Wavelet Denoising for Multi-lead High Resolution ECG Signals

M. Kania, M. Fereniec, R. Maniewski

Institute of Biocybernetics and Biomedical Engineering
Ks. Trojdena 4, 02-109 Warsaw, Poland
Email: mkania@ibib.waw.pl

Abstract. *The aim of this study was to investigate the application of wavelet denoising in noise reduction of multichannel high resolution ECG signals. In particular, the influence of the selection of wavelet function and the choice of decomposition level on efficiency of denoising process were considered and whole procedures of noise reduction were implemented in MatLab environment. The Fast Wavelet Transform was use. The advantage of used denoising method is noise level decreasing in ECG signals, in which noise reduction by averaging has limited application, i.e. in case of arrhythmia, or in presence of extrasystols.*

Keywords: high resolution ECG, signal processing, wavelet denoising

1. Introduction

Noise reduction in ECG signals is one of the main problems, which appear during analysis of electrical activity of the heart. The most troublesome noise sources contain frequency components within ECG spectrum, i.e.: electrical activity of muscles (EMG), and instability of electrode-skin contact. Such noises are difficult to remove using typical filtering procedures. Efficient analytical tool which allows to increase signal to noise ratio is a technique of averaging of cardiac cycles. Effectiveness of this method strictly depends on stable sinus rhythm. That requirement is however not fulfilled in case of arrhythmia, or the presence of many extrasystoles. In such signals noise reduction is only possible with using, more advanced signal processing method, as wavelet denoising technique.

In this work efficiency of denoising for different wavelet functions and different levels of signal decomposition were examined. Wavelet denoising method was compared to signal averaging method (using cross-corelation method [1]) in case of arrhythmia patients.

2. Subject and Methods

The first step of wavelet denoising procedure is selection of mother wavelet – $\psi_{m,n}(t)$, which forms set of functions (family of wavelets), by compression or stretching or translation. In further analysis following mother wavelet was used:

$$\psi_{m,n}(t) = 2^{-\frac{m}{2}}\psi\left(2^{-m}t - n\right) \tag{1}$$

where

n coefficient of time translation,

m coefficient of scale (compression).

The next step is the selection of number of decomposition levels of signal $x_i(t)$. First decomposition level is obtained by using two complementary high- and low-pass filters and then half of samples are eliminated.

The filters cut frequency is equal to half of bandwidth of analyzed signal. Such algorithm, which is amplification of discrete wavelet transform (DWT), is known as fast wavelet transform [2].

As a result of this transformation so-called approximations (cA_j) and details (cD_j) are obtained. Approximations (cA_j) correspond to low frequency components present in signal, while details (cD_j) contain high frequency components. Next levels of decomposition of signal x(t) – detail coefficients cD_{j+1} and approximation cA_{j+1} are obtained in analogous way, when in place of original signal approximation coefficients of j-th decomposition level are analysed (Fig. 1).

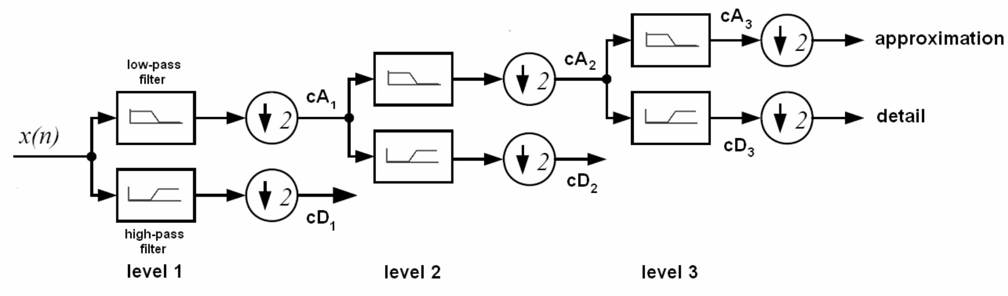

Fig. 1 Diagram of multiresolution analysis of signal $x_i(t)$.

Procedure of noise reduction in signal $x_i(t)$ in i-th channel is based on decreasing of noise content in high frequency components (details) of signal. In first step threshold values for details coefficients at every level of decomposition are determined according to relationship [3]:

$$THR_j = \sqrt{2\log\left\|cD_j\right\|}\,, \tag{2}$$

Next step is the modification of values of j-th level detail coefficients basis of appointed threshold. This method is called soft thresholding procedure [4]:

$$cD_j(t) = \begin{cases} \operatorname{sgn}(cD_j(t))(|x| - THR_j) & cD_j(t) > THR_j \\ 0 & cD_j(t) \le THR_j \end{cases} \tag{3}$$

The final step of the analysis is reconstruction of signal $x_i(t)$ based of approximation coefficients chosen i-th level of decomposition (cA_i) and modified detail coefficients from i-th (cD_i) as well as higher levels of decomposition:

$$x_i(t) = \sum_n cA_{m,n}\varphi_k(2^{-m}t - n) + \sum_{m=m_0}^{m_k}\sum_n cD_{m,n}\psi_{m,n}\left(2^{-m}t - n\right), \tag{4}$$

where

$\varphi_k(t)$ is scaling function from k-th level of decomposition,

$\psi_{m,n}(t)$ are wavelet functions for $m=m_0 \ldots m_k$ levels of decomposition.

Procedures of noise reduction were implemented in MatLab environment. Program user has opportunity to test effectiveness of denoising process for 19 wavelet functions: Daubechies proposed functions [5] (db2, db3, db4, db5, db6, db7, db8), and their modifications so-called Symlets wavelets (sym2, sym3, sym4, sym5, sym6, sym7, sym8) as well as biorthogonal wavelets (bior3.3, bio4.4, bio6.8). It is also possible to select the decomposition level of analyzing signal.

3. Results

Main window of developed program with example of ECG signal denoising is shown in Fig. 2.

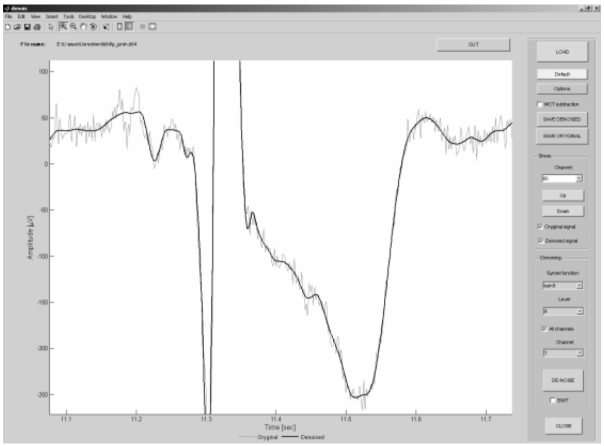

Fig. 2 Enlarged fragment of original (grey line) and denoised (black line) ECG signal from single lead is shown. Wavelet function sym8 and 5th level of decomposition were used

By analysis of different mother wavelets in multilead high resolution ECG signals the best wavelets were chosen with regards to signal morphology preservation i.e. db1 (for 4^{th} and higher decomposition levels), sym3 (for 4^{th} level) and sym8 (for 4^{th} decomposition level). In Fig. 3 results of signal denoising using these optimal wavelet functions are presented.

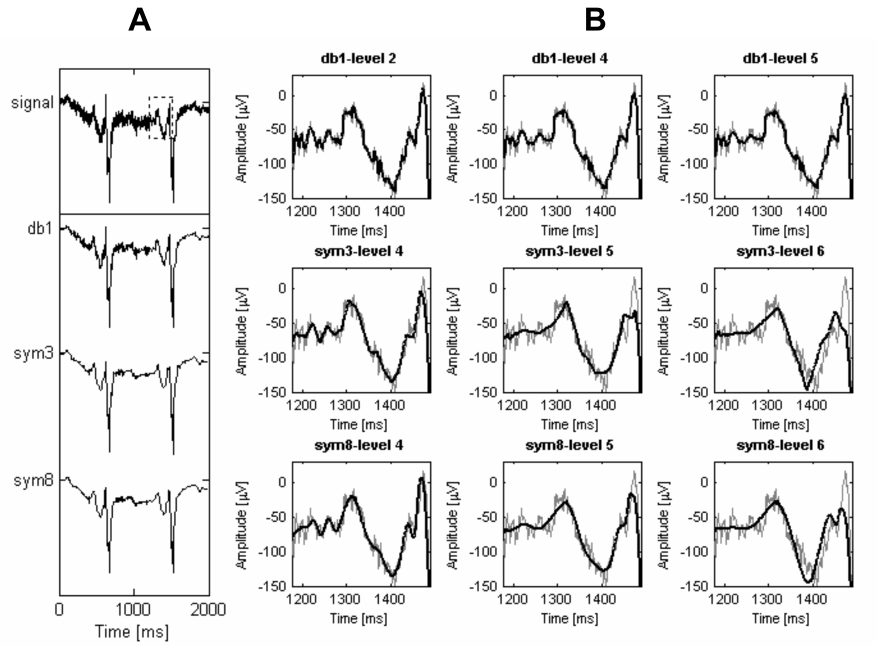

Fig. 3 Results of wavelet denoising. A – original signal and result of denoising procedure obtained by using wavelets: db1, sym3 and also sym8 (all with use of 5^{th} decomposition levels), B – magnified fragment (dashed box in A) of original signal and result of denoising procedure for wavelets: db1, sym3 and sym8 for successive levels of decomposition. Grey line represent original signal with noise, black line correspond to signal after denoising process.

Interesting results of noise reduction gives also application of wavelet sym8 for 5th level of decomposition. This function allows for good approximation of parts of ECG with lower frequency components P wave and T wave. However, it is done at expense of higher frequency components of ECG signal and affects morphology of the QRS complex.

A **B** **C**

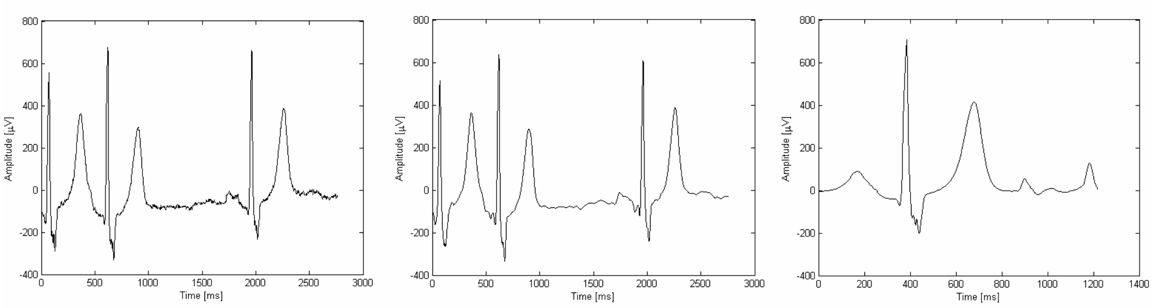

Fig. 4 Outcome of denoising procedure of ECG signal in a case of arrhythmia (lead V4): A – original signal, B – result of wavelet filtration (sym8 – level 5), C – result of averaging of cardiac cycles with use of cross-correlation method.

Comparing averaged ECG signal of patient with arrhythmia, obtained by cross-correlation method (Fig. 4C), and signal after wavelet denoising (Fig. 4B) the advantage of time-frequency technique over averaging method is noticeable. In arrhythmia case morphology of ECG signal is changing form beat to beat, that is why the procedure of averaging may lead to distortion of ECG morphology, in particular to smooth out lower frequency present in signal (first of all connected with depolarization phase of heart ventricles).

4. Discussion

In present study wavelet filtration was applied to ECG signals denoising and compared to averaging technique results. Different mother wavelets were examined to optimize denoising procedure. The crucial choice in wavelet filtration is selection of right mother wavelet, which could fit optimally to examined signal. Suitable number of decomposition levels is also important. The best results from among tested functions with regard to noise reduction showed wavelet db1, with 1^{st} to 4^{th} and higher levels of decomposition as well as sym3 for 4^{th} level of decomposition.

Increase of denoising efficiency of low frequency ECG components (T wave) in case of using sym8 function, at expense of worse approximation of higher frequencies (QRS complex), indicate validity of adaptable selection of wavelet function and the level of decomposition, depending on phase of electrical activity of the heart.

The advantage of wavelet method is possibility to receive good quality signal for beat to beat analysis and possibility to have high quality signal while averaging technique is impossible, as causing morphology distortion of ECG signals.

5. References

[1] Gomes J. A.: Signal-Averaged Electrocardiography: Concepts, Methods and Applications. Kluwer Academic Publications, Dordrecht, 1993.

[2] Mallat S.: A theory for multiresolution signal decomposition: the wavelet representation. *IEEE Pattern Anal. and Machine Intel.*, 1989, vol. 11, no. 7, pp. 674-693.

[3] Donoho D., Johnstone I.: Adapting to unknown smoothness via wavelet shrinkage. *J. ASA*, 1995, vol. 90, pp. 1200–1223.

[4] Donoho D. L.: De-Noising by soft-thresholding. *IEEE Trans. on Inf. Theory*, 1995, vol. 41, 3, pp. 613-627.

[5] Daubechies I.: Ten lectures on wavelets, SIAM, Philadelphia, 1992.

[6] Chouakri SA, Bereksi-Reguig F.: Wavelet denoising of the electrocardiogram signal based on the corrupted noise estimation. *Computers in Cardiology*, 2005, 32:1021-1024