Moving Window Signal Concatenation for Spectral Analysis of ECG Waves

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Abstract

In this paper we postulate a replacement for the averaging of successive waves spectra, by the concatenation of selected type waves (P, QRS or T) in a moving time window. The window size is selected as a result of compromise between the spectrum resolution (high for long window) and temporal response (fast for short window). To avoid the influence of a border effect, the order of concatenated waves is optimized with regard to the maximum smoothness of resulting signal. The smoothness estimate is based on the similarity of the first derivative of the adjacent signals.

Our results for a 10s window shows a considerable drop of estimated P-wave bandwidth from 151Hz to 107Hz (CSE Dataset3), which seems to be much more reasonable considering the physiological limitations of ECG signal generation. Similar results were observed for QRS and T waves.

1. Introduction

Spectral analysis of ECG waves is useful as a background for the medical analysis, as well as for studies on ECG signal aiming at estimation of the necessary throughput of transmission channel or storage space [1-3]. Recently introduced non-uniformly sampling ECG recorders also use the local bandwidth estimate to adjust the asynchronous data acquisition to expected local properties of the signal [4-6].

1.1. State of the art

Conventional tools for the signal spectrum analysis are the ARMA modelling and the Fast Fourier Transform. Although the ARMA models is robust to interferences and works well with short signal sections, the result is only a rough estimate of the Power Spectral Density (PSD) function [7]. Despite its most common usage, the FFT [8] is not directly applicable to the ECG waves spectral estimation due to their short duration. Consequently the spectrum of a single wave is sparse and studies on variability of the spectral content with time are restricted by the beat-to-beat length variability of each wave. Fortunately, in many applications the spectral analysis of consecutive wave sequences is performed for selected wave types. Two solutions were proposed as far to increase the resolution of resulted spectrum: concatenating of the signal sections and averaging of the corresponding spectra. These methods are mathematically equivalent thanks to the linearity of the Fourier Transform. Unfortunately, both of them suffer from the edge effect, which is the main cause of inaccuracy of FFT-based spectrum for short signals. The edge effect appears due to the discontinuity present at the ends of signal sections or, in case of wave trains, at the wave concatenation points [9].

1.2. Novelty of the presented approach

The main idea of presented method is minimizing the edge effect by optimization of waves order in a train. The waves' content, which is the subject of spectrum investigation, remains unchanged, while the signal discontinuity at the wave concatenation points is minimized through waves reordering. The optimization of the waves' order is based on the analysis of the signal value and derivative in the initial and terminal section of each wave. Consequently, each subsequent wave in the train is selected so as its initial section is best matching the terminal section of the preceding wave. This approach minimizes the global contribution of high frequency components not present in the waves, but resulting from discontinuity at the joint points.

The prototype optimization procedure was first implemented for the purpose of investigation of the waves' spectra in a recorded ECG. It considers each wave of considered type (P, QRS or T), previously delimited in selected lead. There is no restrictions on the sequence length or exclusion of selected waves (e.g. with significant distortions) from the train. The optimization procedure was also prepared for a moving window implementation allowing for real time analysis of the waves' spectra in the electrocardiogram. The window size is set as time-invariant or as covering a given number of waves. Each window position results in an optimized waves' train, but due to the variable length of waves, the train length and the spectrum bins number are irregular.

2. Material and Methods

2.1. Signal analysis

The raw electrocardiogram is first subject to the analysis performed with use of a subset of regular diagnostic procedures: heartbeats detection and waves delimitation. These procedures can be performed on a single ECG lead representative for the record or on each considered lead separately. Once waves' borders are calculated, the procedure estimates signal attributes in the initial and terminal parts of the wave (fig. 1). Selected attributes are:

- the value of first-order derivative used to match initial and terminal sections of adjacent waves aiming at maximum signal continuity,
- the average value of the signal used to compensate for the wave-to-wave voltage difference.

The signal analysis results with a table of section borders and attributes containing also data validity/exclusion flags.

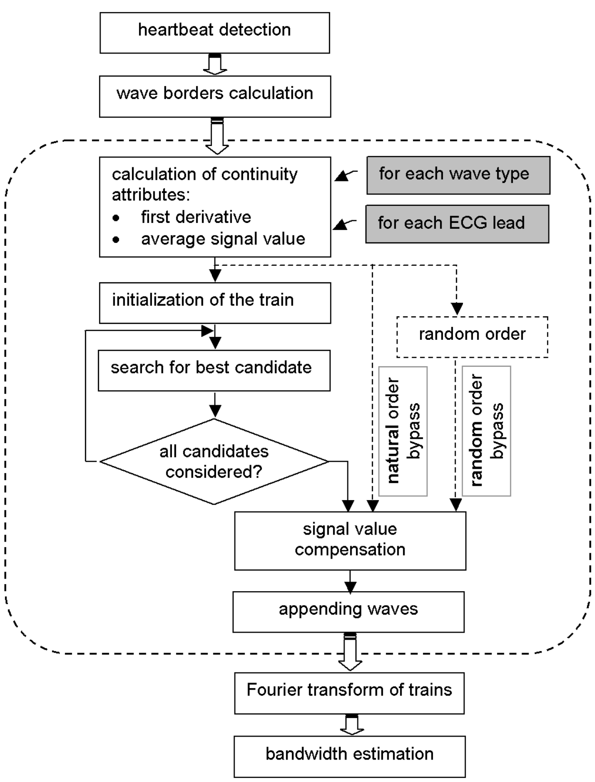

Figure 1. Signal processing diagram for investigation of the waves' spectra in a recorded ECG, procedures for optimization of waves order in a train are within the dash bordered area.

2.2. Minimizing the signal discontinuity

The optimization of the waves' order is based on the table of attributes. The iterative process matches the derivative value of the terminal section of the last wave in the train with the derivative value of the initial sections of all candidate waves. Once the minimum difference is found, the candidate wave is appended to the train and the absolute difference is added to the cumulative error value. The optimization lies in the minimization of the cumulative error, which represents least contribution from discontinuities in the waves' train spectrum.

Appending the wave to the train requires also compensation of possibly large difference in local signal values. The appended wave is shifted in the amplitude domain by the value of difference between amplitude attributes of corresponding terminal and initial sections.

2.3. Real time optimization

The specificity of real time implementation of the optimization procedure lies in the use of moving window in which the waves of specified type are recruited to the train. The train and the resulted spectrum are updated for each most recent wave at the input. The count of the waves in the window can be set as constant or the time span of the window can be set as constant, what decides whether the most obsolete wave should be considered. In both variants the train length and the spectrum resolution cannot be guaranteed as constant, because of variability of the waves' length.

Except for the most recent wave, the attributes of waves' initial and terminal sections do not need to be recalculated. If the existing waves' train was optimal in the sense of signal continuity, the most recent wave is simply inserted into the train after the wave it matches best. The preceding part of the train was left untouched, unfortunately, the subsequent part needs reordering.

The scheme of moving window optimization of P-wave train is presented in fig. 2.

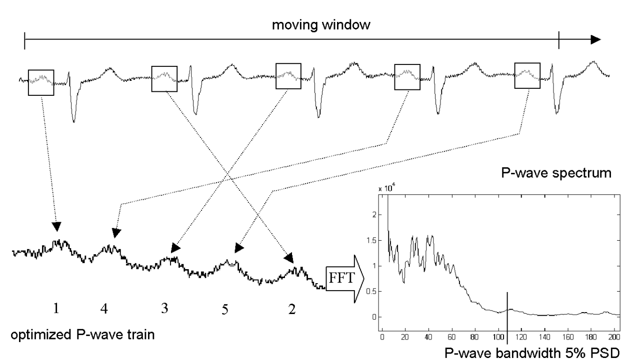

Figure 2. Diagram of the real time processing for moving window-based optimization of P waves order.

3. Experiment setup

The experimental validation of the proposed ECG waves' train optimization procedure was performed with the use of CSE Multilead Database [10] Dataset 3 (12 bits per sample, 12 channels ECG and 3 channels VCG, signal length 10s, sampling frequency 500Hz). Besides the research reproducibility, the advantage of this database was the availability of the reference wave border points. The records with no measurement points (e.g. 67 and 70 with the paced beats) or with no wave present were excluded from the experiment. Resulting P wave trains, independent in each lead, were composed of 110 and QRS and T wave trains of 123 signal sections. The signal continuity was estimated from its first derivative calculated from 5 consecutive points symmetrical to the reference wave's border. Before concatenation, the voltage difference of the adjacent waves was estimated and compensated based on the average value of the 5 points mentioned above.

The experiment was coded in Matlab as three main steps:

- signal access, waves extraction and analysis of their initial and terminal parts,
- optimized wave train calculating procedure,
- spectrum calculation and analysis of bandwidth.

We performed the comparative spectrum analysis for two other versions of waves' trains: the natural and the random sequence order. While in case of natural sequence, the waves' order in all leads was the same, in case of random and optimized versions, each lead was considered separately and the resulting waves' order differs from lead to lead.

The waves' train bandwidth was defined as the frequency value corresponding to 95% of the total power spectrum (PSD), not including the Fourier coefficient at the origin, representing the average baseline level (DC).

4. Results

The example spectrum of the P-wave train averaged for all 15 leads (ECG+VCG) is displayed in figure 3. The results of the bandwidth for the ECG waves calculated for all three waves' train orders are presented in table 1.

Table 1. Results of bandwidth estimation (95% PSD) for the ECG waves' trains using natural, random and optimized waves' sequence.

waves' train	wave sequence order		
	natural	random	optimized
P	151	145	107
QRS	185	215	153
T	38	41	28

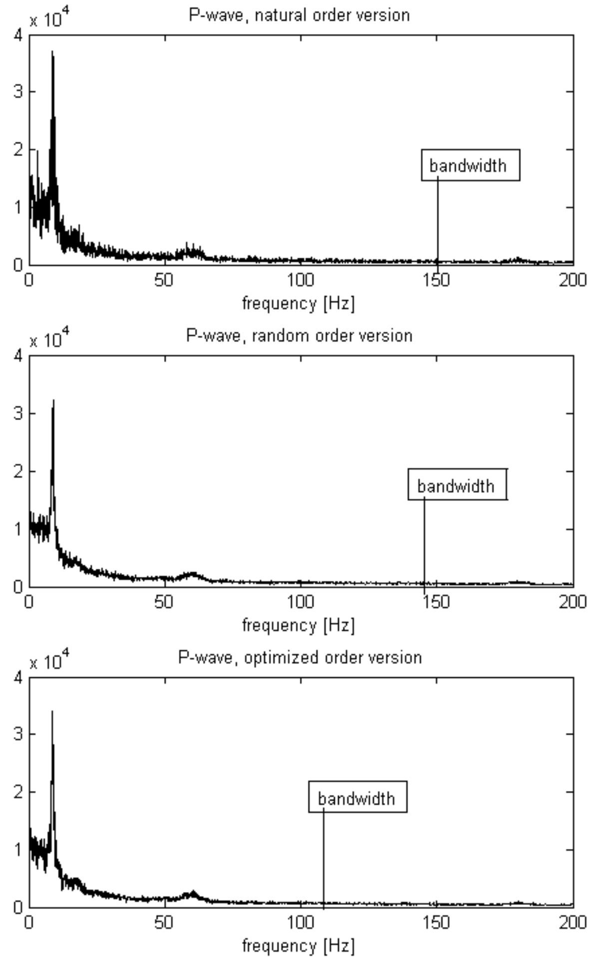

Figure 3. Example P-wave spectra and bandwidth limits for three tested wave sequence versions.

5. Discussion

The bandwidth estimated for the natural and random sequence versions are close for each wave types (4% for P wave, 16% and 8% for QRS and T respectively). This suggests that from the viewpoint of signal continuity and distance to true spectrum, the natural waves' order is not particularly advantageous. In any of the randomly selected waves' order, the resulting spectrum and bandwidth are similar. On the contrary, the optimization of the waves' order leads to a significant reduction (41% for P wave, 21% and 36% for QRS and T respectively) of the estimated bandwidth (what can also be seen in the spectrum plot, fig. 3). Since the waves' content was unchanged, the only reasonable explanation are manipulations of the waves' order minimizing the signal discontinuity at the joint points. Therefore the spectra and bandwidth values calculated from the optimized waves' trains are much closer to true.

The analysis of the heart's electrical activity in medical aspects shows that the depolarization speed of a single cell is limited by the membrane conduction effects usually lasting for several milliseconds. This limits the bandwidth of direct electrical activity of cells, whereas higher frequencies are present in case of interferences (e,g, in EMG). Physiologically in the heart all adjacent myocites acts synchronically, therefore no high frequency component are expected except for rare pathologies like ventricular late potentials (VLP). This justifies that the bandwidth derived from the naturally ordered waves' train is usually overestimated.

It is worth a remark, that the optimization of the waves' order has weaker effect in case of the QRS. This may be explained by the highest amplitude and bandwidth of this wave, which reduce the influence of edge effect to the spectrum.

It is noteworthy that in a given set of separated waves, discontinuities at the joint points can be reduced, although not fully eliminated. The signal theory requires derivatives of all orders to be equal in a point to guarantee the signal continuity. In practical application, for the reason of computational complexity, the derivative orders should be limited to the first (probably the second in future procedure versions) and the equity cannot be achieved in real signal sections.

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References

[1] Thakor N.V, Webster, J.G. and Tompkins WJ. Estimation of QRS complex power spectra for design of QRS filter, IEEE Trans. Biomed. Eng. 31: 702-706.

[2] Al-Nashash HAM. A dynamic fourier series for the compression of ECG using FFT and adaptive coefficient estimation. Medical Engineering & Physics, 1995;17(3):197-203,

[3] Augustyniak P, Tadeusiewicz R. The bandwidth variability of a typical electrocardiogram. European Medical and Biological Engineering Conference EMBEC'99, Wien Austria, 1999;394-395

[4] Clayton RH. Murray A. Estimation of the ECG signal spectrum during ventricular fibrillation using the fast Fourier transform and maximum entropy methods. Computers in Cardiology 1993;867 – 870

[5] Augustyniak P. ECG sampling rate controlled by signal contents. IFMBE Proc. 2002;2:154-155

[6] Haque F, Hanif A, Kiber A, Tanvir H. Detection of small variations of ECG features using wavelet ARPN Journal of Engineering and Applied Sciences 2009;4(6):27-30.

[7] Ribeiro M, Moura J. Dual algorithm for ARMA spectrum estimation. Acoustics, Speech, and Signal Processing, IEEE International Conference on ICASSP '87.

[8] Smith WW, Smith JM. Handbook of real-time fast Fourier transforms. New York: IEEE Press, 1995.

[9] Augustyniak P. Time-frequency modelling and discrimination of noise in the electrocardiogram. Physiol. Meas. 2003;24(3):753-767

[10] Willems JL. Common Standard for Quantitative Electrocardiography Multilead Atlas – Measurements results Data Set 3 Commission of the European Communities – Medical and Public Health Research, Leuven 1988

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