Simulation Study and Performance Evaluation of T-Wave Alternans Detector

Juan Pablo Martínez, Salvador Olmos and Pablo Laguna

Abstract— **Several methods for T-wave alternans (TWA) detection have been proposed so far. In this paper a simulation study of T-wave alternans is proposed in order to compare the performance of TWA detectors, as well as to quantify the performance characteristics in terms of sensitivity, positive predictivity and beat-to-beat amplitude estimation accuracy. FFT-based approach is the most extended TWA detection method, although it does not provide any beat-to-beat amplitude estimation. Complex Demodulation (CD) and Correlation Method (CM) were applied and also two new methods, Capon filtering (CF) (which is a variant of CD) and another approach based on Karhunen-Loève Transform which also includes CF. In this study, ECG signals are simulated repeating a single beat, and adding noise from 4 different noise sources at different levels. TWA episodes with different amplitudes and waveforms were added to the signals. We can conclude from this study that the CM obtained much lower detection rates than the other methods, especially in sensitivity for low amplitude TWA. The amplitude accuracy in the detected episodes was also found to be the worst with CM. The filter-based approaches (CD, CF and KLT+Capon) have shown a similar behavior. However, the KLT+Capon method needs a much higher computational complexity. In general, alternans are detected with rates near 100% for SNR greater than 10 dB for physiological noise sources. A new TWA information is introduced: TWA waveform along the ST-T complex that could be related to the alternans source localization inside the heart.**

Keywords— **T-wave alternans, cardiac repolarization, ST-T complex, complex demodulation, Correlation Method, Karhunen-Love Transform, Capon filtering.**

I. Introduction

Sudden cardiac death (SCD) is the leading cause of cardiovascular mortality in the developed countries [1]. There is no an effective diagnostic method to identify patients at high risk for SCD. Nowadays, the challenge is to develop new broadly used non-invasive methods that will allow the identification of high-risk patients before their experience at major arrythmic events. Some of the non-invasive tests related to high-risk SCD are: frequent and complex ventricular arrythmias in 24-hour Holter monitoring, ventricular late potentials in signal-averaged ECG, low heart rate variability, and increased dispersion of repolarization. However, the positive predictive value of these tests is too low to consider them as sufficient to make a decision about specific treatment, especially defibrillator implantation. Recently, risk stratification research has been focused on T wave alternans, which is considered as a promising clinical marker of arrhythmic events.

J.P. Martínez, S. Olmos and P. Laguna are with the Communications Technologies Group at the Department of Electronic Engineering and Communications, University of Zaragoza, Spain. E-mail: olmos@posta.unizar.es. This work was supported by projects TIC97-0945-CO2-02 from CICYT, P40/98 from CONSI+D DGA and 2FD97-1197-CO2-01 from CICYT-FEDER (Spain).

Electrical T-wave alternans (TWA), defined as a consistent 2:1 variation in the T wave morphology has long been recognized as a marker of electrical instability in a wide range of experimental and clinical situations, such as congenital long QT syndrome, myocardial ischemia and infarction and several other pathologic conditions. Visible TWA, as detected by visual inspection, is an infrequent phenomenon. However, in recent years, computerized analysis of digital ECG recordings allowed the identification of subtle and non-visible (microvolt) TWA, which was found to be much more common than visible TWA.

Several methods for TWA detection have been proposed so far. All of them are based on the well-known problem of spectral estimation. The first proposed method used the FFT to analyze the frequency component 0.5 cycles/beats over the aligned ST-T complexes [2]. This method assumes stationarity of TWA episodes during the analysis window (typically 64-128 heartbeats), and it usually requires special recording conditions, such as cardiac pacing or exercise. This method treats the alternans signal as a sine wave of constant magnitude and phase. This technique yields an average measure of T-wave alternans over the analysis window and the TWA is considered as "present" or "not present".

Since TWA is a very dynamic phenomenon that can occur during resting sinus rhythm, new techniques have been proposed that can be applied for ambulatory monitoring. The second category of techniques comprises dynamic methods which include complex demodulation [3], and transformation methods like the Correlation Method [4, 5] and Karhunen-Loève transform (KLT) based method [6].

The aim of this paper is to propose a simulation study of TWA detectors because of two reasons: a performance comparison of several TWA detectors and also to quantify the performance characteristics in terms of sensitivity, positive predictivity and amplitude estimation accuracy.

The complex demodulation method is equivalent to a high-pass filtering of every sample of the aligned ST-T complexes along the beat dimension in order to reject all the frequencies different of 0.5 cycles/beat. More recently several global methods have been applied that consider the repolarization as a whole, instead of using a independent analysis for each sample of the ST-T complex [4, 6]. In this paper we propose a new method based on the KLT plus Capon high-pass filtering.

The content of the rest of the paper is as follows. Section II summarizes the detection methods, and a new method is proposed based on the KLT. In section III-A we propose a simulation study in order to evaluate the performance of several detection methods: fast Fourier trans-

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formation, complex demodulation, CF, CM and the proposed KLT+Capon filtering approach. Results obtained from simulated signals and actual Holter ECG records from European ST-T database are shown in Section IV. Finally, some conclusions are given.

II. Methods

A. Preprocessing

Preprocessing required for alternans detection includes the following steps:

- QRS detection: Aristotle software [7] was used for this task.
- Baseline wander suppression: It is necessary to attenuate ST-T variations non-repolarization related, like the ones produced by respiration. This was performed using a cubic spline interpolation [8].
- Segmentation of the ST-T complex: It was done by selecting intervals of 300 ms, beginning at a distance from the QRS fiducial point dependent on the RR interval [9]. The onset of the interval for the i-th beat, b_i, is given by the expression

$$b_i = 40 + 1.3\, RR^{1/2}\ (ms). \tag{1}$$

B. TWA Detectors

We consider the three main techniques used up to date: FFT-based analysis, complex demodulation and CM. We also propose a variation of complex demodulation, and a new approach based on KL transformation.

B.1 FFT-Based Detector

The amplitude of alternans in this method is quantified by performing the Fast Fourier transformation of the beat-to-beat variation of each sample points over 128 consecutive beats [2]. This detector identifies ECG changes occurring at 0.5 cycles per beat, this way discriminating them from other non-alternating fluctuations.

This method permits the visualization of which segments inside the repolarization phase are being affected by alternans. However, in the form it has been used so far, this approach doesn't allow the tracking of the alternans amplitude on a beat-to-beat basis. It would be possible to obtain a continued quantification of the TWA amplitude by using a sliding window, but this implementation is indeed a special case of complex demodulation, as we will see.

B.2 Complex Demodulation Detector

This method was proposed in [3] as an alternative to FFT-based methods. Each time series is demodulated by multiplying it by a complex exponential with the desired beatquency (0.5 cycles/beat in this case), and the resulting series is low-pass filtered. Finally, the power of the output series is calculated. This detector allows tracking the amplitude of the TWA beat-to-beat. It is also possible to locate the alternans temporally within the ST-T complex.

It is easy to show that this processing is equivalent to directly filtering the original time series with a high-pass filter (whose impulse response would be that of the low-pass filter modulated with an exponential at 0.5 cycles/beat).

According to this interpretation, we propose a new variant, which consists in using a data-dependent Capon filter instead of a deterministic filter (method B.4).

B.3 Correlation-Based Detector

This recently introduced time-domain approach [4] differs from previous ones in that it analyzes the repolarization period as a whole, as it had been proposed in [6]. It compares each consecutive ST-T complex to the median ST-T complex, representative for a series of beats. An alternans correlation index is computed for every beat. TWA is detected when the correlation index alternates between values that are greater and smaller than one. At least seven consecutive alternating beats are required to detect an episode. The amplitude of alternans is obtained as a function of the correlation index and the median ST-T complex.

CM reduces all the information of the repolarization to only one number, the correlation index, and thus, no information about temporal location of alternans within the ST-T complex can be extracted.

B.4 Capon Filtering Detector

We propose this variation of the complex demodulation method. It consists on replacing the deterministic filter by a data-dependent Capon filter.

Capon filtering [10] minimizes the energy of the output series, under the restriction that the response at the desired frequency (0.5 cycles/beat) is one. This way the filter adapts to the statistics of the series and the method is reliable to be more robust than a deterministic filter using a similar order.

B.5 KL Transformation-Based Detector

The Karhunen-Loève transformation (KLT) is the orthogonal transform that minimizes the error between a signal and a reduced linear combination of the basis functions. Thus, KLT is a signal dependent transformation and it is the best possible characterization of the signal in a few independent coefficients [11]. If the KL basis is computed for every 128-beat set, a limited reduced of coefficients (usually 2-4) concentrate almost all the energy of the signal. It has been shown [12] that the reconstruction of the ECG beats using a reduced number of KL coefficients is equivalent to a periodic time-variant filtering adapted to the characteristics of the signal at each time, thus performing a "morphological" filtering rather than a frequency-domain filtering. The KLT was already used for alternans detection [6], although here an improved approach is proposed.

Figure 1 shows a schematic diagram of the detection method. Let $x_i[n]$ be the sample series corresponding to the i-th sample of the ST-T complex $i = 1, \ldots N$. . The proposed method converts the N temporal series in a reduced number of feature series $kl_j[n]\, j = 1, \ldots, p$ with $p < N$, by means of the KLT. This p time series are then Capon filtered at 0.5 cycle/beat obtaining $fkl_j[n]$, $j = 1, \ldots, p$,

in order to attenuate non-alternans components. Finally, temporal series $y_i[n]$, $i = 1, \ldots, N$ are reconstructed with the inverse KL transform. The signal $y_i[n_0]$, $i = 1. \ldots, N$ is actually an estimation of the alternans signal waveform at the n_0-th beat. Finally, the RMS value of the TWA is obtained for each beat (although, according to Parsevals's relation, this value can be obtained directly from $fkl_j[n]$). A new KL basis is calculated every 128 beats.

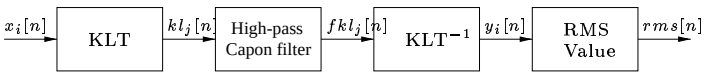


Fig. 1. Schematic diagram of KLT + Capon TWA detector.

This KLT+Capon method has some points in common with other methods:

- Methods B.4 (CF) and B.5 (KL + Capon) share the same kind of approach to isolate alternans variations (data-dependent Capon filtering).
- Conceptually, the proposed method is also related with B.3 (CM). CM can be understood as the projection of each ST-T complex over a single function: the median complex. The KLT method is also a projection approach. However, the KLT optimally concentrates the energy in a reduced number of coefficients.

This method allows tracking the alternans amplitude and, as it has been said, it is also possible to obtain the waveform of the alternans for each ST-T segment.

III. Materials

A. Simulated ECG signals

As in actual ECG recordings the exact value and timing of the T-wave alternans episodes are unknown, we propose the simulation study shown in Fig. 2 in order to quantify the effects of different types and levels of noise in alternans detectors. The clean ECG signal is obtained as the periodic repetition of a single beat. Noise and alternans are added to this signal.

Four different noise sources have been considered: simulated Gaussian white noise, and three records of physiological noise from the *MIT-BIH Noise Stress Test* database [13]: baseline wandering ('bw'), electrode motion ('em') and muscular activity noise ('ma'). Signal-to-noise ratios simulated range from 5 dB to 20 dB.

For each simulation, an alternans waveform is alternately added and subtracted from the ECG simulated signal. The amplitude of the alternans is modulated by an "episode shape". The noise type and level, the alternans waveform, its amplitude, the episode shape and its duration are the parameters of the proposed simulation.

B. European ST-T database

The *European ST-T database* [14] consists of 90 ECG recordings, each of two hours duration, extracted from Holter tapes (2-lead ECGs) that contain ST-T complex episodes annotated on an individual lead basis by cardiologists. This database was chosen by two reasons: firstly, previous studies found T-wave alternans episodes, some of them related to annotated ischemic episodes. Secondly, this database is well-known and available by many research groups [6].

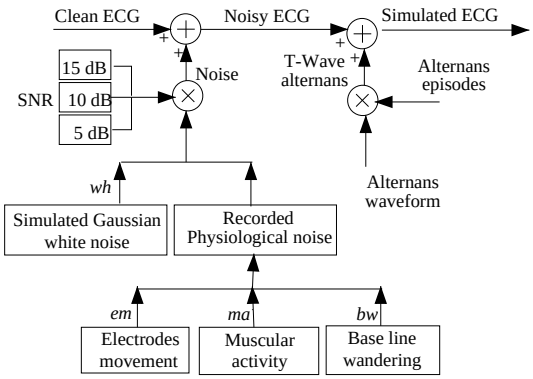


Fig. 2. Simulation of ECG signals with T-wave alternans episodes and four noise sources.

C. Performance measures

The detector performance needs to be evaluated with regard to the following aspects, detection rate duration and magnitude of detected episodes. The validation of the detector should begin with a comparison of the simulated TWA episodes and the detector output, in terms of sensitivity (S) and positive predictivity ($+P$). The sensitivity is defined as the number of correctly detected episodes divided by the total number of simulated episodes, i.e.

$$S = \frac{TP_s}{TP_s + FN}\,. \tag{2}$$

The positive predictivity is calculated as the number of detected episodes that matched simulated episodes divided by the total number of detections, i.e.

$$+P = \frac{TP_p}{TP_p + FP}\,. \tag{3}$$

Note that, for the same signal, TP_p and TP_s may differ because of the possibility that there is not a one-to-one correspondence between simulated and detected episodes (e.g. two simulated episodes can be detected as only one and vice versa). To consider matching between two episodes (simulated and detected) it is required that one episode contains at least half of the duration of the other.

It is also necessary to measure the duration of the events and therefore the sensitivity and positive predictivity for episodes duration are calculated as

$$S_D = \frac{I_{DS}}{I_S} \qquad +P_D = \frac{I_{DS}}{I_D}\,, \tag{4}$$

where I_{DS} represents the total overlap time between detected and simulated episodes (correct detection duration of the TWA), I_S represents the total duration of the simulated episodes, and I_D the total duration of the detected episodes.

With respect to the accuracy in the episodes magnitude estimation, it is possible to compare event-by-event the

simulated episode amplitudes to the values obtained by the detector, obtaining then the Root Mean Square (RMS) value of the difference.

IV. Results

A. Simulated ECG signals

Different methods for TWA detection have been applied to thirty-minute signals simulated as explained in section III-A. We selected a heartbeat from an actual ECG Holter recording sampled at 200 Hz and quantified with 5 μV/LSB. The results are given in this manuscript only for 'electrode motion' and 'muscular activity' noise, for conciseness reason. Signal-to-noise ratios were 5, 10, 15 and 20 dB. The alternans waveform added to every ST-T complex was a Hanning window, while the episode amplitudes were triangle-shaped with duration of 31 beats, as shown in Fig. 3. Thus, 20 TWA episodes were simulated in each thirty-minute signal. Simulated amplitudes in the peak of the episode range from 25 μV to 400 μV, but we have selected two representative cases to be shown: low amplitude alternans (25 μV) and high amplitude alternans (150 μV).

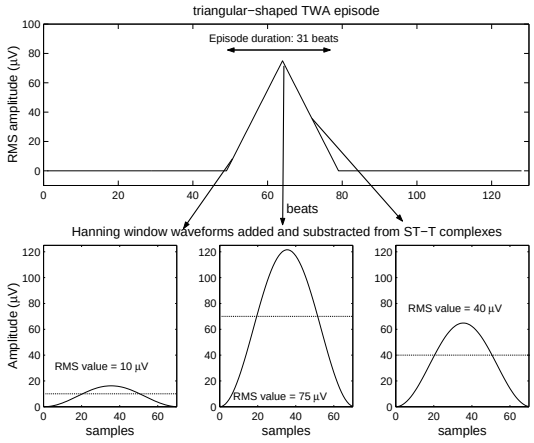


Fig. 3. Simulated TWA alternans episodes and waveforms.

The methods have been applied as follows:

- **FFT-based detector:** in its original form, it cannot provide a beat-to-beat amplitude estimation of TWA, and thus, it is not an adequate method for the purpose of this study. The sliding window version of this method is a particular case of complex demodulation method, already considered in the analysis.
- **Complex demodulation detector:** A 21st-order low-pass equirripple FIR filter modulated to 0.5 cycle/beat was used. The low-pass filter transition band was between 0.02 and 0.055 cycle/beat, for a stop-band attenuation of 25 dB.
- **Correlation Method:** It was applied as it was defined at [4]. Only spurious detections below 10 μV have been removed.
- **Capon filtering detector:** The order selected was p=9.
- **KLT + Capon detector:** We selected the first 4 coefficient series of the KL transform and a 9th-order Capon filter was utilized.

In Complex demodulation, CF and KLT + Capon filtering methods, a continuous TWA amplitude is given by the detector. Therefore, a final stage is needed to define the onset and offset of episodes, based on an adaptive amplitude threshold. The threshold accounts for slow drift changes TWA amplitude estimator by applying an exponential averager that defines the baseline for the TWA amplitude series. The baseline is estimated only from those beats considered as non-alternans by the detection algorithm.

Results of episode and duration sensitivity and positive predictivity are given in the following figures: 'em' and 'ma' noise with 150 μV amplitude TWA in Figures 4 and 5 respectively. It can be seen that the episode sensitivity was near the 100% for a wide range of SNR. However, the positive predictivity of the CM degraded at low SNR, especially for 'ma' noise. Duration parameters show a different behavior: CM obtained lower duration sensitivities and higher duration positive predictivities than the other detectors. This results show that CM got shorter episodes than the simulated ones. In contrast, the other methods used to detect larger episodes, due to the filter smearing.

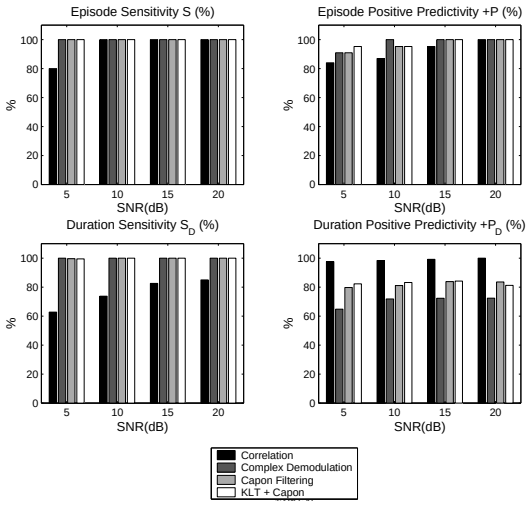


Fig. 4. Detection rate parameters for 'em' noise and 150 μV TWA amplitude.

Figures 6 and 7 show episode and duration sensitivity and positive predictivity for 25 μV amplitude TWA. Once more, the CM obtained the worst episode detection parameters, with a larger difference with the other methods. Specially poor sensitivity results were obtained for low SNR.

The amplitude estimation accuracy obtained by the detectors is shown in Fig. 8. The RMS values (μV) correspond to the difference between the simulated TWA and the detected alternans in the interval obtained as the intersection of all detected intervals and the simulated ones.Once more, the CM was the method with worse performance. The amplitude accuracy of the detected low amplitude TWA episodes with filtered methods was around 5 μV, i.e., one quantization level. The amplitude accuracy for high amplitude TWA episodes was a bit larger, between 10 and 15 μV. Considering that 100 μV is equivalent to 1 mm in normal ECG printouts, the lower TWA amplitudes considered are almost invisible.

Finally, different TWA waveforms along the ST-T com-

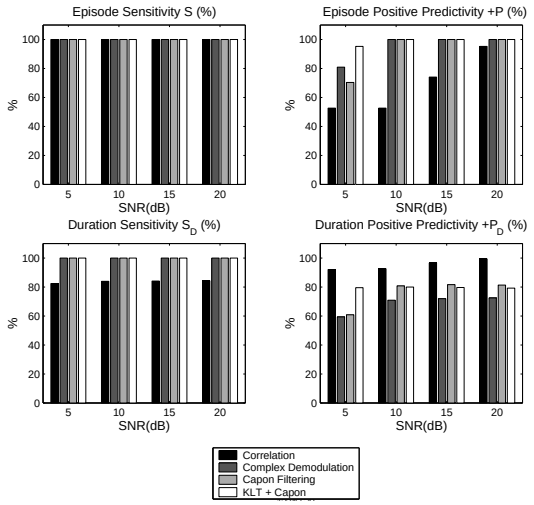


Fig. 5. Detection rate parameters for 'ma' noise and 150 μV TWA amplitude.

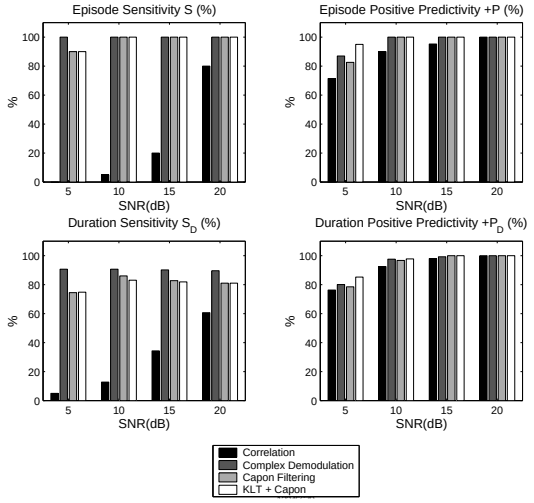


Fig. 6. Detection rate parameters for 'em' noise and 25 μV TWA amplitude.

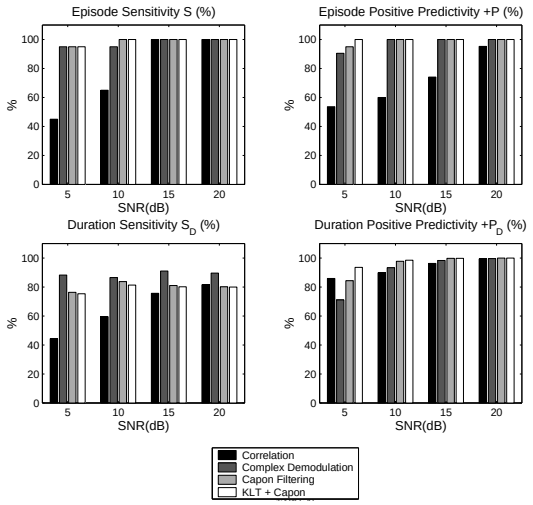


Fig. 7. Detection rate parameters for 'em' noise and 25 μV TWA amplitude.

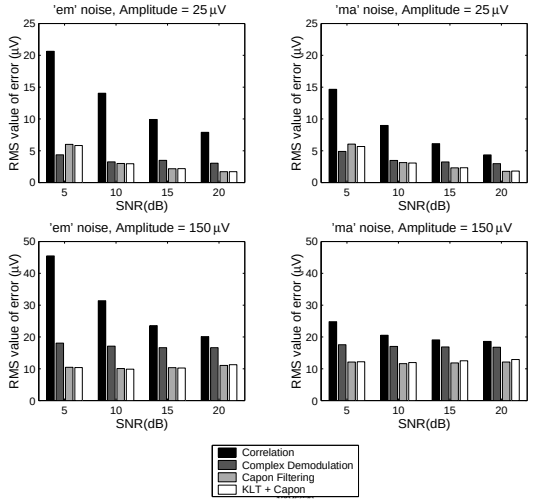


Fig. 8. Amplitude accuracy of the detectors.

plex were used in the analysis. We show in Fig. 9 the episode sensitivity for rectangular, Hanning and biphasic waveforms in the case of 'ma' noise and low amplitude TWA (25 μV). The episode sensitivity of the CM was greatly degraded in the case of the biphasic waveform because the alternans waveform projection onto the median ST-T complex was very low. In consequence, many false negatives occurred. CD, CF and KL+Capon methods obtained similar results. We also show in Fig. 10 some TWA waveform estimations obtained by several methods in the same case of 'ma' noise and 25 μV.

B. European ST-T database

The TWA detectors have also been applied to actual ECG recordings from the *European ST-T* database. We show one example for the record e0105 which presented large ST elevation annotated episodes (Prinzmetal's angina). Visible TWA were also found in some of these episodes. The TWA amplitude (RMS in μV) estimation of the Complex Demodulation method in shown in Fig. 11. The adaptive amplitude threshold used to define the onset and offset of the episodes is also shown.

We show in Fig. 12 the ECG waveform corresponding to the ST-T complex of the selected record e0105 at two episodes: the first larger amplitude episode at minute 7 and a lower amplitude episode at minute 53. In both cases, the detected episodes corresponded to actual TWA, in the case shown in (a) more clearly visible than in (b).

A new information that is not already used in T-Wave alternans analysis and may be useful in clinical applications is the alternans waveform along the ST-T complex, as it can be seen in Fig. 12. This waveform is related to the localization of the alternans source in the heart. In record e0105 all the alternans waveforms were very similar and scaled by the amplitude factor shown in Fig. 11. Different patients will present different TWA waveforms.

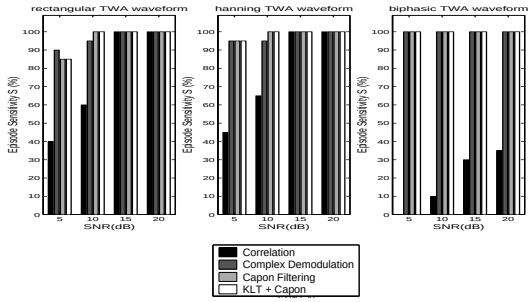


Fig. 9. Episode Sensitivity values for several alternans waveforms with 'ma' noise and 25 μV TWA amplitude.

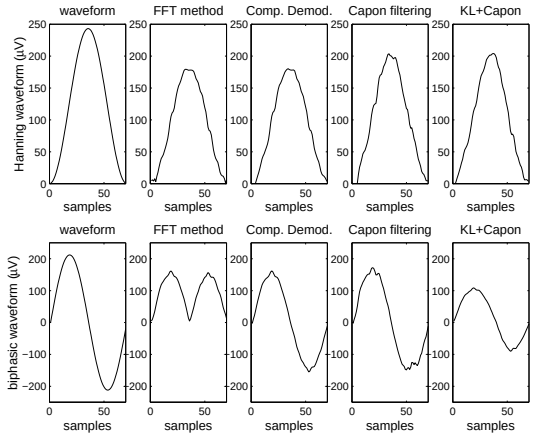


Fig. 10. TWA waveform estimations for 'ma' noise and and 25 μV TWA amplitude.

V. Conclusions

In this paper a simulation study for the performance evaluation of T-Wave alternans detectors was proposed. Several detection methods were used: FFT, Complex Demodulation, Correlation Method, Capon Filtering and KLT+Capon method. The Correlation Method obtained much lower detection rates than the other methods, especially in episode sensitivity at low amplitude TWA. Moreover, the RMS of the estimated TWA amplitude by the Correlation Method in the detected episodes was much higher than the filter-based methods. The filter-based methods (CD, CF and KLT+Capon) obtained similar results in both detection rate and amplitude accuracy. However, the KLT+Capon method needs a much higher computational complexity, especially in order to estimate the KL basis functions. Therefore, it is not worth using this method.

The episode detection rate for both high (150 μV) and low (25 μV) amplitude TWA in the simulation study was almost 100% with SNR larger than 10 dB. for all filtered methods. The amplitude accuracy of the detected low amplitude TWA episodes with filtered methods was around 5 μV, i.e., one quantization level. The amplitude accuracy for high amplitude TWA episodes was a bit larger, between 10 and 15 μV. Considering that 100 μV is equivalent to 1 mm in normal ECG printouts, the lower TWA amplitudes considered are almost invisible.

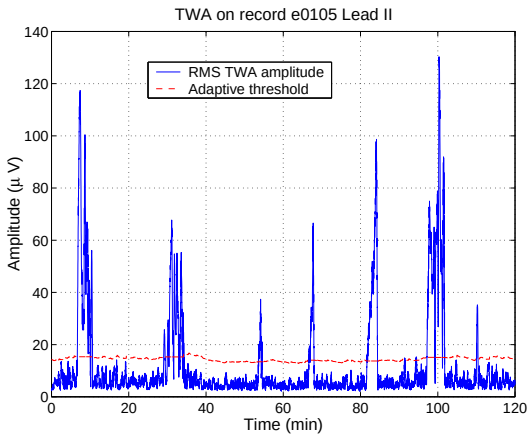
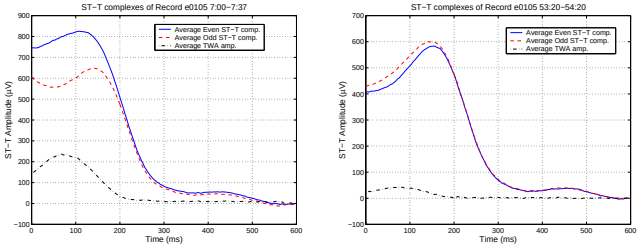


Fig. 11. TWA amplitude estimation of Complex Demodulation on record e0105.



(a) Episode at minute 7. (b) Episode at minute 53.

Fig. 12. ECG waveform (ST-T complex) corresponding to some detected TWA episodes in record e0105.

A new information of the T-wave alternans waveform along the ST-T complex is introduced in this paper, that could give more information about the localization of the alternans source inside the heart.

References

[1] A. Bayés and J. Guindo, *Sudden Cardiac Death*. Spain: MCR, 1989.

[2] D. S. Rosenbaum, L. E. Jackson, J. M. Smith, H. Garan, J. N. Ruskin, and R. J. Cohen, "Electrical alternans and vulnerability to ventricular arrhythmias," *The New England Journal of Medicine*, vol. 330, pp. 235–241, January 1994.

[3] B. D. Nearing and R. L. Verrier, "Personal computer system for tracking cardiac vulnerability by complex demodulation of the T wave," *Journal of Applyied Physiology*, vol. 74, pp. 2607–2612, 1993.

[4] L. Burattini, W. Zareba, J. Courdec, E. Titilebaum, and A. Moss, "Computer detection of non-stationary T-wave alternans using a new correlation method," in *Computers in Cardiology*, vol. 24, pp. 657–660, 1997.

[5] L. Burattini, W. Zareba, J. P. Courdec, J. Konecki, and A. Moss, "Optimizing ECG signal sampling frequency for T-Wave Alternans detection," in *Computers in Cardiology*, pp. 721–724, 1998.

[6] P. Laguna, M. Ruiz, G. B. Moody, and R. G. Mark, "Repolarization alternans detection using the KL transform and the beatquency spectrum.," in *Computers in Cardiology*, pp. 673–676, IEEE Computer Society Press, 1996.

[7] G. B. Moody and R. G. Mark, "Development and evaluation of a 2-lead ECG analysis program," in *Computers in Cardiology*, pp. 39–44, IEEE Computer Society Press, 1982.

[8] C. Meyer and H. Keiser, "Electrocardiogram baseline noise estimation and removal using cubic splines and state-space computation techniques," *Comput. Biomed. Res.*, vol. 10, pp. 459–470, 1977.

[9] F. Badilini, W. Zareba, E. Titlebaum, and A. Moss, *Analysis of ST segment variability in Holter recordings*, pp. 357–372. Nonin-

vasive Electrocardiology: Clinical Aspects of Holter Monitoring. Frontiers in Cardiology, London, UK: W.B. Saunders Company Ltd, 1996.

[10] P. Stoica and R. Moses, *Introduction to spectral analysis*. NJ (USA): Prentice-Hall, 1997.

[11] C. W. Therrien, *Discrete random signals and statistical signal processing*. New Jersey: Prentice-Hall, 1992.

[12] S. Olmos, J. Garcia, R. Jané, and P. Laguna, "Truncated orthogonal expansions of recurrent signals: equivalence to a periodic time-variant filter," *IEEE Trans. Signal Processing*, vol. 47, pp. 3164–3172, Nov. 1999.

[13] G. B. Moody and R. G. Mark, "The MIT-BIH arrhythmia database on CD-ROM and software for use with it," in *Computers in Cardiology*, pp. 185–188, IEEE Computer Society Press, 1990.

[14] A. Taddei, G. Distante, M. Emdin, P. Pisani, G. B. Moody, C. Zeelenberg, and C. Marchesi, "The European ST-T database: standards for evaluating systems for the analysis of ST-T changes in ambulatory electrocardigraphy," *European Heart Journal*, vol. 13, pp. 1164–1172, 1992.

Simulation Study and Performance Evaluation of T-Wave Alternans Detectors

J P Martinez*, S Olmos, P Laguna, University of Zaragoza, Zaragoza, Spain.

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Track: 23 Signal Processing

Short Paper Available

Several methods for T-wave alternans (TWA) detection have been proposed so far. In this paper a simulation study of T-wave alternans is proposed in order to compare the performance of TWA detectors, as well as to quantify the performance characteristics in terms of sensitivity, positive predictivity and beat-to-beat amplitude estimation accuracy. FFT-based approach is the most extended TWA detection method, although it does not provide any beat-to-beat amplitude estimation. Complex Demodulation (CD) and Correlation Method (CM) were applied and also two new methods, Capon filtering (CF) (which is a variant of CD) and another approach based on Karhunen-LoËve Transform which also includes CF. In this study, ECG signals are simulated repeating a single beat, and adding noise from 4 different noise sources at different levels. TWA episodes with different amplitudes and waveforms were added to the signals. We can conclude from this study that the CM obtained much lower detection rates than the other methods, especially in sensitivity for low amplitude TWA. The amplitude accuracy in the detected episodes was also found to be the worst with CM. The filter-based approaches (CD, CF and KLT+Capon) have shown a similar behavior. However, the KLT+Capon method needs a much higher computational complexity. In general, alternans are detected with rates near 100% for SNR greater than 10 dB for physiological noise sources. A new TWA information is introduced: TWA waveform along the ST-T complex that could be related to the alternans source localization inside the heart.