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Processing of ECG Signals Detected by Portable Devices

N. V. Myasnikova*, M. P. Beresten, and L. A. Dolgih

Specific features of processing ECG signals (ECS) detected by portable devices are considered. ECS enhancement against a noisy background is achieved by ECG decomposition with further selection of components forming the useful signal. Extremum filtering rather than empirical mode decomposition is used to reduce the computational effort without affecting the results of decomposition. This advantage of extremum filtering allows it to be used in portable electrocardiograph software.

Introduction

ECG signal (ECS) enhancement against a noisy background is an important problem of electrocardiography. ECS fragments bearing valuable diagnostic information can be identified using modern techniques for digital processing of signals [1-4].

High-frequency noise is usually caused by the recording system, interference of concomitant signals, etc. Low-frequency artifacts and the isoline drift can be produced by coughing, breathing, or limb movements (in the case of ECG recording from limb leads). Low-frequency artifacts can also be caused by poor electrode–skin contact. Physiological interference is not characterized by a specific waveform or spectral composition; usually, it is dynamic and non-steady. Thus, the main types of noise affecting the ECS include the isoline drift, muscular tremor, power line noise, and motion artifacts [5].

Modern portable ECG recorders allow ECG to be detected under field conditions. However, this can lead to considerable signal distortion due to interference from other portable devices, transmitting stations, power transmission lines, etc. As a result, the task of ECG processing becomes more difficult.

ECS detected using the the CardioQVARK cardiomonitor implemented as an iPhone cover were used in this work. These ECS are available from the CardioQVARK database [6].

Penza State University, Penza, Russia; E-mail: avitel@pnzgu.ru
* To whom correspondence should be addressed.

There are two approaches to noise removal from detected ECS. The first approach is based on filtering, usually linear, applied to the PQRST wave. Low-frequency filters with cut-off frequency up to 100 Hz (i.e., in the range containing the major part of diagnostically valuable information) effectively remove high-frequency noise. However, use of such filters can smooth the QRS complex and modify the characteristics of the PQ and ST segments [7]. Moreover, this approach is hardly compatible with high-frequency electrocardiography intended to detect the low-amplitude high-frequency components in the range up to and above 500 Hz. Use of low-frequency filters for removal of the isoline drift often leads to distortion of the P and T waves. Adaptive and nonlinear filters, as well as the Wiener and Kalman filters, are especially often used for this purpose and provide more effective noise removal [8, 9]. The main disadvantage of the use of these filters is that the efficiency of processing is highly dependent on the model used. Any differences between the ECS and the model used for filtering can lead to inadequate interpretation of the ECS parameters.

The second approach to the ECS processing for noise removal is based on ECS decomposition with further selection of components forming the useful signal. This approach makes use of wavelet analysis with subsequent thresholding, the method of principal components, etc. [10, 11]. It is more adaptive to the tested signal and provides analysis within the frequency range selected by the user. Its main disadvantage is high labor input, as well as the problem of selection of components bearing valuable diagnostic information.

Methods

Two decomposition methods should be considered: the empirical mode decomposition (EMD) [12, 13] and the extremum filtering technique [14-19] protected by an RF patent [20]. The extremum filtering has an advantage over the EMD: it is based on a simpler decomposition algorithm that allows the computational effort to be reduced without affecting the results of decomposition. This makes the extremum filtering especially useful for rapid ECG analysis.

The EMD is widely used for digital processing of signals. This method is highly adaptive to the tested signal, which allows accurate evaluation of the properties of various steady and non-steady processes. The technique provides decomposition of any complex signal into a finite (and often small) number of empirical modes bearing information on the process under consideration.

The empirical mode decomposition is performed in several steps: a) all extremums $x_{\min}$, $x_{\max}$ of the signal x are extracted; b) the envelopes $e_{\min}$, $e_{\max}$ are constructed; c) the mean $m = 0.5(e_{\min} + e_{\max})$ is calculated; d) the mode $d = x - m$ is isolated; e) the steps (a)-(d) are applied to the remaining components of m.

It was shown in [14-18] that EMD has common features with the extremum filtering technique, which allows a multi-extremum signal to be decomposed into alternating components.

The following operator is used for smoothing based on the extremum values y_{ei} at time points t_{ei}, $i = 1, ..., K$:

$$y_{ci} = 0.25y_{\mathrm{e}i-1} + 0.5y_{\mathrm{e}i-1} + 0.25y_{\mathrm{e}i+1}. \qquad (1)$$

Then, the alternating component is extracted:

$$y_{pi} = -0.25y_{\mathrm{e}i-1} + 0.5y_{\mathrm{e}i-1} - 0.25y_{\mathrm{e}i+1}. \qquad (2)$$

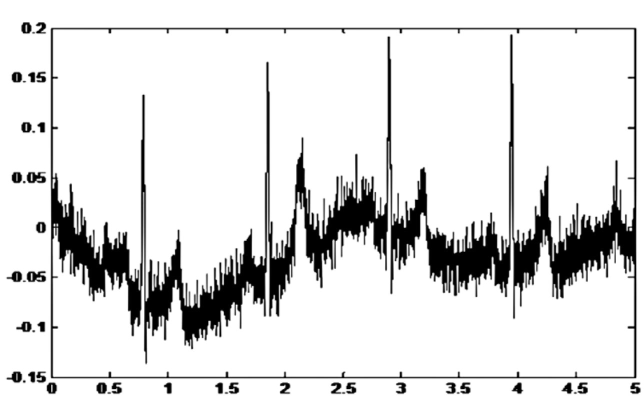

Fig. 1. ECS detected with a portable device.

During the subsequent iterations the high-frequency component is extracted from the component y_{ci} smoothed during the previous step; then the high-frequency component is, in its turn, smoothed.

This technique is based on the iteration procedure of extraction of a component with given frequency determined locally by the time intervals between the extremums. This procedure corresponds to adaptive high-frequency filtering [Eq. (2)] with simultaneous smoothing by adaptive low-frequency filtering [Eq. (1)].

The main difference between this technique and EMD is that the smoothed component is extracted directly from the sequence of extremums without constructing the signal envelope. The sequence of extremums is smoothed by calculating the mean between the average values of the current and the preceding extremum and the mean between the average values of the current and the next extremum. The alternating component of the signal is extracted by calculating the difference between the initial and the smoothed sequences of extremums.

The mode decomposition is performed by sequential application of Eqs. (1) and (2). Multiplication by 2^{-1} or 2^{-2} can be replaced by shifting to the right by one or two digits, respectively. This allows the labor intensity of the procedure to be reduced. MATLAB simulation of the ECS processing using a 1-sec sliding window showed that the labor intensity of the EMD was almost five times higher than that of the extremum filtering technique.

The modes are represented by their extremums only, so that the mode recovery is attained by approximation with bell-shaped pulses with the required accuracy [19].

An example of ECS detected with a portable 20-kHz device is shown in Fig. 1. The decomposition of this signal is illustrated in Fig. 2 (only the first high-frequency modes are shown). The abscissa is the time (seconds), and the ordinate is the signal (dimensional units). It can be seen from Figs. 1 and 2 that the first three components are the high-frequency noise, while the subsequent components form the ECS proper. The lower-frequency components of the frequency are caused by breathing, low-frequency trend, etc.

The components providing valuable diagnostic information contain alternating signal/noise segments. To develop an automatic procedure for extraction of the diagnostically valuable components, it is thus necessary to provide extraction of the QRS complexes (a task similar to the classical detection problem). The dispersion becomes considerably higher at the diagnostically valuable segments of these components. This effect is not observed in components that do not contain diagnostically valuable information (Fig. 3). The dispersion vari-

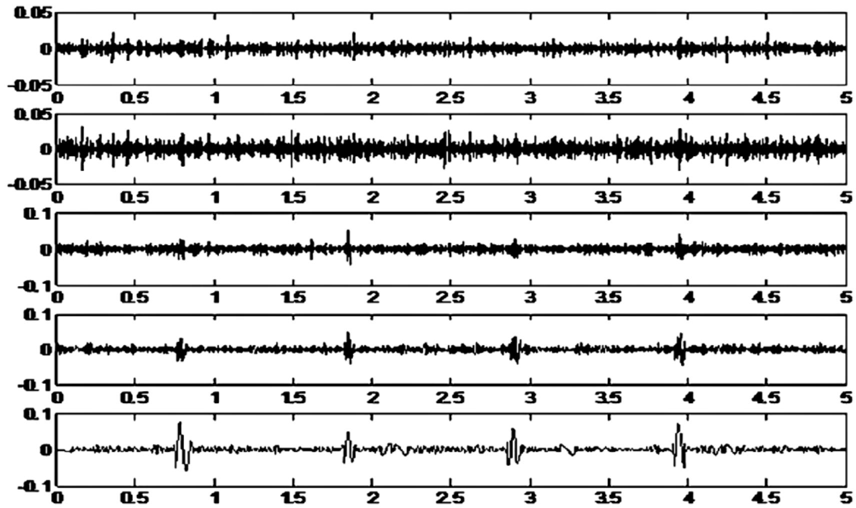

Fig. 2. First modes obtained by decomposition with an extremum filter.

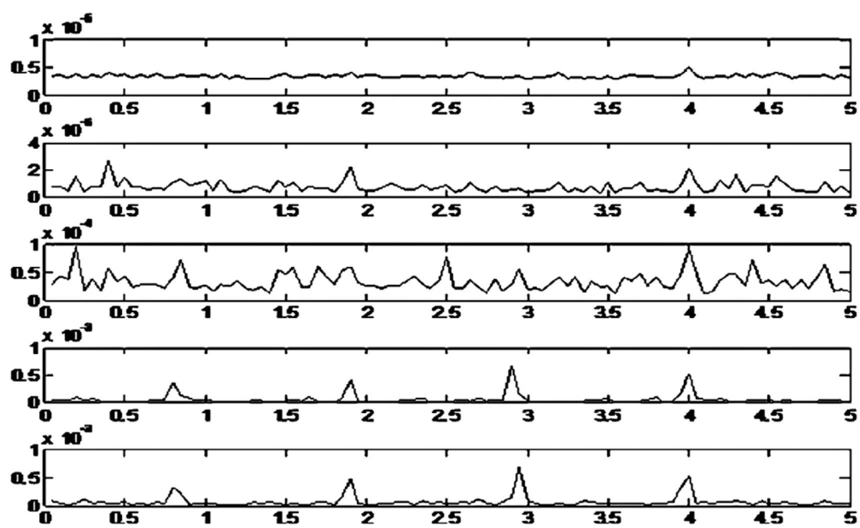

Fig. 3. Variation of the component dispersion in the sliding window.

ance indicates thus the diagnostically valuable components.

As noted above, the diagnostically valuable modes are characterized by alternation of high-frequency noise “leaks” and QRS complex components. This leads to an increase in the dispersion and a decrease in the number of extremums indicative of the frequency content. Thus, the noise in the diagnostically valuable modes has higher frequencies and lower dispersion values, while the QRS complex has lower frequencies and higher dispersion values. This can be used as an additional (frequency) criterion for identification of the QRS complex components.

It should be noted that in the case of a sufficiently clear signal there can be no noise leaks between the QRS complex components. In this case, theoretically, the frequency in the diagnostically valuable segments increases, while in the intervals between these segments a steady component is observed.

Results

Special software was developed for implementation of the extremum filtering of noisy ECS.

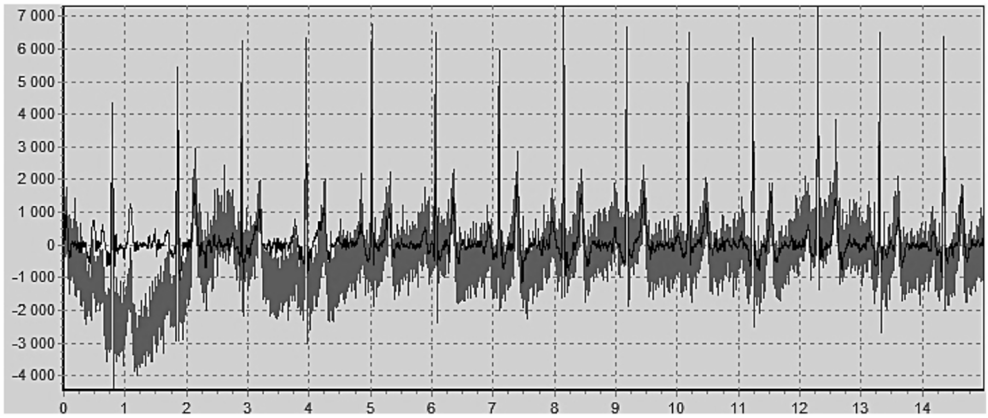

Fig. 4. Initial ECS and the results of its processing using the extremum filtering technique.

The software provides filtering of high-frequency noise and trend components of ECS detected by a portable ECG device. It implements the following functions:

– initial data entry from the CardioQVARK database using API protocols;

– extremum filtering of ECS noise;

– reduction of the filtered signal frequency down to 1 kHz;

– visualization of the initial data and the processed ECS.

The ECS filtered using the algorithm described above is shown in Fig. 4 against the background of the initial signal.

It can be seen that application of the extremum filtering removes the trends, straightens the isoline, and considerably reduces the level of high-frequency noise.

Conclusion

In addition to rapid assessment of the signal characteristics, the extremum filtering technique can also be used for complex signal restoration. This technique can be effectively used in developing software for portable CardioQVARK cardiomonitors.

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