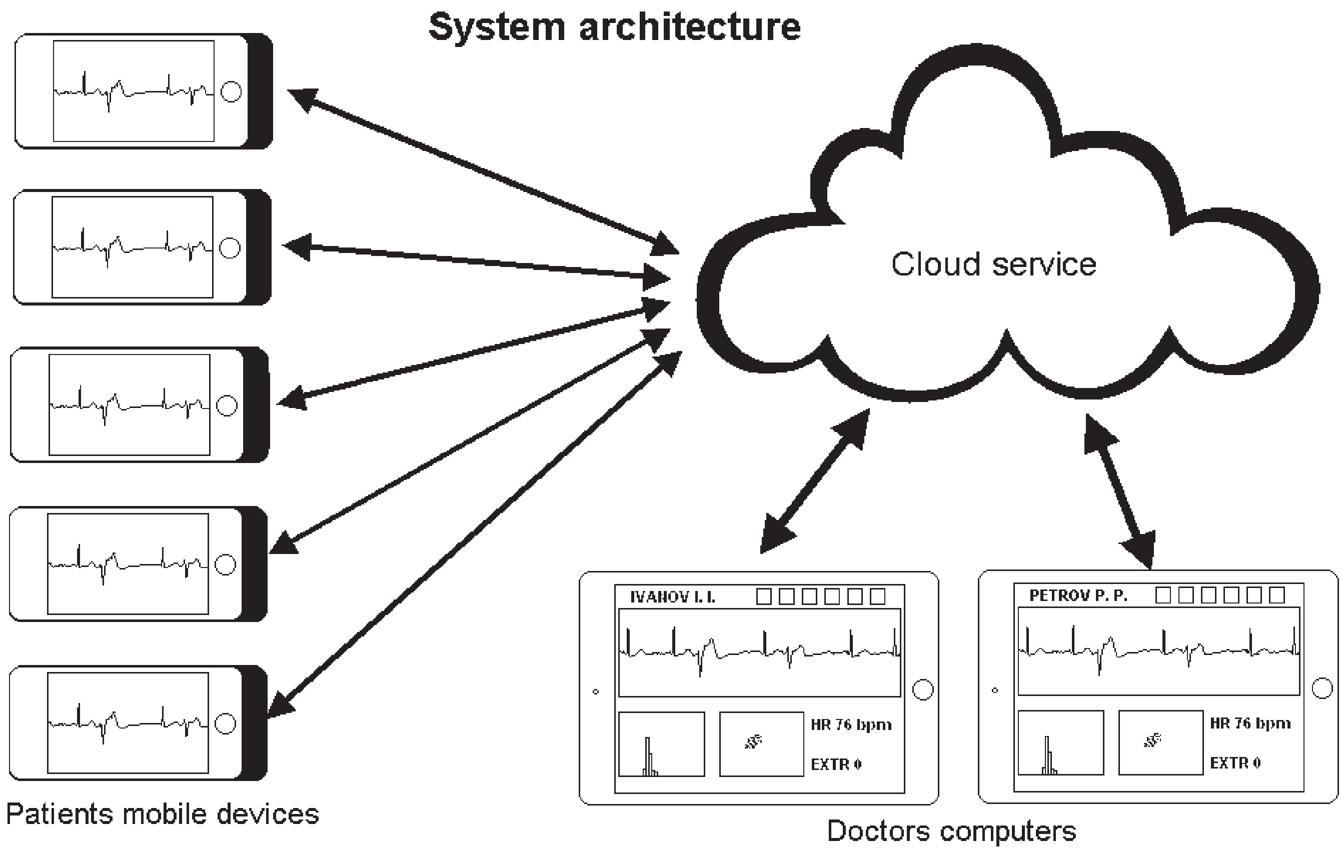

Fig. 1. Common architecture of the mobile cardiac monitoring system. Patients use their personal smartphone based ECG acquisition devices for the ECG registration and transfer to the cloud service via mobile phone connection and Internet. Doctors get access to the patients data with the use of their smartphones or computers.

The part of the preprocessing procedures (including pacemaker pulses detection), that has to be implemented in the real-time mode, is realized at the smartphone while most of the ECG analysis algorithms are concentrated in the cloud service software. So in case of some algorithms modernization, most part of the ECG analysis software should be updated only at the cloud service.

The following main functions of the ECG processing and analysis are realized:

- pacemaker spikes detection (if they are present);
- heart rate control and measuring of RR-intervals;
- cardiac arrhythmia recognition;
- HRV parameters estimation.

B. ECG processing and analysis algorithms realized at the smartphone

The ECG analysis algorithms included into the patients smartphone software realize the following main functions:

- primary estimation of noise intensity in the signal; the fragments with excessively high noise level are not processed further;
- recognition of pacemaker spikes, if they are present in the signal;
- preliminary filtering of the signal;
- decimation of the signal for the transfer to the cloud service.

If a patient has implanted pacemaker, it is very important to use a method of ECG acquisition and processing that provides the pacemaker spikes detection and visualization. As most of the modern pacemakers use bipolar mode, that is characterized by very small amplitude of pacemaker spikes in ECG signal (typically about several millivolt and 0.4 -1.5 ms duration [6], [7]), the routinely used standard ECG acquisition equipment doesn't provide reliable detection and display of the pacemaker spikes due to the limited frequency bandwidth of the signal and to the low sampling rate [8]. The analog detection of pacemaker spikes [9], [10], [11] sometimes is not effective as it based on rather simple threshold detectors. Due to the use of wide frequency range of ECG signal amplifier and very high sampling rate 20000 Hz, the procedures of pacemaker spikes detection and estimation of their parameters are realized at the smartphone by fully digital methods.

The following main requirements to developed pacemaker spikes detection algorithm were postulated:

- real-time ECG processing to provide current display of the signal with minimal time delay;
- the algorithm should not use any preliminary information concerning presence of pacing in each particular signal;
- the algorithm should work both in case of paced ECG and in case of ECG without pacing.

At the first stage of the spikes detection procedure the current mean QRS-complexes amplitude estimation is implemented. This amplitude estimation is needed for the further adjusting of some thresholds used in the detection algorithm. The spikes detection procedure itself includes the following stages:

- estimation of background high frequency noise level for the adaptive correction of pacemaker spike detection thresholds;
- pacemaker spikes search, based on the detection of two steep slopes separated by a plateau having duration between 0.15 and 1.0 ms;
- estimation of the detected pulse parameters (duration and magnitude);
- compensation of the signal jump (just after the spike) caused by the pacemaker electrodes polarization; this procedure is based upon polynomial approximation.
- deleting the detected spike from the signal with the use of linear interpolation;

The pacemaker spikes detection algorithm causes the signal delay about 30 ms. Fig. 2 illustrates the spike detection process and the further signal correction.

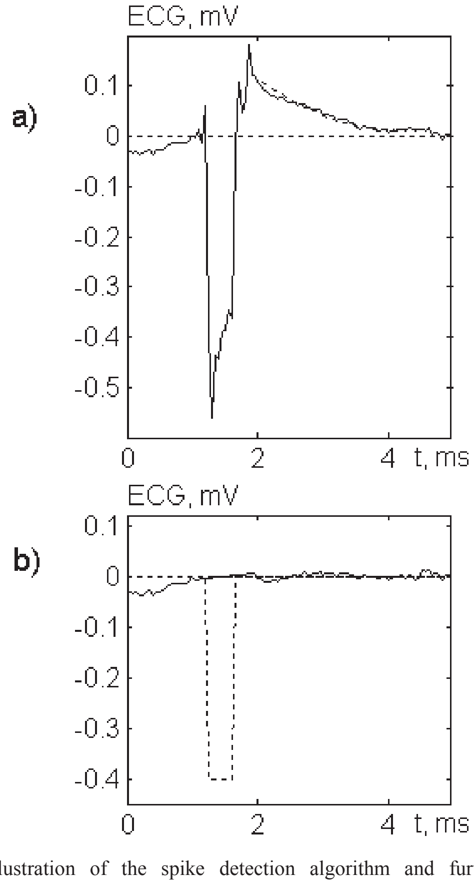

Fig. 2. Illustration of the spike detection algorithm and further signal correction: a) a fragment of raw signal containing a pacemaker spike (solid line) and polynomial curve used for the polarization jump compensation (descending dotted line); b) the same signal fragment after the pulse deleting and the jump compensation (solid line); dotted line shows the detected pulse restored with the use of its parameters.

To prepare the ECG for display on the smartphone screen the signal after spikes deleting is filtered by two digital filters: notching (removing AC interference) and low-pass (smoothing) filter. If some pacemaker spikes were detected, they are inserted in the filtered signal as vertical lines having the height equal to the measured amplitude of the spikes (Fig. 3).

After the spikes detection procedure the signal is decimated to 1000 Hz with preliminary smoothing and then translated to the cloud service in parallel with the detected spikes parameters.

The ECG signal with sampling frequency 1000 Hz transmitted from the smartphone is stored in the cloud service database both in original and filtered forms. The signal filtering is implemented with the use of comb filter (removing DC component, AC interference and its harmonics) and low-pass filter with the cutoff frequency about 35 Hz. The obtained signal together with the parameters of the detected pacemaker spikes is used further for off-line display.

The unfiltered signal with sampling frequency 1000 Hz is used as an input for the further ECG analysis stages. As pacemaker pulses and polarization jumps are removed from the signal, the same QRS detection algorithm is used as for the ECG without pacing [12].

After the spikes detection procedure the signal is decimated to 1000 Hz with preliminary smoothing (low-pass filtering with the cutoff frequency 250 Hz) and then is translated to the cloud service in parallel with the detected spikes parameters.

C. ECG analysis at the cloud service

The ECG signal with the sampling frequency 1000 Hz transmitted from the smartphone is stored in the cloud service database both in original and filtered forms. The signal filtering is implemented with the use of comb filter (removing DC component, AC interference and its harmonics) and low-pass filter with cutoff frequency about 35 Hz.

The unfiltered signal with sampling frequency 1000 Hz is used then as an input for the further ECG analysis stages [12]. First the noise level of the signal is estimated. If the noise level is too high, the corresponding ECG fragment is excluded from the further processing. If the signal is considered as noiseless, it is filtered by the adaptive AC interference filter and smoothing filter. After this preliminary filtering the signal is passed through high-pass filter with the cutoff frequency 5 Hz and differentiating filter to accentuate the signal components related to QRS-complex. Absolute values of the obtained signal samples are used as an input of the QRS detection procedure that represents a logical algorithm based on the threshold rules. This algorithm is adaptive to the current ECG amplitude and to the mean current heart rate. The beginning and the end points of each detected QRS-complex are then determined and also a reference point used for RR-interval estimation.

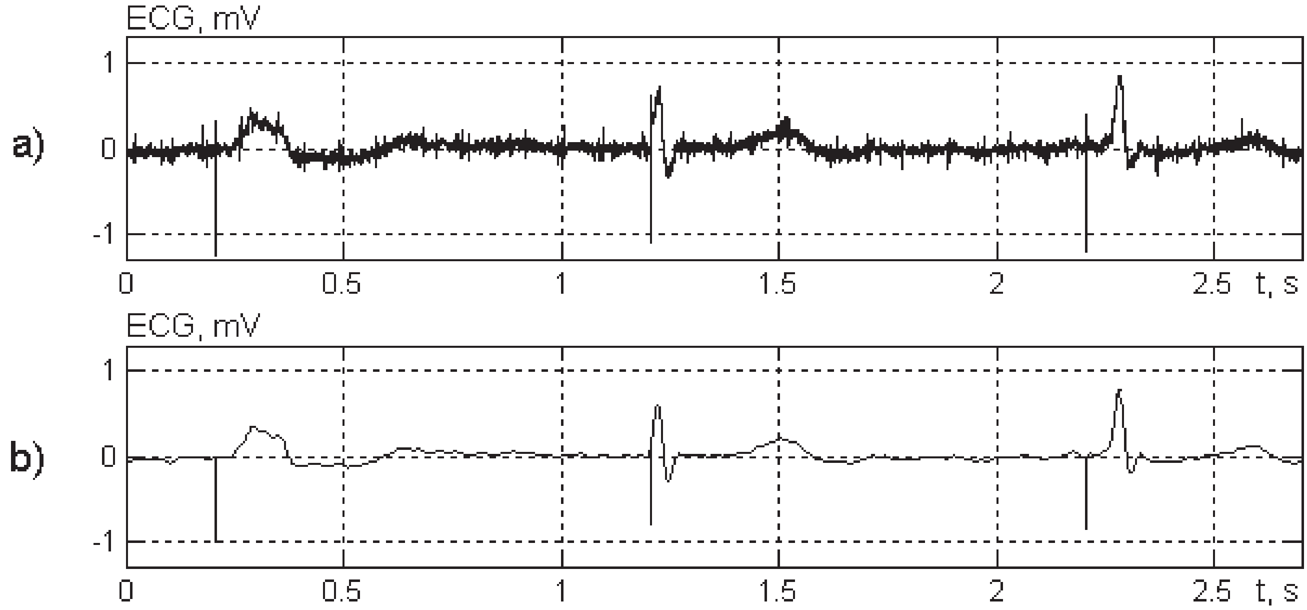

Fig. 3. Reconstruction of the detected pacemaker spikes for the ECG display. Raw wide-range ECG signal with sampling frequency 20000 Hz in which pacemaker pulses take place (upper plot) and the same signal after the correction of the segments containing spikes, smoothing, decimation and restoring of the detected pulses (lower plot).

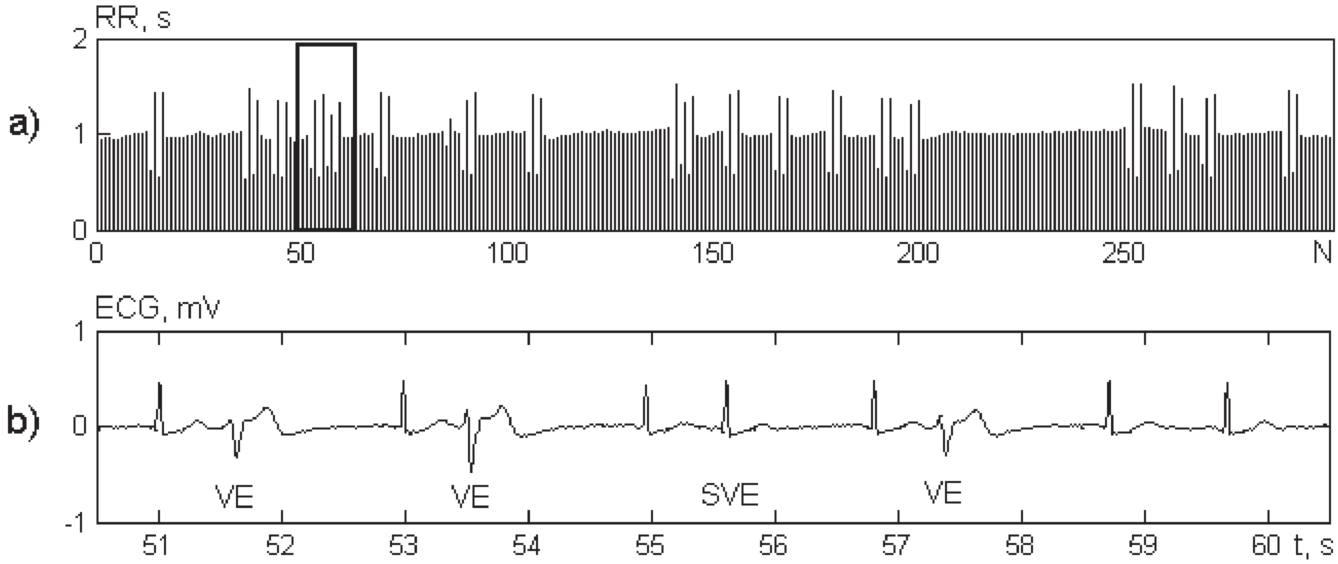

Fig. 4. Review of the arrhythmia recognition results at the screen of doctors computer: a) tachogram providing pictorial display of common rhythm as well as occurring arrhythmic events; a doctor can localize any ECG fragment of interest moving a special frame along the tachogram; b) ECG fragment corresponding to the tachogram segment marked by the moving frame: automatically detected arrhythmias are marked on the ECG; in this case they are three ventricular extrasystoles (VE) and one supraventricular extrasystole (SVE)

All detected QRS-complexes are grouped into clusters with the use of dynamical clusterization algorithm based on the following three indices characterizing the complexes similarity:

- linear decision rule using four QRS features (duration, amplitude, square and shift relative to the baseline);
- correlation based index;
- spectrum based index.

Each of the obtained clusters is labeled then as “normal”, “pathological” or “indefinite”.

The RR-interval values and the results of QRS forms classification are used further for the recognition of arrhythmia. The following types of arrhythmic events are recognized:

- supraventricular premature beats (extrasystoles);
- ventricular extrasystoles (including R/T, groups, multiform);
- missed beats;
- ventricular bigeminy and trigeminy runs.

The arrhythmia recognition algorithm is based on a set of empirically derived decision rules. All automatically detected arrhythmia events are marked at the displayed ECG for their visual review (Fig. 4).

The cardiac rhythm irregularity analysis including detection of atrial fibrillation is implemented by separate algorithm based on graphical representation of some regularities in the RR-intervals values and sequence [3].

The analysis of HRV is also based on the RR-intervals sequence and the QRS morphology classification results. Only the intervals between adjacent “normal” QRS-complexes (so called NN-intervals) are used for the HRV parameters estimation. The NN-interval values themselves as well as heart rate control function derived from these intervals with the use of spline interpolation are used for the HRV parameters calculation. The most widely used HRV indices both in time and frequency domains are determined by this procedure [13].

The system software provides not only calculation of commonly used HRV parameters [13] but also graphical presentation of cardiac rhythm in the forms of tachogram, histogram, Poincare plot and power spectral density plot (Fig. 5). These forms of graphical presentation are available both for patient and for doctor.

IV. RESULTS AND CONCLUSION

The pacemaker spikes detection algorithm was tested with the use of real ECGs set including 83 recording, each 300 s long. Following pacing modes underwent analysis: AAA (n=6), VVI (n=11), DDD (n=66), including biventricular pacing (n=17). Total number of the verified pacemaker spikes was 37921. The algorithm correctly detected 37276 spikes (98.3 %) while showed 531 false positives (1.4 % of the total pulses number).

The standard arrhythmia database MIT/BIH [14] was used for the QRS-complex detection and arrhythmia recognition algorithms testing. QRS detection algorithm showed sensitivity 98.90 % and specificity 99.88 % while for the ventricular premature beats these indices had values 87.2 % and 92.1 % correspondingly. The atrial fibrillation recognition algorithm was tested with the use of Atrial Fibrillation Database [14] and showed sensitivity 93.22 % and specificity 95.57 %. The achieved quality level corresponds to the best published algorithms for the arrhythmia detection [3].

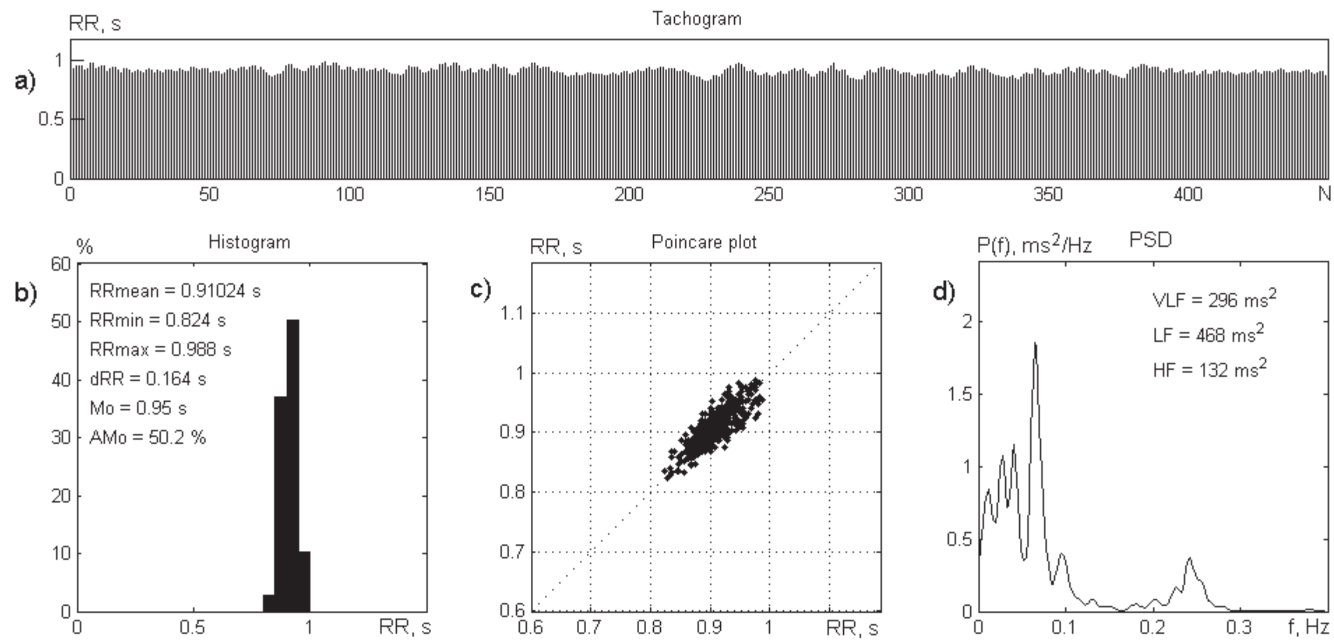

Fig. 5. The forms of cardiac rhythm graphical representation used in the system: a) RR-intervals tachogram; b) RR-intervals histogram and time domain HRV parameters; c) Poincare plot of RR-intervals; d) heart rhythm power spectral density plot and frequency-domain HRV parameters

Today all algorithms presented here are included into the software of mobile cardiac monitoring system CardioQVARK. The whole volume of data stored in the system database is permanently reviewed in order to reveal ECG analysis mistakes that take place in some situations. The results of this review are used for the further enhancement of the algorithms quality. Widening of the ECG analysis techniques scope is planned also at the further stages of the system development.

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