Novel adaptive approach for correcting baseline wander from ECG signals

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Abstract— **The purpose of this study is to create effective algorithm for eliminating baseline wander from ECG signals and compare performance of different approaches for baseline wander correction. A new adaptive method for baseline wander elimination, based on reference signal composition of adaptive filter by using multiresolutional wavelet transform of noisy ECG signal, was proposed. Efficiency of different baseline wander correction methods for processing model ECG signals contaminated by baseline wander was researched. The accuracy of determining the ST-segment deviation for real ECG signals by using proposed approach in comparison with established baseline wander filtering techniques was studied. The proposed method of adaptive filtering with reference signal obtained by wavelet decomposition is distinguished from existing baseline wander correction methods by relatively high processing efficiency and small distortions of the ECG signals after filtering.**

Keywords— **ECG signal, baseline wander, multiresolution wavelet analysis, adaptive filtering, ST-segment**

I. Introduction

Electrocardiographic (ECG) signal processing is the gold standard of modern cardiac diagnostics to detect abnormalities of cardiac conduction system, cardiac arrhythmias, and predictive identification of severe cardiovascular diseases, such as cardiac ischemia, myocardial infarction etc [1 – 3]. ECG signal recorded by surface electrodes located on the human body is accompanied by the presence of interference and noise of different intensity and origin.

Interference caused by human breathing and the displacement of electrodes due to involuntary movements, leads to significant distortion of the ECG signal, the occurrence of baseline wander and increasing the measurement errors of ST-segment parameters, which are widely used for diagnosing cardiac ischemia. From the point of view of the spectral characteristics baseline wander of the ECG signal is a quasi-periodic signal with the baseband is below the average human heart rate, and the majority of researchers in their work for the baseband of baseline wander suggest a range from almost dc to 0.6 – 0.8 Hz [4, 5]. The stochastic nature of baseline wander and partial spectral overlapping with ECG signal are the main reasons why new advanced digital processing methods should be developed.

The main aim of this research is to create novel method for effective ECG baseline wander elimination and at the same time causes insignificant phase distortions of ST-segments. In this paper we have developed the effective technique for baseline wander eliminating based on adaptive filtering of ECG signal while obtaining a reference signal by using multiresolution wavelet decomposition of noisy ECG signal.

II. Theory

In current practice, for filtering baseline wander from the ECG signal in the time domain, approximation methods are used. However these methods have fundamental limitations in the typical frequency range of the presented baseline wander [4]. As the main frequency of the baseline wander increases, the accuracy of filtering the ECG signal becomes worse, and when the noise frequency reaches a value equal to half of the average heart rate, which is the actual sampling frequency of the baseline wander, reconstruction becomes impossible because the conditions of the Sampling theorem are not fulfilled. Considering that the human heart rate varies in the range 0.5–3 Hz and the average and most common value is about 1 Hz, the actual frequency range of the baseline wander to be properly isolated from the ECG signal by using approximate methods is 0–0.4 Hz.

Baseline wander correction methods, based on linear frequency filtering of ECG signal, by using high-pass or low-pass filters, do not have the indicated disadvantages. In the first case, low-frequency additive wander is filtered out from the biosignal, while in the second case it is isolated by the filter from the additive mixture of the signal and the noise and then subtracted. However, due to the unavoidable overlap between the frequency spectra of the original ECG signal and the baseline wander, in both cases losses in the information part of the biosignal spectrum are unavoidable as well as phase distortion of ST-segments during digital processing, and therefore this approach is quite ineffective for quality suppression of baseline wander.

III. Materials and methods

Adaptive filtering of the baseline wander for the ECG signal is not widely used due to the intrinsic complications

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of recording a reference signal correlated with the noise signal, which is a necessary condition for the applicability of the adaptive noise cancellation methods [1]. Nevertheless, in this paper we attempt to develop an effective baseline wander correction method based on using an adaptive filter, where the reference signal could be obtained only by advanced digital processing of the noisy ECG signal.

The ECG signal processing based on discrete wavelet transforms represents decomposition of the original signal into a series of approximation and detail coefficients [6]. Our preliminary studies as well as results of other researchers have shown that the series of approximation coefficients obtained from high levels of wavelet decompositions has a frequency spectrum similar to the spectrum of the baseline wander, which allows us to use multi-resolution wavelet analysis to isolate the baseline wander from the original noisy ECG signal [7].

Fig. 3 shows the block diagram of the proposed adaptive canceler for correcting baseline wander from the ECG signal; 1 – primary input of the adaptive canceler, which contains the raw ECG signal; 2 – the unit for multiresolution wavelet transform of the raw ECG signal; 3 – the series of approximation coefficients; 4 – the series of detail coefficients; 5 – the filter with finite impulse response, the output of this filter contains the estimation of presented baseline wander for reference input of the adaptive canceler; 6 – the output of the adaptive canceler, which contains ECG signal almost free from baseline wander contamination.

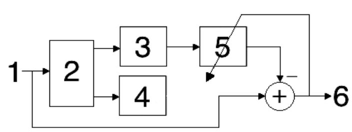

Fig. 1. Block diagram of the proposed adaptive canceler of baseline wander from the ECG signal

One of the possible ways to investigate the performance of different baseline wander correction methods is to model the filtering process of ECG signal. The mathematical model of ECG signal with presented baseline wander is assumed to be additive. The model ECG signal was obtained by using a dynamical model developed by P.E. McSharry and coauthors [8]. For studying the optimal parameters of baseline wander elimination, we used model fragments obtained for an average heart rate of 1 Hz.

Analysis of the factors affecting appearance of baseline wander in the ECG signal showed that this type of noise represents a low-frequency signal arising stochastically and could be described mathematically as an additive combination of deterministic and random components:

$$N(k) = N_{\max} \cdot \left(\sum_{i=1}^{4} \sin\left(2\pi f_i \frac{k}{f_s} \right) + \psi(k) \right) \quad (1)$$

where $N_{\max}$ is the amplitude of the model baseline wander; f_i is the set of frequencies for additive harmonic signals representing the deterministic components of the noise signal; f_s is the sampling frequency; and $\psi(k)$ is the random component, obtained by filtering the white Gaussian noise using a low-pass filter with cut-off frequency 0.8 Hz. In this case, for modeling baseline wander we used the frequency values f_1, ..., f_5 equal respectively to 0.1, 0.2, 0.4, 0.6, 0.8 Hz.

As one of the quantitative criteria for evaluating the performance of the baseline wander correction, we propose the distortion factor δ of the ECG signal after passing through the corresponding processing stages:

$$\delta = 100\% \cdot \sqrt{\frac{\sum_{i=1}^{M} [Y_f(i) - Y(i)]^2}{\sum_{i=1}^{M} Y^2(i)}} \quad (2)$$

where i is the sample's number of the signal; M is the number of samples in the considered fragments of the signal; $Y_f(i)$ is the sample of the ECG signal after filtering; $Y(i)$ is the sample of the model ECG signal free of baseline wander.

Optimal parameters of baseline wander filtering were selected by minimizing distortion of ECG signal in the wide range of signal-to-noise ratio calculated as follows:

$$SNR = 10 \lg \frac{ECG}{BW} \quad (3)$$

where SNR is signal-to-noise ratio, dB; BW is spectral power of baseline wander $N(k)$; ECG is spectral power of model ECG signal.

For practical implementation of ECG signal filtering MATLAB R2013a software with the Wavelet Toolbox application program was used.

IV. Results

The performance of different baseline wander correction approaches for the ECG signal processing was analyzed for the following methods: an approximation method (**AM**); high-pass filtering (**HPF**); the proposed method of adaptive filtering with reference signal obtained by wavelet decomposition (**AFWT**); the direct subtracting high level approximation coefficients from raw ECG signals (**WT**) (the same block diagram as Fig. 1 but without using adaptive filter 5).

The performance of approximation method depends primarily on the uncertainties in detecting the fiducial points of the ECG signal (nodes of the approximation), and also on the interpolation method. To identify the nodal points, we used the highly effective QRS-wave detector based on pass-band filtering, Hilbert transform and adaptive thresholding [9].

Our studies have shown that the most effective interpolation method is provided by cubic spline interpolation: the average value of δ for the ECG signal (in the considered range of signal-to-noise ratio from 0 to 20 dB) was 9%; for linear interpolation 10.6%; for quadratic polynomial interpolation 9.8%.

Correct baseline wander removal by applying high-pass filter will be dependent on the cut-off frequency and the filter's type. The results of our research have shown that the highest efficiency of processing the ECG signal is achieved by using FIR high-pass filters with a linear phase, while the optimum value of the cut-off frequency is 0.6 Hz.

The effectiveness of generating a reference signal for an adaptive filter based on using multi-resolution wavelet transforms is determined by the type of wavelet function and the level of the decomposition [6]. Taking into consideration the nature of the ECG signals, the most effective wavelet filtering results are obtained by using Daubechies wavelets: a family of orthogonal wavelets that calculated iteratively [6].

For quantitative estimating the effectiveness of baseline wander extraction, we choose Pearson correlation coefficient R between the model noise signal $N(k)$ and the series of approximation or detail signals, obtained at the corresponding level of the multi-resolution wavelet transform for the additive combination of the model ECG signal and baseline wander. Figure 2 shows the variation of R vs. the level of the decomposition S while using different types of wavelet functions.

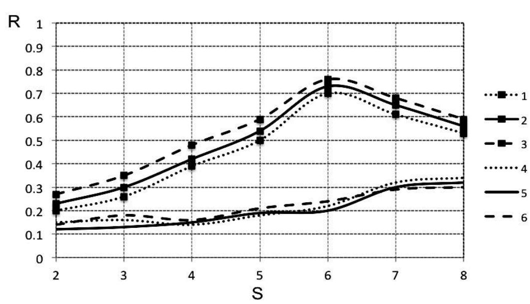

Fig. 2. Correlation coefficient R vs. level of the decomposition S for different types of wavelet functions: *1*, *2*, *3* are approximation signals for 2nd, 4th, and 6th order Daubechies functions, respectively; *4*, *5*, *6* are detail signals while using the same Daubechies functions

According to the obtained data the optimal estimate for baseline wander of the ECG signal is formed by using series of approximation coefficients at the 6^{th} level of wavelet decomposition; and the optimal wavelet function is 6^{th} order Daubechies wavelets.

The quality of the adaptive filtering of baseline wander will depend on the algorithm for determining the coefficients of the adaptive filter that maximizes the signal-to-noise ratio [1]. Our research has shown that the least distortion of model ECG signal and the best correlation between the estimate of the baseline wander at the output of the adaptive filter (5 on the Fig. 1) and the model baseline wander has been provided by software implementation of the recursive least-squares method based on the solution of the Wiener-Hopf equation; the best processing quality is achieved for the following parameters of this algorithm: the forgetting factor λ is 0.96; filter order is 12.

The performances of different approaches for ECG signal baseline wander correction are shown on Fig. 3; for quantitative comparison we use the variation in distortion factor δ of the ECG signal vs. the signal-to-noise ratio *SNR*.

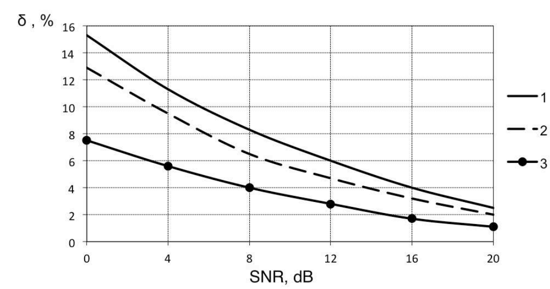

Fig. 3. Distortion factor δ vs. signal-to-noise ratio *SNR* for different baseline wander correction methods: *1* – HPF; *2* – AM; *3* –WT; *4* – AFWT

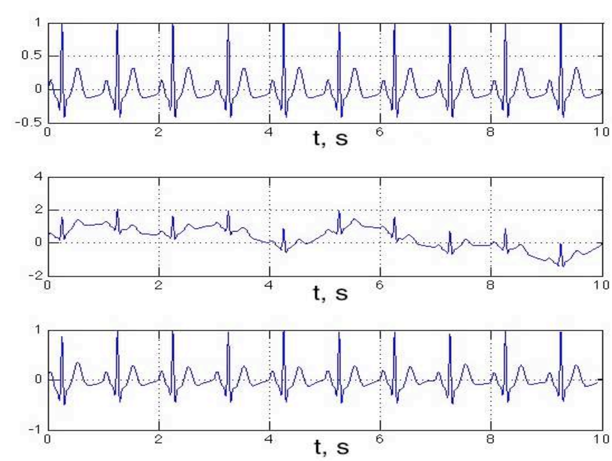

Fig. 4. Processing the noisy model ECG signal by using proposed approach. From top to bottom: the original ECG signal; the ECG signal contaminated by baseline wander; ECG signal after adaptive filtering

Figure 4 illustrates the ECG signal processing at the presence of intensive baseline wander by using proposed approach based on adaptive filtering and wavelet multiresolution transform. These illustrations show the high quality of ECG signal processing; at the output of the adaptive filter presence of baseline wander is almost insignificant.

For a comparative analysis of the errors that occur in the determination of peak levels of ST episodes when processing real clinical recordings of ECG signals with baseline wander we have used open access European ST-T database from MIT Physionet (http://physionet.org). The European ST-T database is the most suited database for our research, it contains annotations for ST episodes by giving its beginning, its peak and its end, and also contains an interval of at least 30 seconds during which the absolute value of ST-segment deviation is more than 100 μV [10].

Table 1 contains the ST-segments levels processed by using several approaches for eliminating baseline wander in clinical ECG recordings. Signs '+' or '–' indicate an elevation or depression of the ST-segment respectively, while the number represents the peak level of the ST episode in μV.

Table 1. Peak levels of ST episode for European ST-T database in μV

Recording	AM	HPF	WT	AFWT
e0103 (+150)	+140	+120	+140	+150
e0105 (–150)	–120	–90	–130	–145
e0106 (–100)	–80	–70	–90	–95
e0107 (+300)	+260	+240	+310	+310
e0108 (–200)	–170	–150	–180	–190
e0110 (–600)	–560	–510	–590	–600
e0112 (–400)	–340	–350	–380	–390
e0113 (–250)	–200	–190	–220	–240
e0114 (–100)	–60	–50	–80	–90
e0118 (+350)	+300	+250	+320	+330

V. Conclusion

In this research we proposed an effective method for correcting baseline wander in ECG signals based on simultaneous using of adaptive filtering and multiresolution wavelet transform. Proposed approach is an effective method for elimination of baseline wander from ECG signals and provides the least distortions of the processing ECG signals in a wide range of the signal-to-noise ratio.

Analysis of obtained results for processing clinical ECG recordings indicates that the proposed adaptive method for baseline wander elimination from the ECG signal provides the lowest measurement error of ST-segment deviations. Among the classical approaches based on approximation and spectral filtering the smallest inaccuracy in determining the level of ST-segments deviations as well as less distortions of processing ECG signals are achieved by using the cubic spline approximation method.

The proposed method is distinguished from existing baseline wander correction methods by relatively high processing efficiency and small distortions of the ECG signals after filtering. This approach also could be successfully used to remove the baseline wander from other physiological signals, such as pulse wave signals and so on.

Conflict of Interest

The authors declare that they have no conflict of interest.

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