# Effect of Electrocardiogram Signal Quality on T-Wave Alternans Measurements: A Simulation Study

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**Abstract**

*In this work a simulation study of T-wave alternans is proposed in order to determine the ability of TWA detectors to quantify the performance characteristics in terms of amplitude estimation accuracy. ECG signals were simulated by repeating a single beat, and by adding four types of noise each at two different levels of power. TWA episodes with different amplitudes and waveforms were added to the signals. In simulated ECG signals sampling frequency as well as amplitude resolution were reduced. We can conclude from this study that all analysed methods of TWA detection are resistant to changes of amplitude resolution but there is strong influence of sampling frequency on the precision of TWA amplitude estimation .*

## 1. Introduction

Sudden cardiac death (SCD) is the leading cause of cardiovascular mortality in developed countries [1]. The efforts of many medical scientists and doctors are concentrated on the prediction and the prevention of SCD by different diagnostic tools and therapies. At present, there is no generally accepted non-invasive risk index of SCD. T-wave Alternans (TWA) is a very promising marker of the vulnerability to ventricular arrhythmia. It is defined as a beat-to-beat change in the T-wave amplitude that repeats every other beat and indicates the spatial heterogenity of the ventricular repolarization. Both temporal and spatial distribution of the electrical potentials on the surface of the body generated by heart could be investigated by High Resolution Body Surface Potential Mapping. Since TWA is a transient and very dynamic phenomenon, continuous long-term TWA analysis in Holter recordings is needed. TWA detection at microvolt level needs advanced ECG signal processing. Signal is usually sampled at 1kHz frequency with 12 or 16 bits amplitude resolution. A reduction in the sampling frequency and amplitude resolution of the ECG signals would allow for a significant decrease of signal processing time and facilitate TWA analysis both in Holter and multi-lead systems.

In the presented study the results of the TWA assessment by using four methods are presented. Two FFT-based methods with non-coherent (FFTM) and coherent (FFTCM) averaging as wall as complex demodulation (CDM) and correlation method (CM) were applied. Simulated ECG signals disturbed by four types of noise and with simulated different shape of TWA episode were used.

The aim of the study was to determine the ability of the TWA detection methods to identify TWA episodes in ECG signals with lower technical quality, in particular lower sampling frequency and amplitude resolution.

## 2. Methods

The simulated ECG signal was obtained as the periodic repetition of a single beat, which consisted of 128 T-waves, with 310 ms time duration each. In Figure 1 T-wave extracted from ECG signal and used for further analysis is shown.

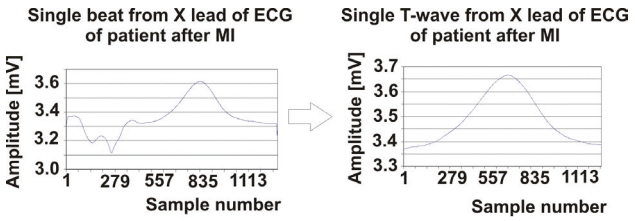


Figure 1. ECG test signal – periodic repetition of single beat

Recording of a patient after myocardial infraction was used. Electrocardiographic signal was recorded from the surface of the patient's body. Six silver-silver chloride electrodes were positioned in orthogonal XYZ leads configuration. ECG signal was amplified (gain, 1000), filtered (bandwidth, 0.05 Hz to 500 Hz) and digitized (2 kHz sampling frequency, 22 bits resolution) with a high resolution ECG recorder. Noise and T-wave alternans episodes were added to this signal.

For each simulation, an alternans waveform was alternately added and substracted from the ECG signal. The alternans waveform added to every T-wave was a Hanning window. The amplitude of the T-wave alternans was modulated by a TWA episode shape, as shown in Figure 2.

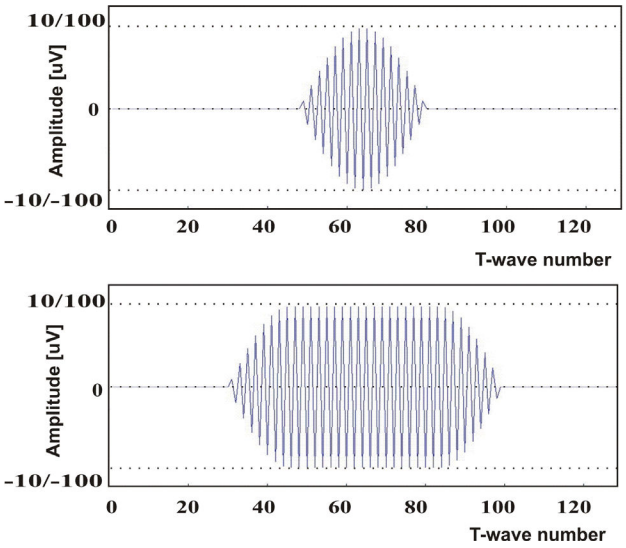


Figure 2. Simulated T-wave alternans episodes

Four types of episodes were simulated: long (64 beats) and short (32 beats) both with two different amplitudes: 10uV and 100uV.

Four types of noise were added at different power levels (S/N=10dB, S/N=20dB). Simulated Gaussian white noise (GN) and three records of physiological noise from the MIT-BHI Noise Stress Test database: electrodes movement (EM), muscular activity (MA), baseline wandering (BW) were considered.

Simulated ECG signal with original sampling frequency of 2kHz and amplitude resolution 22 bits were re-sampled to obtain sampling frequencies of 1kHz, 500Hz, 250Hz and 100Hz and the amplitude resolution was changed to obtain 16, 12, 10 and 8 bit resolution

The separated T-waves of simulated ECG signal were located in data matrix $A_{mxn}$, where m indicates the consecutive T–wave number, and n indicates the sample number. Four methods of T-wave alternans detection were tested. One method use of the data matrix $A_{mxn}$ analysis (or vector created from this matrix) in the time domain and three in the frequency (spectral) domain. In the following part of the study, each method is shortly described, and for each the alternans marker is defined.

*FFT based method (FFTM) [2]* In the FFT-based method, power spectrum for each sample point (columns of matrix $A_{mxn}$) 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 in the amplitude of the T waves 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 alternans.

From the cumulative spectrum, alternans cumulative voltage $A_V$ and alternans ratio AR can be obtained:

$$A_v = \sqrt{P_{0.5} - \overline{noise}} \tag{1}$$

$$AR = \frac{P_{0.5} - \overline{noise}}{\sigma_{noise}} \tag{2}$$

where: $P_{0.5}$ -amplitude of the spectral peak at the frequency 0.5 cycles per beat; $\overline{noise}$, $\sigma_{noise}$ - 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).

*FFT based method with coherent averaging (FFTCM) [3]* This method is an option 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 decrease in the level of noise in the cumulative power spectrum. In this method, all the remaining procedures are the same as in the previous method.

*Complex Demodulation method (CDM) [4]* 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 by the signal demodulation. The alternans signal is modeled as a sine wave at the frequency $f_o$=0.5 cycles per beat, with a varying amplitude and phase. If the alternans exists, it is demodulated by multiplying each column of data matrix $A_{mxn}$ by a complex exponential $2\exp(-2\pi j\, f_o\, m)$ with the alternans frequency $f_o$

$$B_{mxn} = A_{mxn} \cdot 2 \cdot \exp(-2\pi j f_0 m) \tag{3}$$

After multiplication, the alternans components are shifted to low frequency. The low frequency alternans signals are calculated from columns of new matrix $B_{mxn}$ by low-pass filtering. For filtering, the 11-th order Kaiser window filter ($\beta$= 0.5) 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 alternans voltages for

all T wave sample points are obtained. The alternans marker is the mean value of the amplitude calculated form the output series.

*Correlation method (CM) [5]* In this method, each consecutive T-wave ($T_m$) is compared to the median T wave ($T_{mdn}$) computed from all of 128 T waves contained in the rows of data matrix $A_{mxn}$. For every beat the Alternans Correlation Index (ACIm) is calculated.

$$ACI_m = \frac{\sum_{n=1}^{N} T_m(n)\, T_{mdn}(n)}{\sum_{n=1}^{N} [T_{mdn}(n)]^2} \qquad (4)$$

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

Equation 4 contains the cross-correlation function between $T_m$ and $T_{mdn}$ in the nominator and the auto-correlation function of $T_{mdn}$ in the denominator. Thus, a value of $ACI_m$ greater then 1 indicates that $T_m$ is „larger" then $T_{mdn}$ , while a value of $ACI_m$ smaller than 1 indicates that $T_m$ is „smaller" then $T_{mdn}$. $ACI_m$ can measure morphological changes of each of the consecutive $T_m$ waves in comparison to $T_{mdn}$. The T wave alternans occurs, when ACI changes its value around 1 for at least seven successive heart beats.

The alternans amplitude $ACM_m$ can also be estimated using the formula:

$$ACM_m = 2 \cdot \left| ACI_m - 1 \right| \cdot \frac{\sum_{n=1}^{N} T_{mdn}(n)^2}{\sum_{n=1}^{N} \left| T_{mdn}(n) \right|} \qquad (5)$$

where $ACI_m$ – Alternans Correlation Index of the m-th beat, $\mathbf{T}_{mdn}$ – average T-wave vector, n – sample number.

The alternans marker is expressed as the mean ACM value calculated from beats where TWA was found (ACI changes its value around 1 for at least seven consecutive heart beats).

To determine influences of ECG signal parameters on the precision of Alternans Ratio estimation by detection methods the Alternans Ratio Error (ARE) was calculated for all simulated signals, according to formula 6.

$$ARE = \frac{abs\left(AR_{REF} - AR_{SYM}\right)}{AR_{REF}} \cdot 100\% \qquad (6)$$

where: $AR_{REF}$ - Alternans Ratio calculated with use of the ECG signal with 22 bits amplitude resolution and 2kHz sampling frequency; $AR_{SYM}$ - Alternans Ratio calculated with use of the ECG signal with lower amplitude resolution or sampling frequency

## 3. Results

In Figures from 3 to 5 plots of Alternans Ratio Error (ARE) calculated for simulated ECG signals are shown.

In Figure 3 calculations performed for simulated ECG signals with continuous TWA during whole recording and with amplitude of 10μV and with different amplitude resolution are shown.

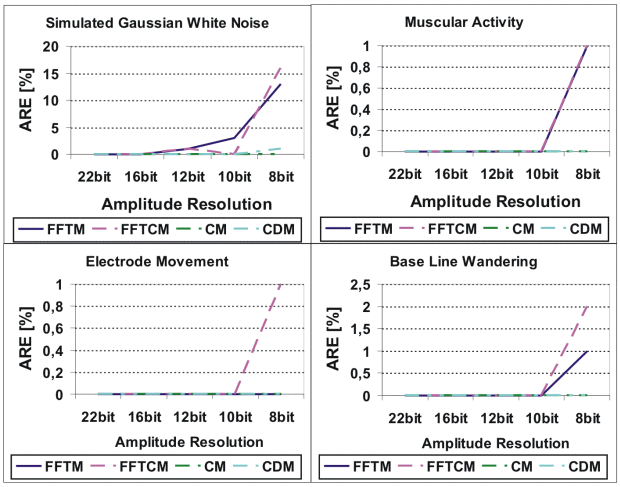


Figure 3. Alternans Ratio Error plot measured in ECG simulated signals with reduced amplitude resolution.

In Figure 4 calculations performed for simulated ECG signals with continuous TWA during whole recording and with amplitude of 10μV and with different sampling frequency are shown.

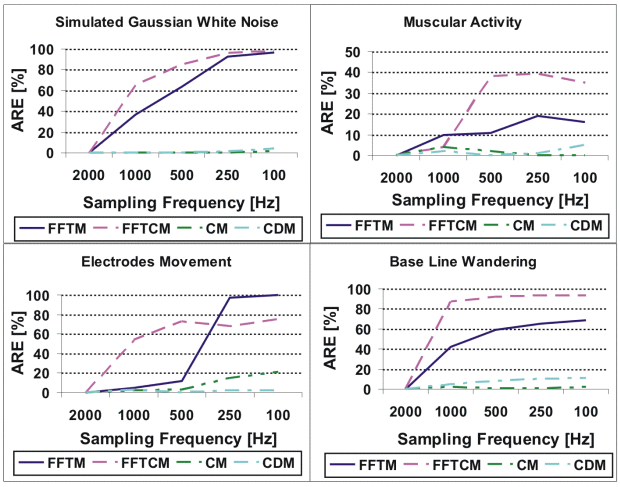


Figure 4. Alternans Ratio Error plot measured in ECG signals with different sampling frequency.

In Figure 5 calculations performed for simulated ECG signals with different TWA episodes with amplitude of 10μV and with different sampling frequency are shown.

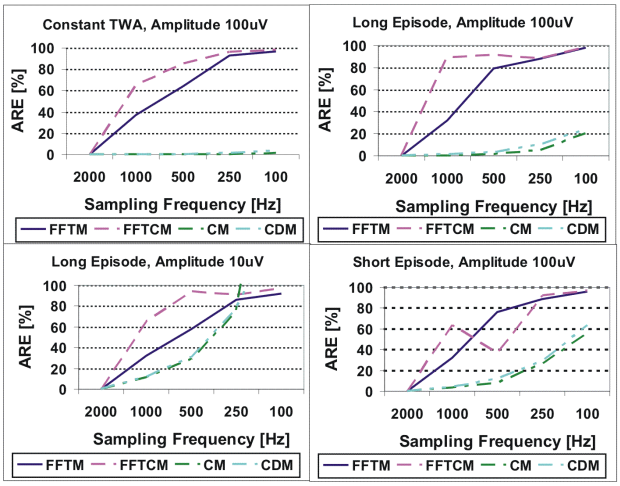


Figure 5. Alternans Ratio Error plot measured in ECG signals with different sampling frequency and episode waveform shape done.

## 4. Discussion and conclusions

TWA is non-stationary phenomenon and the duration of a TWA episode can vary from few beats to few hundreds of beats. As a consequence of transient nature of the TWA phenomenon, a continious long-term TWA analysis in Holter ECG recordings seems appropriate. Spatial heterogeneity of repolarization caused by mechanisms underlying TWA needs measurements performed in ECG signals recorded in multi-lead systems. However, TWA analysis is computationally demanding and consequently restricted to relatively short ECG segments (usually 128 beats). Independently of the used technique (spectral method, complex demodulation method or correlation method) the time needed to perform a TWA analysis is dependent on various factors: length of ECG recording, length of the repolarization segment, and technical parameters of ECG signal. We cannot change the repolarization segment duration (that is specific for each ECG) but amplitude resolution and sampling frequency can be reduced what seems to be practical approach to enable less time-consuming computer processing.

Our study showed that ECGs with amplitude resolution of 22, 16, 12 and 10 bits yield very similar results of TWA analysis. For continuous TWA with constant amplitude ARE is rising very fast (until 100%) for calculations done by spectral methods. TWA analysis done by correlation method and complex demodulation method is also strongly dependent on sampling frequency if TWA episodes are shorter and have smaller amplitude. In conclusion, we demonstrated that all analysed TWA detection methods are resistant to changes of amplitude resolution but changes of the sampling frequency should be done very carefully.

## Acknowledgements

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## References

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