

Evaluation of the T-wave alternans detection methods: a simulation study

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ABSTRACT

Objective: The aim of this study was to evaluate influence of noise, T-wave jitter and electrocardiographic (ECG) signal parameters on sensitivity of T-wave alternans (TWA) detection methods.

Methods: Methods of the TWA detection were tested: correlation (CM), spectral (FFTM), spectral with coherent averaging (CFFTM), complex demodulation (CDM), Karhunen-Loeve transform (KLT) and KLT realized by adaptive filtering. The TWA amplitude and duration time were estimated on simulated ECG signals. Gaussian and physiological noises at different level were added. Influence of sampling frequency and amplitude resolution of the ECG signal was tested. Detection sensitivity was calculated.

Results: The TWA episodes in presence of white noise with signal to noise ratio (SNR) greater than 15dB were reliably detected. For signals with high noise level better sensitivity was received with the CM. For the spectral methods, the best parameters were obtained with the CFFTM but for physiological noises all the methods were unable to detect the TWA episodes when SNR was lower than 10dB. Analysis done using the CM and the CDM strongly depended on sampling frequency if the TWA episodes were short and had low amplitude.

Conclusions: All spectral methods are sensitive to physiological interference. Changes of the sampling frequency should be very carefully applied. (*Anadolu Kardiyol Derg 2007; 7 Suppl 1; 116-9*)

Key words: electrocardiography, arrhythmia, sudden cardiac death

Introduction

T-wave alternans (TWA) is a non-invasive marker of the vulnerability to ventricular arrhythmia (1). Methods used for the TWA measurements allow detecting the periodic changes of the consecutive T-waves amplitude at microvolt level. Reliability of the detection process depends on the properties of the detectors and their susceptibility to noise interference. The methods should enable non-stationary T-wave alternans signals detection and precise TWA signal parameters quantification. Several tests using simulated electrocardiographic (ECG) signals with known parameters were run to determine properties of the tested methods. The aim of this study was to evaluate the influence of noise interference, T-wave location jitter, and ECG signal parameters on the sensitivity of the TWA detection.

Methods

The T-wave alternans was detected in simulated ECG signals. The consecutive T-waves extracted from the electrocardiogram were located in the $A_{m \times n}$ data matrix, where m indicates the T-wave number and n indicates the T-wave sample number. Six TWA detection methods were tested. Below there is a brief description of all examined methods.

1. Correlation Method (CM) (3). In this method, each consecutive T-wave (T_m) is compared to the median T-wave (T_{mdn}) computed from all 128 T-waves contained in the rows of the $A_{m \times n}$ data matrix. For every beat the Alternans Correlation Index (ACI) is calculated.

$$ACI_m = \frac{\sum_{n=1}^N T_m(n) T_{mdn}(n)}{\sum_{n=1}^N [T_{mdn}(n)]^2} \quad (1)$$

where T_m – the m -th T-wave vector, T_{mdn} – median T-wave vector, n – sample number.

Equation 1 contains the cross-correlation between T_m and T_{mdn} in the nominator and the auto-correlation of T_{mdn} in the denominator. The ACI_m value greater than 1 indicates that T_m is „larger” than T_{mdn} , while the ACI_m value smaller than 1 indicates that T_m is „smaller” than T_{mdn} . Thus, ACI_m can measure morphological changes of each of the consecutive T_m waves in comparison to T_{mdn} . The T-wave alternans occurs, when ACI value fluctuates around 1 for at least seven successive heart beats. The correlation method can deliver the information about the amplitude and the temporal location of the alternans episode in the ECG signal.

2. FFT- based method (FFTM) (2). In the FFT-based method, power spectrum for each sample point (columns of Amxn matrix) of 128 time-aligned T-waves is calculated by squaring the magnitude of the fast Fourier transform. The cumulative power spectrum is estimated by summing the power spectra obtained for each sample point. In the cumulative spectrum, the beat-to-beat fluctuation of the T wave amplitude appears as the spectral peak at the frequency of 0.5 cycles per beat; hence, the magnitude of this peak is a direct marker of the alternans. From the cumulative spectrum alternans ratio (AR) can be obtained:

$$AR = \frac{P_{0.5} - noise}{\sigma_{noise}} \quad (2)$$

where: P0.5 -amplitude of the spectral peak at the frequency 0.5 cycles per beat; noise, σ_{noise} - mean level and standard deviation of the noise registered in the spectrum in the predefined window located outside the alternans frequency (0.5 cycles per beat).

According to Rosenbaum et al. (2), a patient is classified as an „alternans positive” if the alternans ratio (AR) exceeds 2.5. The FFT-based detector enables the registration of the alternans along the T-wave by analysis of the power spectrum for each sample point. The disadvantage of this method is assessment of the alternans signal as a stationary sine wave with constant amplitude and phase, which is not true in general.

3. FFT-based method with coherent averaging (CFFTM) (4). This method is a version of the FFT-based method in which the real and imaginary parts of the fast Fourier transform are separately averaged. This kind of averaging used for the alternans detection results in a considerable noise level decrease in the cumulative power spectrum. In this method, all the remaining procedures are the same as in the previous method.

4. Complex demodulation method (CDM) (5). In the complex demodulation method, similar to the FFT-based method, the alternans signal with the frequency of 0.5 cycles per beat is searched for by the signal demodulation. The alternans signal is modeled as a sine wave at the frequency $f_0=0.5$ cycles per beat, with a varying amplitude and phase. If the alternans exists, it is demodulated by multiplying each column of the Amxn data matrix by a complex exponential $2 \exp(-2\pi j f_0 m)$ with the alternans frequency fo

$$B_{m \times n} = A_{m \times n} \cdot 2 \cdot \exp(-2\pi j f_0 m) \quad (3)$$

After multiplication, the alternans components are shifted to low frequency. The low frequency alternans signals are calculated from the columns of new Bm xn matrix by low-pass filtering. For filtering, the 11-th order Kaiser window filter is used with half-power cutoff frequency 1/40 cycles per beat. In this way, at the output of the filter, a beat-to-beat series of the alternans voltages for all T-wave sample points are obtained. The alternans marker is the mean value of the amplitude calculated from the output series.

5. The Karhunen-Loeve transform method (KL-FFTM) (6). The Karhunen-Loeve transformation (KLT) is a signal dependent, orthogonal, linear transform that in the small number of coefficients concentrates the maximum signal information and the minimum noise, which is not correlated with the signal. In this way, the influence of the noise contained in the ECG signal on the alternans detection was reduced. The KLT allows forming the new orthogonal basis for all 128 T-waves in the Amxn matrix rows. In the new basis nearly all the signal energy is concentrated in a small

number of k coefficients ($k \ll m$), and the noise level is significantly reduced. Then the certain number of the coefficients (in our case $k=4$) are used for the alternans detection. The alternans marker is calculated with the use of FFT based method (FFTM) from the signal reconstructed the from KL data space reduced to the first 4 coefficients.

6. The KLT method with adaptive filtering (WF-FFTM) (6). The Widrow’s adaptive filtering can also be used to the KL-FFTM method. The adaptive filtering dynamically estimates the quasi-periodic T-wave signals in the KLT basis, with the small number of the basis functions. The adaptive estimation permits a better noise reduction than the above-described method (KL-FFTM). By adaptive filtering, all the T-waves contained in the Amxn matrix rows are transformed to the new reduced space, and all the remaining procedures for the alternans detection are the same as in the KL-FFTM method.

Twenty six minutes long ECG signals were simulated by repeating a single beat from the electrocardiogram which was recorded with 2 kHz sampling frequency and 22 bits amplitude resolution. The distance between the simulated TWA episodes was 128 heart beats. Two types of the TWA episodes were simulated: short (32 consecutive heart beats) and long (64 consecutive heart beats) with low (10 μ V) or high (100 μ V) amplitude. Four different types of noise (Gaussian white noise and three recorded physiological disturbances: baseline wandering, electrode motion, and muscular activity) at different levels were added to the simulated ECG signals. The simulation diagram is given in the Figure 1. The TWA amplitude and the total episode duration time were estimated. Sensitivity and positive predictive value of the T-wave alternans detection, and sensitivity and positive predictive value (PPV) of detection of T-wave alternans episode duration were calculated. Accuracy of the TWA episode amplitude estimation was analyzed. The episode duration influence on the accuracy of the TWA amplitude detection was also tested.

Results

Results were divided into two parts. In the first part, the results of calculation using the CM and the CDM that provides information about time distribution of the TWA amplitude (for consecutive heart beats) and the opportunity for estimation of the TWA episode duration were shown. In the second part, results of calculation using the spectral methods where detection sensitivity was tested for short ECG signals were shown.

Correlation method (CM) and complex demodulation method (CDM)

Short TWA episode with low amplitude (EPk10)

For low level Gaussian noise (SNR=15, 20, 25 dB) the TWA detection sensitivity for all methods is close to 100%. For SNR=5 or 10 dB the CM has better sensitivity than the CDM. For signals disturbed with physiological noises the CDM detection sensitivity ($S > 60\%$, SNR=15dB) for high frequency interferences (electrode motion and muscular activity) is better than the CM detection sensitivity, but for low frequency interferences (baseline wandering) the CM is more robust ($S > 50\%$, SNR=15dB). No TWA episodes in signals disturbed with physiological noises with SNR=5 or 10 dB were detected using the CM as well as no such episodes in signals disturbed with baseline wandering noise with SNR=5dB were detected using the CDM. In case of CM better than 50% detection sensitivity was found for signals with SNR>20dB and in case of CDM for signals with SNR>15dB.

All the methods have low PPV (detected episodes are shorter than the half of simulated episodes duration) and detection sensitivity of episode duration. The PPV of episode duration detection is greater than 80% for all the methods and for all types of interferences with SNR>15dB.

Short TWA episode with high amplitude (EPk100)

Sensitivity of the TWA episodes detection is close to 100% for all the methods and for all types and levels of noise. Similar results were obtained for calculation of the PPV of episode detection where SNR>15dB. Close to zero value was obtained applying the CM to the signals disturbed by physiological noise with SNR=5dB. In the same conditions, the PPV was close to 100% for the CDM (except the signals disturbed with baseline wandering noise where the PPV was equal to 40%). Sensitivity of episode duration detection was greater than 90% for calculation applying the CM and the CDM to the signals disturbed with Gaussian noise (for all simulated SNR). For signals, disturbed with physiological noises better values of this parameter were received using CDM than CM. Positive predictive value of the TWA episode detection was greater than 80% for all the methods and all types and levels of noise. All the methods show high sensitivity of detection of episode duration.

Long TWA episode with low amplitude (EPd10)

For all types of noise and with SNR>10dB the CDM has better than the CM, greater than 90%, sensitivity of the TWA episode detection. No TWA episodes was detected applying the CM to the signals disturbed with muscular activity or baseline wandering noise with SNR=5dB. Because of low sensitivity of episode duration detection for all the methods, the PPV of detection was also low. For all the methods and all interferences types with SNR>10dB the PPV of the episode duration detection was greater than 90%.

Spectral methods FFTM, CFFTM, KL-FFTM, WF-FFTM

To assess sensitivity of the TWA episode detection the alternans ratio was calculated. A simulated ECG signal with single TWA episode was used. The results of calculations for

the spectral methods are shown in the Figure 2. For these methods there were found big differences of the TWA detection sensitivity in signals disturbed by Gaussian noise. The best sensitivity was found for the CFFTM that can detect short episodes with low amplitude in ECG signal where SNR=5 or 10dB (no episode was detected with other methods). From among of alternans ratios calculated using all the spectral methods; these obtained with the CFFTM have the greatest values. In case of analysis of signals disturbed with physiological noise, the detection sensitivity is at comparable level for all spectral methods. The TWA episodes with high amplitude are detected reliably by all spectral methods.

Discussion

Reliable detection of the TWA simulated episodes was found for signals disturbed with white noise with SNR greater than 15dB. For higher noise signals, the worst precision was found for the CDM. For the spectral methods, the best parameters were obtained with the CFFTM. When increasing the amplitude of simulated TWA episodes, both detection sensitivity and sensitivity of episode duration detection improve. For physiological noises, all the methods were unable to detect the TWA episodes in signals with SNR less than 10dB. All the spectral methods were in the same way susceptible to this interference. Low-frequency physiological noise (base line wandering) is properly eliminated with the CM while high-frequency physiological noises (electrode motion and muscular activity) are effectively removed with the CDM.

Conclusion

The usefulness of the methods for the TWA amplitude detection depends on the properties of the ECG signal (non-stationary, SNR). For the signals with the high TWA amplitude all the methods work well. The CM and the CDM can be used in low noise

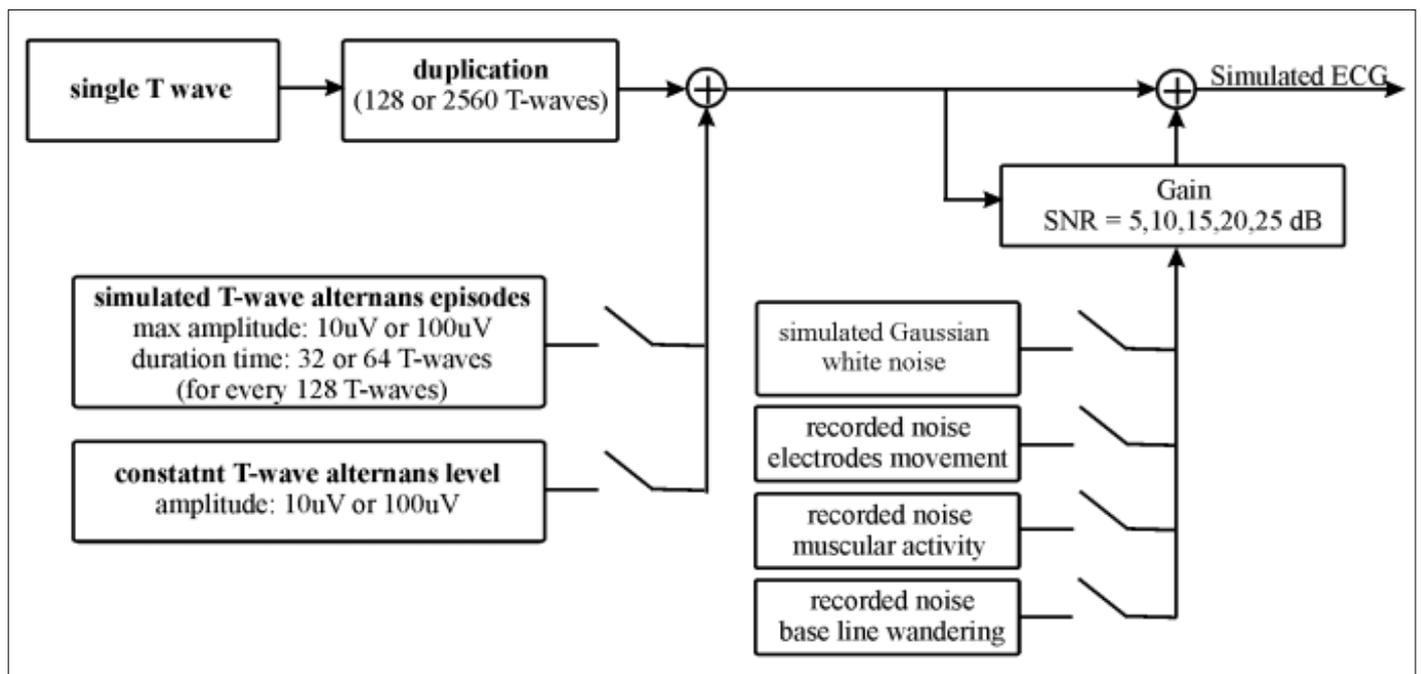


Figure 1. Simulation of ECG signal with T-wave alternans episodes and four noise sources.

signals analysis. Additionally, the CM can be applied to the signals disturbed with high-level white noise however, the method is vulnerable to the physiological disturbance that must be reduced to very low level. From among all spectral methods, the CFFTM is the best one, but it requires the physiological interference to be limited to a very low level. The CM, the CDM and the CFFTM can be used for analysis of the ECG signals with variable heart rhythm where precision of T-wave location detection is limited.

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References

- Zareba W, Moss AJ. Noninvasive risk stratification in postinfarction patients with severe left ventricular dysfunction and methodology of the MADIT II noninvasive electrophysiology substudy. *J Electrocardiol* 2003; 36 suppl: 101-8.
- Rosenbaum DS, Jackson LE, Smith JM, Garan H, Ruskin JN, Cohen RJ. Electrical alternans and vulnerability to ventricular arrhythmias. *New Engl J Med* 1994; 330: 235-41.
- Burattini L, Zareba W, Couderc JP, Titlebaum EL, Moss AJ. Computer detection of non-stationary T wave alternans using a new correlation method. *Comput Cardiol* 1997; 24: 657-60.
- Janusek D, Pawlowski Z, Karczmarewicz S, Przybylski A. Comparison of T-wave alternans detection methods. *Biocybernetics and Biomedical Engineering*. Warsaw; PWN: 2004.
- Nearing BD, Huang AH, Verrier RL. Dynamic tracking of cardiac vulnerability by complex demodulation of the T-wave. *Science* 1991; 252: 437-40.
- Laguna P, Moody GB, Garcia J, Goldberger AL, Mark RG. Analysis of the ST-T complex of the electrocardiogram using the Karhunen-Loeve transform: adaptive monitoring and alternans detection. *Med Biol Eng Comput* 1999; 37: 175-89.

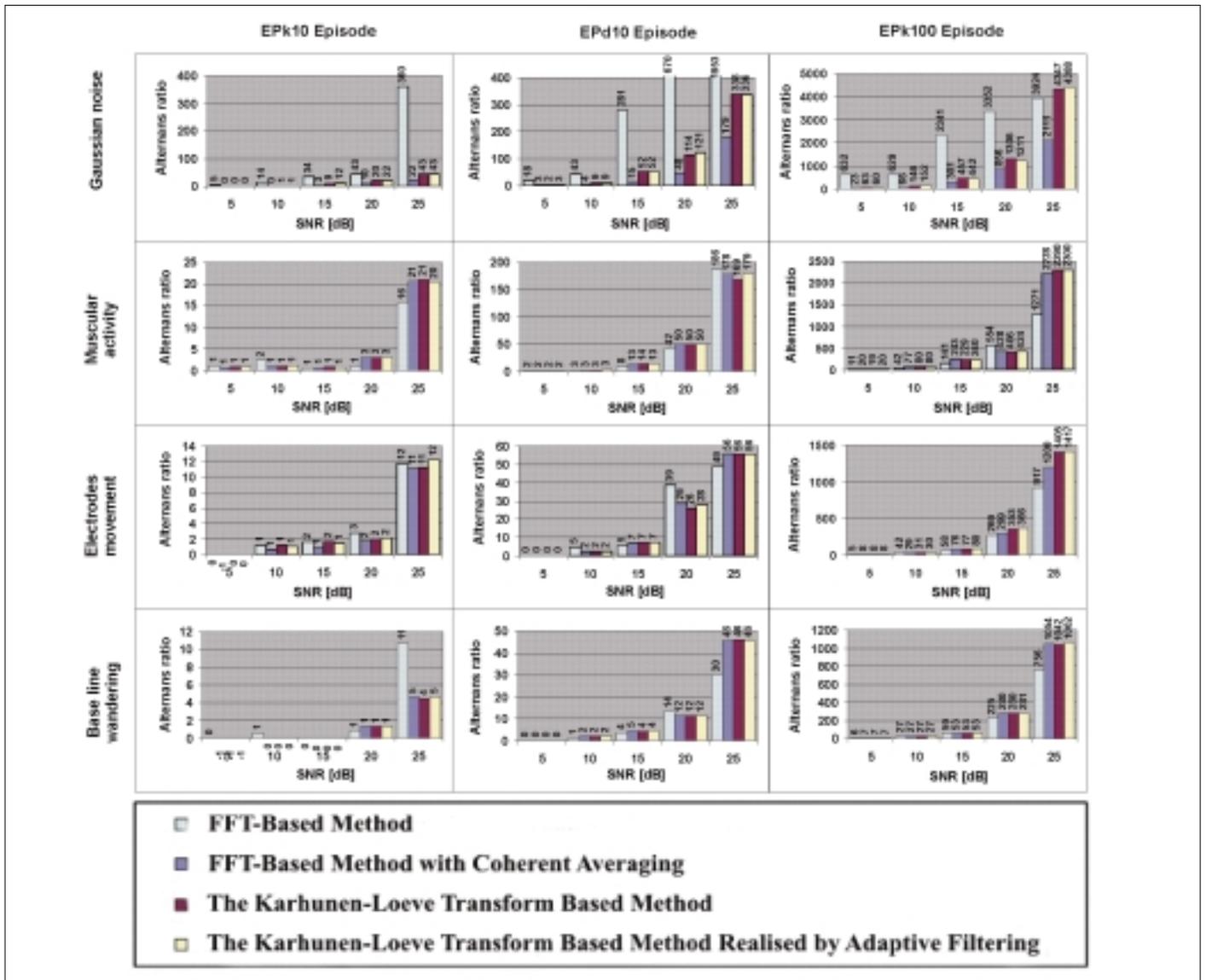


Figure 2. Alternans ratio calculated with use of spectral methods