AUTOMATIC ANALYSIS AND VISUALIZATION OF MULTILEAD LONG-TERM ECG RECORDINGS

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Long-term ECG data collected during physical exercises (stress tests) and ordinary daily activity (holter recordings) are necessary for extended diagnosis of ischemia and transient cardiac arrhythmias. Owing to the computer-assisted systems, the cardiologist decision is considerably facilitated by fast methods for automated ECG analysis. The main requirements to such sophisticated system are high accuracy for identification of each normal and abnormal cardiac contraction, correct measurements over the beats' waveform, as well as adequate visualization of the results in the context of easy diagnostic interpretation. This work presents a PC-based application for automatic analysis of multilead ECG recordings. It implements fast algorithms for multilead QRS detection and classification of the QRS waveforms considering each user-selected channel. Categorized long-term diagrams are plotted showing the timing of each consecutive beat. The RR-interval trend is also provided. Signal-averaged technique is applied to obtain noise-free and stable P-QRS-T pattern at preset time-intervals during physical exercise. Continuos measurements of the P-QRS-T patterns allow the tracing of any changes provoked over time. Adequate graph representation facilitates the iterative visual identification of such changes. The basic software is opened for cardiologist-assistant supplements.

Keywords: ECG system, QRS detection, QRS classification, Signal-averaging, HR Trend

1. INTRODUCTION

Electrocardiographic (ECG) measurements during controlled exercise stress test (treadmill, bicycle, ergometer) are indicated for observing the effects of increases in the myocardial demand for oxygen and finding an evidence of ischemia [1]. Besides, long-term ECG recordings during daily activity (holter recordings) are necessary for identification of patients at risk of arrhythmias (with and without sustained symptoms), and for extended diagnosis of transient arrhythmias [2]. In order to facilitate the cardiologist decision, major efforts are directed towards developments of software solutions for ECG signal processing, which are directly applicable in computer-based systems. It is obvious that an interpretive multilead ECG system for the laptop or desktop computer, connected to ECG acquisition module with wireless data transfer, is a practical and preferable tool for any cardiologist. The latest technologies allow continuous recording of high-resolution ECG signals, which enhance the possibilities of precise cardiac diagnosis. The challenge for development of interactive software application for automatic multilead ECG analysis, which implements accurate algorithms for ECG signal processing and adequate visualization of the results, is under the scope of the present article.

2. METHOD AND SOFTWARE IMPLEMENTATION

Short description of the methodology and the sequence of processing branches implemented in the computer-based ECG system, is described bellow. The software application (Visual C) is running under Windows with minimal PC resource requirements.

2.1 Preprocessing

- *Processing of high-resolution ECG signals* sampled at 1kHz, 12-bit per channel.
- *Reading of 8 input channels* in consent to the typical configuration of multilead analogue ECG acquisition modules. The standard 12 ECG leads are recalculated according to the mathematical transforms described in [3].
- *Preprocessing filtration* of each input channel – it is obligatory for suppression of the most common artifacts, which are induced during ECG acquisition, e.g. baseline wandering, powerline interference and electromyogram noise. Following the principles of ECG signal processing [3], we developed digital filtering procedures, which were successfully applied during real-time detection of pathological ECG events in one previous study of the authors [4]. The same filtering procedures were implemented in the PC-based ECG system, adapted to warrant pass-band of 0.05 Hz - 30 Hz for the ECG analysis module (ECG1), as well as pass-band of 2 Hz – 18 Hz for the QRS detection module (ECG2).
- *Noise detector* – Artificially induced unnatural components in the ECG signal should not be considered during analysis and their appearance should be marked. Digital procedure for detection of artifacts with amplitude at the saturation level, as well as with extremely steep slope was implemented, and applied independently for each ECG lead (on ECG2).
- *Visualization* of 12-lead ECG (see Fig.1);
- *Visual tools* for user-friendly software management:
  (i) manual disable of unconnected or low-quality ECG channels;
  (ii) manual selection of the most informative lead to perform analysis;
  (iii) measurements on manually picked ECG waves – amplitude and duration.

2.2 ECG Analysis

- *QRS detector* – The position of each ventricular complex should be accurately recognized. We embedded a digital procedure for single-channel QRS detector based on analysis of dynamic amplitude and slope thresholds that was previously developed for microcontroller based ECG devices with on-line operation [4]. Besides its simplicity and fast signal processing, the procedure supports our next ECG analysis methods, which require correct localization of a reference point on the QRS complex waveform, corresponding to the maximal amplitude R-peak. The QRS detector [4] was optimized for 8-bit, 250 Hz sampling frequency, and therefore we supplied ECG2 with reduced resolution at the input of the developed QRS detector. The noise immunity of the QRS detector is improved by:
  (i) step over the segments marked by the noise detector;

Fig.1. Computer-based ECG system - Main window of the application.
Upper traces: Visualization of standard 12-lead ECG;
Bottom trace: Visualization of manually selected ECG lead to perform analysis. Convenient visual tools, as well as adequate marks of QRS-detection and QRS-classification, facilitate the fast rhythm review by the physician. Manual measurements are also supported.

(ii) synchronized QRS detection for all ECG leads, that means validation of one QRS mark if it was found within a tolerable QRS-complex interval (for example ±100 ms) in more than 50 % of the user-selected leads.

- *QRS classifier* – Automatic classification of the QRS waveforms is recommendable for almost all ECG diagnostic systems, especially those used for analysis of long-term ECG recordings. The most commonly applied QRS classification is based on considerations regarding the origination of the heartbeat. Following this classification, the QRS complexes are recognized in our system as:
  (i) Normal beats (N) – the beats of the sustained rhythm, with regular sinus node activation. N-beats have repeating narrow waveforms (<120 ms).
  (ii) Supraventricular ectopic beats (S) – known as supraventricular extrasystoles (SVES), which are initiated from ectopic centers in the atrium. S-beats have narrow QRS complexes, resembling the sustained rhythm. They appear earlier than the normal activation, followed by a normal RR interval.
  (iii) Ventricular ectopic beats (V) – known as ventricular extrasystoles (VES), which originate from ectopic centers in the ventricles, earlier than the

normal period of the N-beats. The next RR interval is prolonged. V-beats usually have bizarre waveforms of wide duration (>120 ms).

The proper recognition of the beat type is clinically important, since the frequent occurrence of S and V beats is a sign for disturbance in the depolarization process, preceding in many cases the initiation of malignant cardiac arrhythmias [5]. Therefore, we aimed to embed QRS classifier with high accuracy, implementing the knowledge about the specifics of each beat type, joint with the authors' experience with on-line algorithms for pathological beats recognition. The QRS classifier was realized according to the fast algorithm described in [4], with some additional updates for discrimination of S-beats [6] and QRS duration measurements. Because of the restricted paper space, we shall mention only the principles for QRS classification.

(i) Assessment of the QRS waveform deviation from the QRS pattern of the sustained rhythm – 64x32 histogram matrix is build which accumulates dynamically the amplitude-temporal distribution of the successive QRS pattern waveforms [4]. The R-peak time alignment of all heartbeat waveforms is very important. Fig.2. depicts such a matrix, where N and S beats are superimposed within the dark area of repeating waveforms, while the V beats fall outside this area. The rating of N and S beats is high, while the rating of V-beats is low.

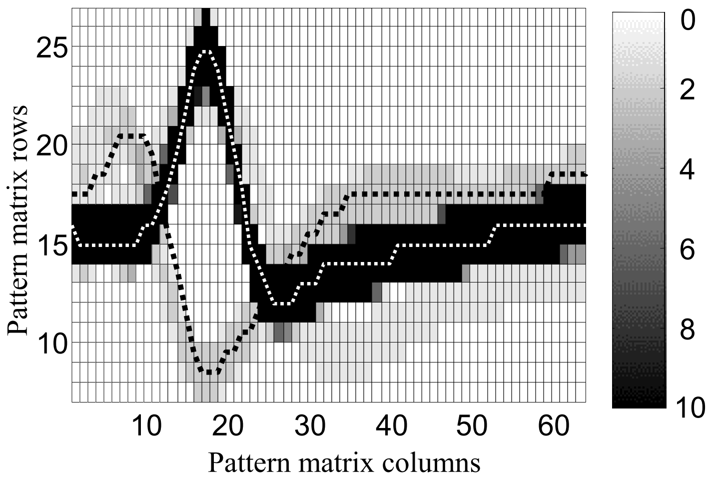

Fig.2. Assessment of QRS waveform by pattern matrix.

(ii) Assessment of RR-intervals: S and V -beats are recognized by differences between the coupling RR intervals and the mean RR-interval [6].

(iii) Measurement of the QRS width – QRS onset-offset detection is applied based on amplitude and slope criteria [3]. V-beats are detected of longer width than N and S.

The outputs of the *QRS detector* and the *QRS classifier,* both applied on the selected ECG lead, are visualized in Fig.1 (bottom trace). The R-peak detection marks are shown above each QRS, together with adequate QRS classification annotations (N, V, S). Each QRS waveform is painted with respective color.

- *Timing diagrams* giving information about the appearance of each consecutive heartbeat over the total duration of the ECG recording (Fig.3). These diagrams are categorized according to the beat type (N, V, S), as well as they show detected noise strips. Manual positioning of the cursor over these timing diagrams allow fast re-positioning of the ECG trace at the time of the underlined heartbeat.
- *Heart-Rate Trend* (Fig.3) - shows the HR variation over time during the full-length ECG recording. A mean HR value is typically presented (instead of single moment value) which averages several consecutive heart cycles. Moving the cursor over the HR trend allows the fast re-positioning of the ECG trace at a selected moment.

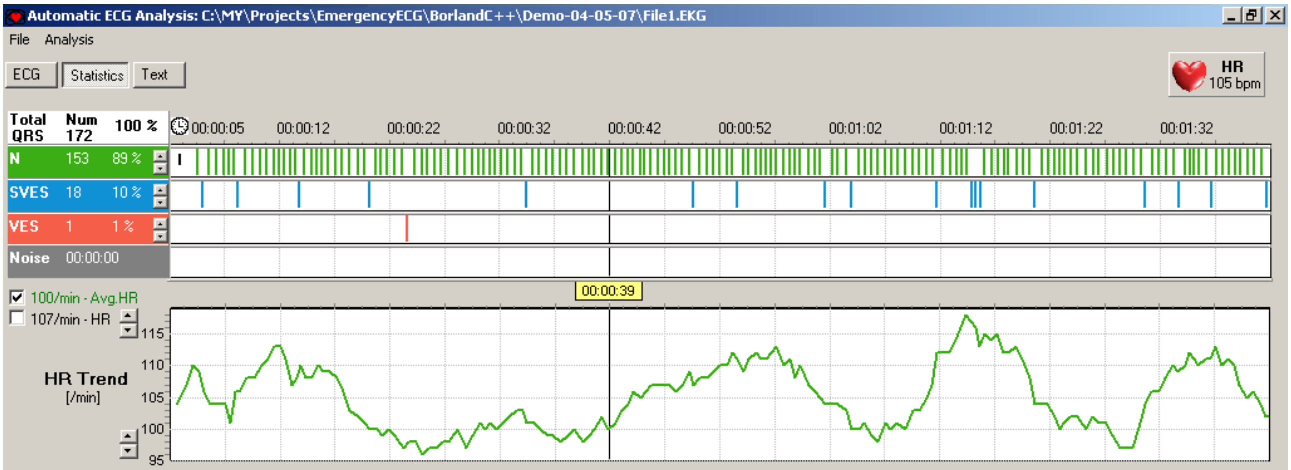

Fig.3. Computer-based ECG system – Window for visualization of timing diagrams showing the appearance of each consecutive N,V,S beat and the noise strips; Plot of the heart rate trend is also provided.

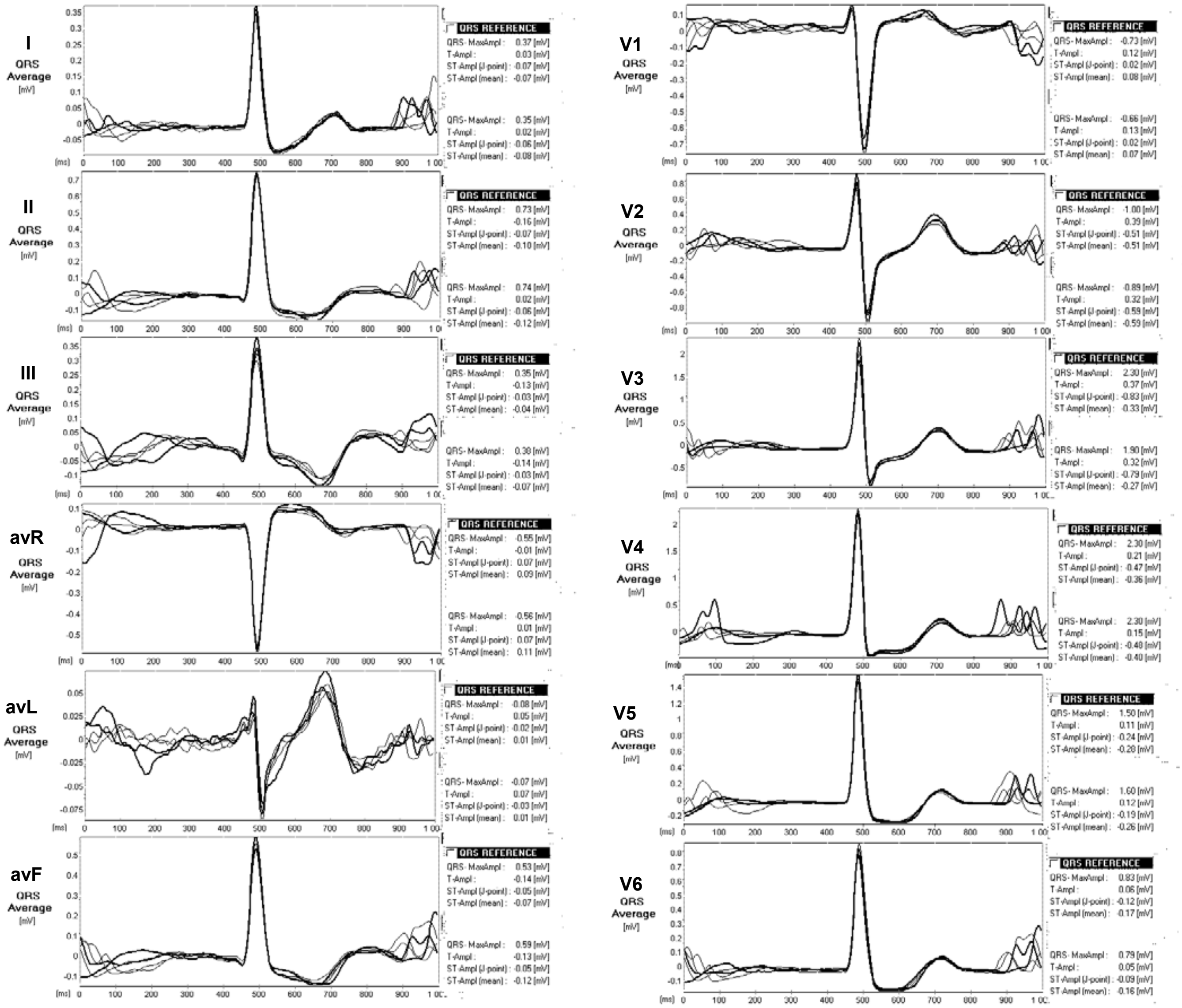

Fig.4. Standard 12-leads: P-QRS-T patterns obtained by signal-averaging technique. Superposition of patterns at consecutive time-intervals allows iterative visual identification of any changes over time in each of the 12 ECG leads. Measurements of specific ECG waves belonging to the initial and current pattern are continuously indicated.

• *Signal-averaging of the heartbeat waveform* - it is known to be a useful tool for extraction and analysis of low-amplitude signal components, containing important diagnostics information, but inadmissible for analysis using conventional 12-channel ECG. Signal-averaging of high-resolution ECGs is widely applied for detection of late potentials [7], as well as recent studies proved its effectiveness for quantitative diagnosis of patients with acute myocardial infarct [8]. Using the user-selected lead of the high-resolution signal ECG1, we applied synchronized averaging of all normal P-QRS-T cycles within a defined time interval (excluding all S and V beats). Thus we obtained patient-specific high-resolution pattern with significant diminution of some delusive changes due to both extracardiac noise influences and interbeat variances. This pattern is representative for the most stable QRS, ST and T-waves, reflecting the actual electrophysiologic condition of the patient's myocardium. The continuos extraction of such stable patterns at different moments during controlled stress test allows tracing of any changes provoked over time by the exercise loading (e.g. ischemia evidences). Adequate graph representation facilitates the iterative visual identification of these changes, such as in Fig.4, where P-QRS-T patterns measured at different moments are superimposed independently for the standard 12 ECG leads.

• *Measurement of ECG waves* – Different techniques are applied over the P-QRS-T pattern to detect QRS, ST and T-waves and to measure their duration and amplitude. The waves' features are indicated continuously for both the reference pattern (selected automatically by the system or manually by the physician) and the current pattern. Thus deflections from the initial/reference state are followed.

3. CONCLUSIONS

We have developed computer-based ECG system for analysis and visualization of multilead long-term ECG recordings. The system integrates complex software skills and knowledge about ECG signal processing. It implements optimized methods for detection, classification and measurements of ECG waves, with adequate visualization of the results in the context of easy diagnostic interpretation. The basic software is opened for cardiologist-assistant supplements.

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