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Application of Wavelet Based Denoising for T-Wave Alternans Analysis in High Resolution ECG Maps

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T-wave alternans (TWA) allows for identification of patients at an increased risk of ventricular arrhythmia. Stress test, which increases heart rate in controlled manner, is used for TWA measurement. However, the TWA detection and analysis are often disturbed by muscular interference. The evaluation of wavelet based denoising methods was performed to find optimal algorithm for TWA analysis. ECG signals recorded in twelve patients with cardiac disease were analyzed. In seven of them significant T-wave alternans magnitude was detected. The application of wavelet based denoising method in the pre-processing stage increases the T-wave alternans magnitude as well as the number of BSPM signals where TWA was detected.

Keywords: T-wave alternans, wavelet denoising, stress test, arrhythmia, sudden cardiac death

1. INTRODUCTION

SUDDEN CARDIAC DEATH (SCD) is the leading cause of cardiovascular mortality in developed countries [1]-[5]. The efforts of many medical scientists and physicians are concentrated on the prediction and prevention of SCD by different diagnostic tools and therapies. At present, there is no generally accepted non-invasive risk index. T-wave alternans (TWA) is a very promising marker of the vulnerability to ventricular arrhythmia often leading to SCD [6], [7]. It is defined as a beat-to-beat change in the T-wave amplitude that repeats every other heart beat and indicates the spatial heterogeneity of the ventricular repolarization.

Both temporal and spatial distribution of the electrical potentials generated by the heart on the surface of the body can be investigated by high resolution Body Surface Potential Mapping (BSPM) [7]-[9]. BSPM is the most promising method of extending medical utility of ECG. As an advantage, body surface electrocardiographic mapping has been demonstrated to have selective sensitivity to individual cardiac regions that is not a feature of standard 12-lead examination [10], [11]. This concerns also TWA, where the maximal values of alternans magnitude are very often detected in signals recorded from electrodes located outside the standard 12-lead ECG system [12]. There are many methods proposed for TWA analysis but only some of them have proven a diagnostic value. For this study, FFT based spectral method was chosen [13]-[15]. Effective TWA detections require increased heart rate which can be obtained by application of the exercise stress test. However, the signal-to-noise ratio (SNR) of ECG signals recorded during the stress test, is decreasing considerably mainly because of patient and cable movements, baseline drifts due to respiration and power line interferences (50 Hz) [16], [17]. Under this condition, the segmentation of the T-waves, as well as the QRS complex, becomes more difficult and in some cases impossible. The use of noisy ECG signals for TWA detection and analysis in clinical routines results in low reliability of providing a medical diagnostic. In this respect, in order to improve the signal-to-noise ratio without loss of the medically important information, the proper rejection of the artifacts and noise in ECG signals is of great importance. This is, however, not a trivial task because the frequency of most of the disturbing signals is inside the ECG frequency band.

Wavelet analysis is used to transform the signal under investigation into joined spectral and temporal representation [18] which allows us to improve signal processing and analysis in many studies [19]. The wavelet transform could be represented as an application of two filters: one highpass and one lowpass filter, both with cutoff frequency at the middle of the sampling frequency.

Based on our study presented in [20], the wavelet transform was chosen for multi-channel signal denoising in T-wave alternans analysis. In the presented study, we have evaluated the influence of different wavelet based denoising methods on the T-wave alternans detection in BSPM signals recorded during the stress test. In terms of TWA detection sensitivity, the best denoising method was selected and advised for medical application.

2. SUBJECT & METHODS

The study group consisted of 12 patients with myocardial ischemia confirmed by Single Photon Emission Computed Tomography (SPECT) and coronarography examinations. Patients were divided into two subgroups: TWA positive (TWA+) consisted of 7 patients with significant value of T-wave alternans magnitude, and TWA negative (TWA-) consisted of 5 patients without the T-wave alternans detected. The study was approved by an institutional ethical review committee and the subjects gave informed consent.

The ECG signals were recorded during an exercise test carried out on supine ergometer (Ergoline Ergoselect 1000L). The 67-channel high-resolution ECG measurement system (Active Two, BioSemi) was used. Unipolar 64 ECG electrodes were located on the body surface and 3 limb electrodes formed WCT signal reference. The ECG electrode layout is shown in Fig.1.

The ECG signals were acquired at 4096 Hz and digitized with a 24-bit resolution. Then, the data were down-sampled by a factor of 4 to 1024 samples/s. Patients were exercised at different load levels. The initial load was 25 W and was increased every 2 minutes to reach at least 85% of the predicted heart rate maximum. For safety reasons, tests were terminated in case of chest pain, fatigue, arrhythmias or marked ST-segment elevation change. The two-minute ECG recordings with heart rate of 100 ±5 bpm were selected for T-wave alternans measurements. In order to achieve a stable heart rhythm during this time period, the load was modified manually. During the pre-processing stage, a bandpass filter was applied with cutoff frequency of 0.05 to 250 Hz. Then, the Fast Wavelet Transform was applied individually to each recorded ECG signal.

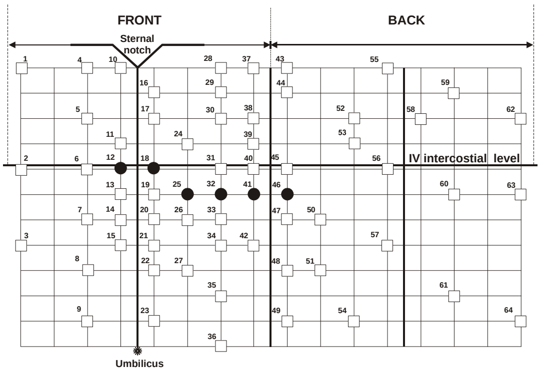

Fig.1. ECG electrode layout on the torso. Standard precardial leads location marked by •.

The noise reduction algorithm using Wavelet Transform [18] in the measured signal is based on the modification of detail coefficients at the i-th decomposition level and reconstruction of original signals using the Inverse Wavelet Transform. The soft thresholding detail modification procedure was applied in this study [21]. Fig.2 exemplifies the denoising procedure.

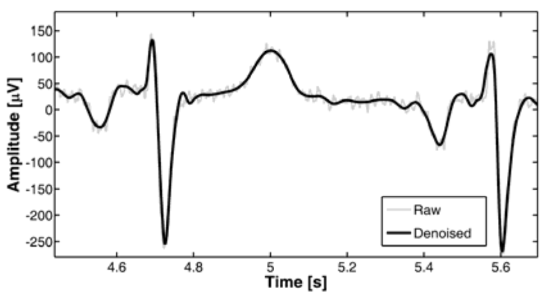

Fig.2. ECG raw data and signal after denoising with the use of Daubechies wavelet.

Based on the results obtained in our previous study [20], 5 wavelet functions with the best denoising properties were chosen: Daubechies 1 level 6, Symlet 3 levels 4 and 5, and Symlet 8 levels 4 and 5. These functions were applied for ECG signal denoising before the TWA analysis.

For the segmentation of T-wave, Principal Component Analysis (PCA) was applied to the multi-dimensional data (ECG maps) [22]. Then, the first three principal components with the highest variance were chosen and averaged over the time. To localize T-waves in each subsequent heartbeat, the R peaks of the previously averaged signal were detected by Pan-Tompkins algorithm [23], then T-wave peaks were found and a constant time segment of 310 ms was chosen which contains the maximal amplitude of T-wave at the middle of the window. In further analysis, ECG signal consisting of 128 T-waves was used. All disrupted PQRST cycles were excluded from the analysis (always an even number of beats was removed to preserve the phase of TWA signal). TWA was analyzed in the frequency-domain using the Fast Fourier Transform (FFT) [13]. Power spectral densities (PSD) were calculated for consecutive samples of T-waves. Based on the level of an averaged PSD at a frequency of 0.5-cycle/beat, an alternans magnitude was calculated.

3. RESULTS

Wavelet function Daubechies 1 level 6 (*db1lev6*) was found to be the best for denoising ECG signals for TWA analysis.

The BSPM maps of TWA magnitude were calculated in TWA positive and negative patients. Examples of the TWA magnitude maps for one TWA positive patient before and after denoising with the use of *db1lev6* function are shown in Fig.3. The increase in the TWA magnitude in the TWA positive region (where the value of TWA magnitude has clinically significant value) and no influence of the denoising procedure on the other parts of the map can be observed.

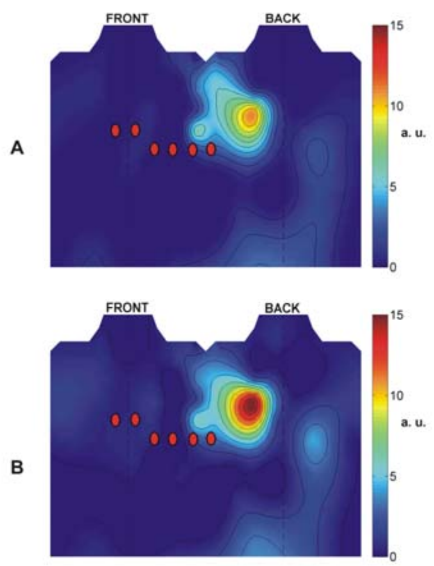

Fig.3. The TWA magnitude maps for one TWA positive patient before (A) and after (B) denoising with the use of *db1lev6* function (a.u.-arbitrary units). Standard precordial leads are marked.

Examples of the TWA magnitude maps for the TWA negative patient, where all TWA magnitude values are below a significant threshold, before and after denoising with the use of *db1lev6* function, are shown in Fig.4. Because of the low level of TWA signal which is not significant, the magnitude scale was 10 times decreased in comparison to Fig.3. No influence of the denoising procedure on all values of the TWA magnitude can be observed.

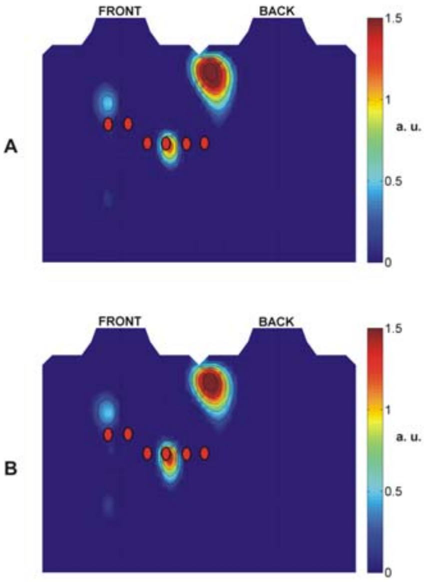

Fig.4. The TWA magnitude maps for one TWA negative patient before (A) and after (B) denoising with the use of *db1lev6* function (a.u.-arbitrary units). Standard precordial leads are marked.

For *db1lev6*, the average value of TWA magnitude calculated in denoised signals was 24.5% greater than in raw ECG data with detectable TWA. The comparison of T-wave alternans gains in magnitude from signals denoised with different wavelets for TWA positive patients is shown in Fig.5.

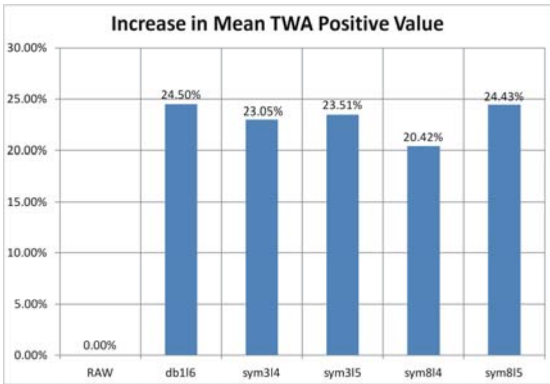

Fig.5. The T-wave alternans gains in magnitude after denoising by using 5 wavelet functions for the TWA positive patients.

The difference between TWA magnitude calculated in signals denoised with the use of *db1lev6* method and other methods was 2% (SD = 3) which is not significant.

The main advantage of using *db1lev6* method is that the number of leads, where diagnostic significant value of TWA was found, is 30% greater than in raw data. In signals, where other denoising methods were used, the mean increase was 13.5% (SD = 35). The comparison for all denoising methods is shown in Fig.6.

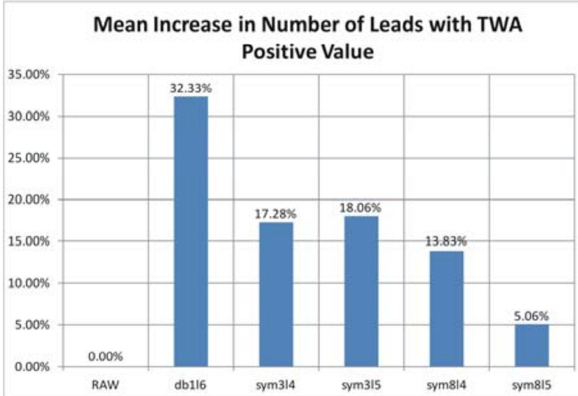

Fig.6. Increase in numbers of leads with significant TWA value after denoising with 5 wavelet functions for the TWA positive patients.

There are no significant differences between TWA magnitude calculated in signals without detectable TWA before and after denoising (0.3%, SD = 0.04), which is shown in Fig.7.

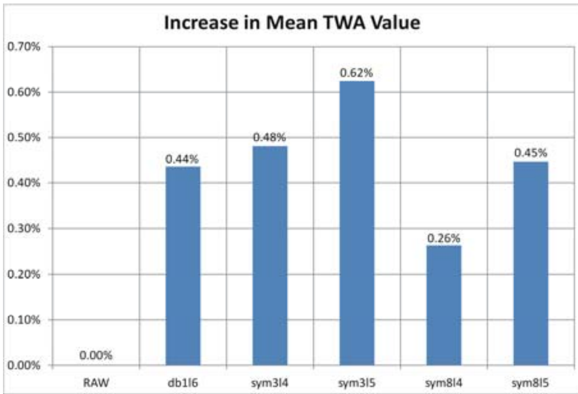

Fig.7. Increase in the T-wave alternans magnitude after denoising by using 5 wavelet functions for the TWA negative patients.

4. Discussion/conclusions

The detection of the TWA in the ECG signal is a very substantial predictor of the vulnerability to ventricular arrhythmia and sudden cardiac death. T-wave amplitude variability is usually too small to be observed by visual inspection of the electrocardiogram, which makes detection of the TWA complicated. Detection of the TWA at the microvolt level allows for indication of patients at risk in early stage of the heart disease. T-wave alternans analysis requires heart rate at the level of 100 bpm, which needs application of the stimulation test. For non-invasive risk assessment, very often stress test is used which makes ECG signals very noisy and difficult for further morphological analysis. In case of the TWA analysis, the T-wave shape preservation is of great importance. Thus, proper denoising procedure is required for effective improvement in signal-to-noise ratio in measured ECG signals. Application of the wavelet denoising fulfills these requirements. According to our previous findings, the wavelet functions presenting the best denoising performance were chosen [20]. Our present study shows that the use of *db1lev6* wavelet function is the best for TWA analysis. We found out that other studied wavelets decrease the noise level and attenuate the TWA signal at the same time. The use of *db1lev6* wavelet function for ECG signal denoising increases the probability of TWA detection not only because of higher TWA magnitude but also because of detection of the TWA diagnostic significant value in greater number of the BSPM leads. This is because the TWA magnitude is calculated in relation to noise. Decrease of the noise level without affecting TWA signal increases the value of TWA magnitude. The obtained results show that there is also increased probability of TWA detection with the use of standard 12-lead ECG system which is very popular in clinical practice and it is used for screening test. The presented results show evident advantage of using wavelet denoising methods in the pre-processing stage before the TWA analysis. This preliminary study needs to be confirmed by analysis on a larger group of patients for more precise verification of the effectiveness of the proposed denoising methods for TWA detection.

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