Fine Tuning of the Dynamic Low-pass Filter for Electromyographic Noise Suppression in Electrocardiograms

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Abstract

In a series of publications, we have proposed and discussed the effectiveness of a dynamic low-pass filter for electromyographic (EMG) noise suppression in electrocardiograms (ECG). The goal of this study is to analyze the filter, and to suggest a better tuning for increasing the noise suppression and, at the same time, decreasing the signal distortion.

The principle of the filter is the creation of a function called 'wings' for evaluation of the frequency spectra of the ECG waves. This function controls the dynamic cutoff frequency of an approximation procedure proposed by Savitzky and Golay, making it adjustable to the frequency spectra of ECG waves.

The new way of forming the "wings" function permits: (i) stronger filtration of the low-frequency ECG components, (ii) reduced filtration in the transition zones of low to high frequency and vice versa (the highly diagnostic QRS onsets and offsets), and (iii) no filtration of the QRS zones of highest frequency.

The newly suggested dynamic low-pass filtration of ECG performs better than the one suggested in the most recent publication.

1. Introduction

The electrocardiogram (ECG) acquisition is often accompanied by high-frequency electromyographic (EMG) noise. EMG noise in resting ECG is quite common in subjects with uncontrollable tremor, in disabled persons having to exert effort in maintaining a position of their extremities or a body posture, in children, etc. The noise is picked up by the same electrodes as the ECG. EMG noise makes impossible the automatic localization of ECG waves and obstructs the visual analysis.

The noise is characterized by a frequency range from 5 to 70 Hz or even 100 Hz and by an amplitude of hundreds of microvolts. It is difficult to be filtered, due to considerable overlapping of its frequency spectrum with the frequency spectrum of the ECG. Setting the low-pass filter of the ECG to a lower cutoff level eliminates not only the muscle noise but also the clinically significant high-frequency components of the signals inside the QRS complex [1], J-waves and pacemaker spikes [2]. For that reason, in 2007, the American Heart Association (AHA) changed its low-pass filter recommendations from 35 Hz cutoff in 1967 [3] to 150 Hz for adolescents and adults and to 250 Hz for children [4].

In the clinical practice, little attention tends to be paid to the filter setting of the ECG instruments, resulting in inappropriate filter application. In fact, Kligfield and Okin [5] found that the low-pass filter setting was 100 Hz and above in 25% of the ECG devices and <100 Hz (most commonly 40 Hz) in 75% of the ECG devices obtained within an American medical community.

The tendency of maximal preservation of the QRS high-frequency components and filtering with a cutoff of >150 Hz leads to a high level of residual noise. The presence of EMG noise could cause serious problems to the analysis of the signal out of QRS and will worsen the detection of ischemia (in the ST-interval), atrial fibrillation and flutter (in the PQinterval), presence of T-wave alternans, etc.

Sayyad and Mundada [8] are using extended Kalman filter and extended Kalman smoother, but in both methods a great signal distortion can be observed in the QRS.

Joy and Manimegalai [9] are using wavelet transform to remove the EMG noise. The proposed method selects the best suitable wavelet function based at the 5th decomposition level. The authors claim that the method retains the distinctive features of the ECG.

Myriad filters are known to perform well with Gaussian and impulsive noise. Tulyakova [10] is showing good results with locally adaptive, low-pass Myriad filters.

The conflicting requirements for a strong suppression of EMG noise, and at the same time for a maximal preservation of the ECG high-frequency components, prompted us to create a dynamic procedure - strong filtration in the low-frequency components of the ECG and mild filtration in the high-frequency ones. A so-called

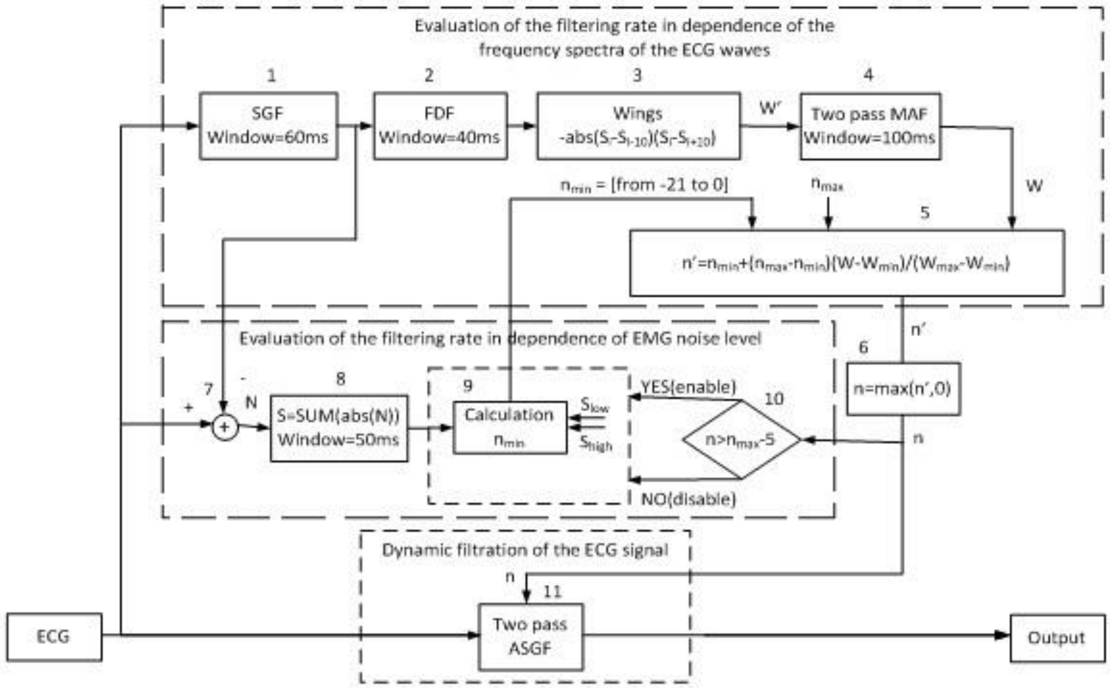

Figure 1. Block diagram of the method: Evaluation of the frequency spectra of ECG waves (blocks 1-5); Evaluation of the filtering rate in dependence of the EMG noise level (blocks 7-10); Dynamic filtering of the ECG signal (block 11);

'wings' function for evaluation of the frequency bands of the ECG elements was created [6, 11-13], which allowed a dynamic application with different filtering rate of the approximation procedure of Savitzky and Golay [7].

The goal of this study is to analyze the filter, and to suggest a better tuning for increasing the noise suppression and, at the same time, decreasing the signal distortion.

2. Method

The dynamic filtering is performed in pseudo-real-time (real-time with a certain delay) mode. It is designed in compliance with the new low-pass filtering recommendations for cutoff [4]. The computational cost depends on the sampling frequency.

The block diagram of the dynamic filtering is shown in Figure 1.

2.1. Evaluation of the filtering rate in dependence of frequency spectra of ECG waves

Evaluation of the frequency spectra of the ECG waves is done by blocks 1–6 of the block diagram of Figure 1 and is demonstrated in Fig. 2. The raw ECG (Fig.2a) is first filtered by Savitzky–Golay (SGF) in a fixed window of 60 ms (block 1 of Fig. 1).

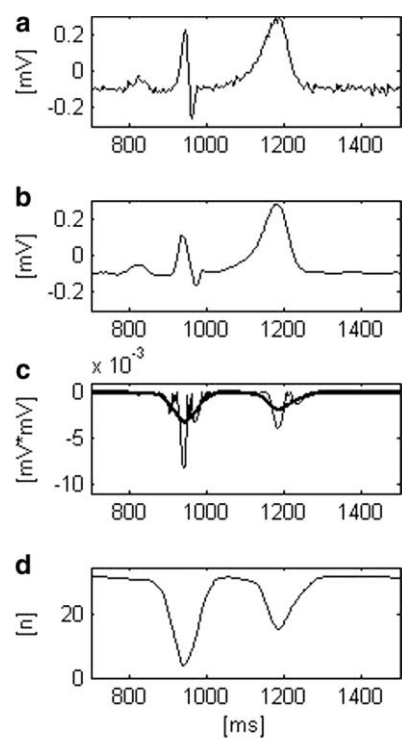

Figure 2. Calculation of the "*n*" signal. a) Input ECG, b) filtered ECG, c) "wings" function, d) transfer the "wings" into "*n*," used to define the dynamic window of the Savitzky–Golay filter

Then, a first-difference filter (FDF - block 2 of Fig. 1) with transfer function of

$$T_{FDF}(z) = (1-z^{m})/2 \quad (1)$$

is applied. The FDF is a comb filter with first notch frequency of $f = 1/(mT_S)$. We selected m to be

$$m=\text{round}(2T_{PL}/T_S), \quad (2)$$

where T_{PL} is the power-line period, and T_S is the sampling interval. The FDF high-pass 3-dB frequency is set at about 6 Hz, and the higher-frequency notches reject all harmonics of the power-line interference.

SGF and FDF filters are intended to filter EMG noise, power-line interference and baseline drift. The goal is a complete suppression of the noises, no matter of the QRS distortion and amplitude reduction, as shown in subplot 'b' of Fig. 2.

A so-called wings function is found by multiplying the slopes of two adjacent segments of 10 ms length having a common point. The product absolute value is then taken and inverted (subplot 'c' of Fig. 2). For a 1000 Hz sampling rate, the "wings" function is:

$$\text{Wings} = \text{abs}((S_i - S_{i-10})(S_i - S_{i+10})) \quad (3)$$

'Wings' is further smoothed by two-pass moving averaging with a window of 50 ms (block 4 of Fig. 1). The two-pass" is performed twice in the same forward direction. The result is a negative wave (shown with a thick line in Fig. 2 'c') that responds to the wave frequency of the ECG.

Blocks 5 and 6 of Fig. 1 transfer the particular values of the "wings" function to a number of samples 'n' (Fig. 2 'd'), defining the window length over which the final Savitzky– Golay filter (block 11) will be applied. If W is the smoothed "wings" and W_{max}, W_{min} its maximum and minimum values, the transfer formula to n, varying from n_{min} to n_{max}, is:

$$n = n_{min} + (n_{max}-n_{min})(W-W_{min})/(W_{max}-W_{min}) \quad (4)$$

2.2. Evaluation of the filtering rate in dependence of the EMG noise level

Blocks 7 to 10 of Fig. 1 are used for dynamic evaluation of n_min according to the level of EMG noise.
The raw ECG and the filtered one are subtracted to obtain the noise (block 7 of Fig. 1). S = sum of all absolute values in a window of 50 ms is calculated (block 8 of Fig. 1). Block 9 transfers the noise level into appropriate n_{min} values from n_{low}=-21 to n_{high}=0. Two constants: S_{low}=200µV and S_{high}=1000µV are set by simulation. The transfer formula is:

$$n_{min} = n_{low} + (n_{high}-n_{low})(S-S_{low})/(S_{high}-S_{low}) \quad (5)$$

Block 10 disables the high-frequency QRS to get involved in the correct calculation of the current level of the noise.

3. Results

The new way of forming the "wings" (shown in Fig.3 with a thicker line) permits:

- Stronger filtration of the low-frequency ECG components by increasing n_{max}=32 to n_{max}=40.
- Reduced filtration in the transition zones of low to high frequency and vice versa (the highly diagnostic QRS onsets and offsets). This is obtained by increasing the window length of the 'Two-pass MAF' (block 4 of Fig.1) from 50 ms to 100 ms.
- No filtration of the QRS zones of highest frequency by dynamic evaluation n_{min} = -21÷0 in dependence of EMG noise level, and no filtration if n'<1

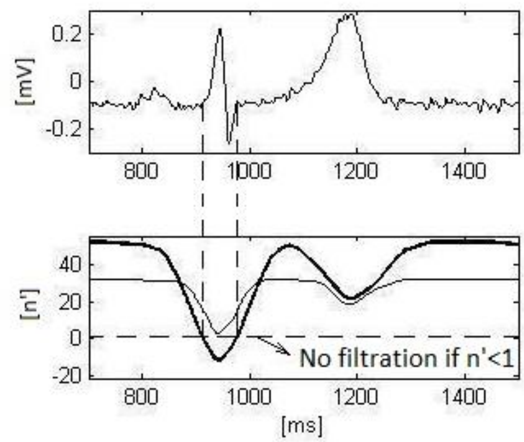

Figure 3. "Wings" function and its transfer to 'n'': thin line is for Christov et al. [13]; thicker line is for the current version.

The EMG noise suppression is demonstrated in Fig. 4.

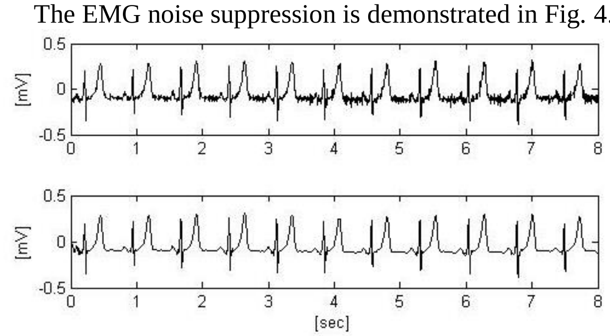

Figure 4. Noise suppression: a) Noisy ECG; b) Filtered ECG

The filtering efficiency is quantitatively evaluated using clean ECGs mixed with EMG noise to calculate the level of noise suppression L by the ratio of the initial n_{ini} and residual disturbances n_{res} after filtering.

$$L=n_{ini}/n_{res} \quad (5)$$

Noise suppression is computed from RMS values. Two values for noise suppression are calculated because of the non-homogeneous (dynamic) procedure. For the same setup as in Christov et al. [13] the current version is characterized by:

- stronger filtration of the low-frequency components of the ECG as P-wave, PQ-interval, ST-interval, T-wave and TP-interval (L_{outQRS} = 10.4 dB vs. L_{outQRS} = 9.3 dB in [13])
- lower filtration of the high-frequency QRS components (L_{inQRS} = 3.0 dB vs. L_{inQRS} = 3.3 dB in [13])

4. Discussions

The dynamic frequency response of the suggested filter is shown in Fig. 5. It can be seen that the low-frequency components of the specific ECG is filtered with a cutoff of 14 Hz, the high-amplitude T-wave is filtered with 26 Hz, and the high-frequency QRS from 100 Hz to infinite (no filtering). When number of samples defining the dynamic window of Savitzky–Golay filter get n<1 (2nd subplot of Fig. 5), no filtering is performed.

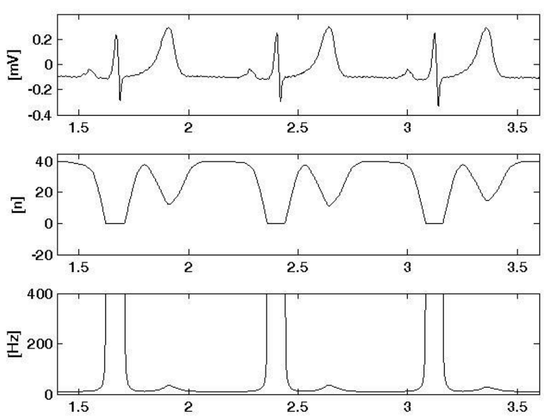

Figure 5. Frequency response of the suggested filter: a) ECG; b) number of samples “n,” defining the dynamic window of the Savitzky–Golay filter, c) instantaneous cutoff frequency of the suggested filter

5. Conclusions

The newly suggested dynamic low-pass filtration of ECG allows stronger filtration of the low-frequency components of the signal and in the same time reduced (or lack of) filtration in the highly diagnostic high frequency QRS.

References

[1] García-Niebla J, Serra-Autonell G. Effects of inadequate low-pass filter application. J Electrocardiol. 2009; 42(4):303–304.

[2] Nakagawa M, Tsunemitsu C, Katoh S et al Effect of ECG filter settings on J-waves. J Electrocardiol. 2014;47(1):7–11.

[3] Subcommittee on Instrumentation Committee on Electrocardiography - American Heart Association. Recommendation for instruments in electrocardiography and vectorcardiography. IEEE Trans Biomed Eng. 1967; 14:60–68.

[4] Kligfield P, Gettes LS, Bailey JJ et al. Recommendations for the standardization and interpretation of the electrocardiogram: part I: the electrocardiogram and its technology. A scientific statement from the American Heart Association Electrocardiography and Arrhythmias Committee, Council on Clinical Cardiology; the American College of Cardiology Foundation and the Heart Rhythm Society endorsed by the International Society for Computerized Electrocardiology. J Am Coll Cardiol. 2007;49:1109–1127.

[5] Kligfield P, Okin PM. Prevalence and clinical implications of improper filter settings in routine electrocardiography. Am J Cardiol. 2007;99:711–713.

[6] Christov II, Daskalov IK. Filtering of electromyogram artifacts from the electrocardiogram. Med Eng Phys. 1999;21(10):731–736.

[7] Savitzky A, Golay M. Smoothing and differentiation of data by simplified least squares procedures. Anal Chem. 1964;36:1627–1639.

[8] Sayyad RA, Mundada K Enhancement and denoising of ECG signal using extended Kalman filter and extended Kalman smoother. J Innov Electron Commun Eng. 2016;6(1):22–26.

[9] Joy J, Manimegalai P. Wavelet based EMG artifact removal from ECG signal. J Eng Comp Appl Sci. 2013;2(8):55–58.

[10] Tulyakova N. Locally-adaptive Myriad filters for processing ECG signals in real time. Int J Bioautom. 2017;21(1):5-18.

[11] Bortolan G, Christov I Dynamic filtration of high-frequency noise in ECG signal. Comput Cardiol. 2014;41:1089–1092

[12] Bortolan G, Christov I, Simova I, Dotsinsky I. Noise processing in exercise ECG stress test for the analysis and the clinical characterization of QRS and T wave alternans. Biomed Sign Process Control. 2015;18:378–385.

[13] Christov I, Neycheva T, Schmid R, Stoyanov T, Abächerli R Pseudo real-time low-pass filter in ECG, self-adjustable to the frequency spectra of the waves. Med & Biol Eng & Comp. 2017;1-10

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