The Effect of Baseline Wandering in Automatic T-Wave Alternans Detection from Holter Recordings

L Burattini[1], W Zareba[2], R Burattini[1]

[1]Polytechnic University of Marche, Ancona, Italy
[2]University of Rochester, Rochester, USA

Abstract

T-wave alternans (TWA) is an electrophysiologic phenomenon associated with an increased risk of death. ECG baseline wandering may prevent correct detection of TWA. The present study was designed to test the effectiveness of our newly developed heart-rate adaptive match filter (AMF) to remove baseline wanders and improve TWA detection. To this aim, both simulated and experimental (10 Holter ECGs of patients with acute myocardial infarction, AMI) data were used. Performance of our AMF was compared with that of a third-order spline (TOS) interpolation. In simulated data, AMF allowed correct detection of TWA almost independently of baseline frequency components, when these were different from TWA own frequency, whereas the TOS interpolation allowed TWA detection only for baseline frequencies lower than TWA frequency. Application of AMF to AMI patients allowed detection of TWA in 2 out of 10, whereas 10 out of 10 were detected as TWA-positive after application of the TOS ($p<0.05$). The two patients that resulted TWA-positive after AMF application were characterized by a larger number ($p<0.05$) of beats involved in the TWA episodes than the number detected by the TOS. Detection of TWA in 100% of AMI patients provided by the TOS-technique (suggesting the presence of false-positive), and presence of false-negative, as deduced from the simulation results, question the reliability of this method. Our AMF allows more reliable identification of TWA almost independently of baseline frequency components.

1. Introduction

T-wave alternans (TWA) consists of a beat-to-beat alternation of the T-wave morphology (amplitude, shape and, sometimes, polarity). Visible TWA is an infrequent phenomenon associated with an increased propensity to life-threatening ventricular arrhythmias [1-2]. Computerized analysis of digital ECG made possible to unmask and detect non-visible, microvolt TWA, so that both visible and non-visible TWA could be associated with electrical instability [3-12]. Various techniques have been proposed to detect microvolt TWA [5-8]. All them require signal preprocessing to control for possible effects of factors that may affect TWA identification [13-15]. In particular, baseline removal is generally recognized as an important processing step that is beneficial to TWA detection, as well as to any signal processing technique finalized to measure ECG amplitude. For TWA detection purposes, a third-order spline (TOS) interpolation has been widely used for baseline removal [13-14]. A new heart-rate adaptive match filter (AMF) was recently proposed by ourselves [16] as a tool to improve detection of TWA, almost independently of frequencies of baseline oscillations. Simulated data were used to test this new method. In the present study the effectiveness of our AMF-technique is tested by application to both experimental and simulated data from patients with acute myocardial infarction (AMI). A comparative analysis with the effectiveness of the TOS-technique is also performed.

2. Methods

Simulated data. Our simulated time series were obtained by repeating a real ECG complex (0.75 sec long, and sampled at 200 samples per sec) with no visible noise and no baseline wanders. A constant RR interval of 0.75 sec was assumed, so that TWA fundamental frequency was 0.67 Hz (that is, 1/(0.75*2 sec) or 0.5 cycles per beat). Simulation of TWA was performed by varying T-wave amplitude in a time window of 160 msec centered around the T-wave apex. T-wave alternation of 50 μV amplitude was considered. Baseline wanderings were simulated with a sinusoid of 100 μV amplitude and various frequencies: 0.30, 0.67 and 1.50 Hz, respectively. These frequencies were respectively lower, equal, and greater than TWA frequency. The frequency of 0.30 Hz relates to usual breathing pattern in patients. To simulate ECG tracings with baseline wandering, baseline fluctuations were simply added to the simulated data.

Two kinds of simulated ECG tracings were considered: a tracing with no TWA (TWA00), and a tracing with 50 μV TWA (TWA50).

Experimental data. ECG recordings from 10 patients with acute myocardial infarction (AMI) were analyzed. For each patient a three-channel (X,Y,Z) digital Holter recording was obtained using Burdick recorders (Burdick Inc., Milton, WI), that sampled the ECG signal at 200 samples per sec. A series of 128 consecutive sinus beats recorded in resting conditions was used to detect and quantify TWA. Among the three leads, the one showing the highest levels of TWA was chosen as the most representative.

Baseline removal techniques. Our heart-rate adapting match filter (AMF) [16], was used to remove baseline wandering with a procedure that emphasizes the TWA signal by filtering out everything else (that is, the baseline and any other ECG component but the TWA). Estimated mean RR interval was used to identify the filter passing TWA frequency, f_{TWA} = 1/(2*meanRR). To allow some variation of the RR interval, this filter was implemented as a 6th order bidirectional Butterworth band-pass filter (rather than a single frequency-pass filter) with a very narrow bandwidth of $f_{TWA} \pm \Delta f$, with Δf =0.06 Hz [16]. Effectiveness of AMF was tested against a classical baseline estimation and removal by means of a third-order spline (TOS) interpolation of fiducial points in the PR intervals [17]. Differently from our AMF, the TOS interpolation is finalized to baseline estimation for subsequent subtraction from the ECG tracing.

TWA detection. Automatic detection of TWA was accomplished by filtering 128 consecutive beats. The TWA signal, as seen at the output of the AMF, is a constant phase, eventually amplitude modulated sinusoid with its maxima and minima over the T waves. A local estimate of the TWA amplitude is directly given by the sinusoid amplitude in correspondence of the T wave. Consequently, a value of the TWA amplitude is given for each beat, that allows detection of both short-time and sustained TWA episodes. Global (i.e., relative to the entire analyzed ECG segment) TWA parameters, also provided by the AMF algorithm are: TWA mean amplitude, number and mean duration of TWA episodes, total number of alternating T waves and TWA magnitude (defined as the product of TWA mean amplitude by the total number of alternating T waves).

TWA detection by the TOS required application of correlation method (CM) [16], that uses the median T wave (T_{mdn}) to compute the alternans correlation index (ACI_j) of individual T_j waves in comparison to T_{mdn}:

$$ACI_j = \frac{\sum_{i=1}^{N} T_j(i) T_{mdn}(i)}{\sum_{i=1}^{N} (T_{mdn}(i))^2} \qquad \text{j=1:128} \qquad (1)$$

TWA occurs when ACI_j alternates around the value of 1. It can be proved [13-14] that TWA amplitude (A_{TWA}) can be estimated by the following equation:

$$A_{TWA} = 2\left|ACI_j - 1\right| \frac{\sum_{i=1}^{N} T_{mdn}^2(i)}{\sum_{i=1}^{N} \left|T_{mdn}(i)\right|} \qquad \text{j=1:128} \qquad (2)$$

Definitions of TWA mean amplitude, number and mean duration of TWA episodes, total number of alternating T waves and TWA magnitude still hold.

3. Results

TWA detection from simulated data processed with AMF is summarized in Table 1. TWA was correctly determined when baseline frequency was either lower or higher than $f_{TWA.}$ For baseline frequency equal to f_{TWA}, false positive detection and overestimation were present.

TWA detection from simulated data processed with TOS is summarized in Table 2. TWA was detected only when baseline frequency components were lower than f_{TWA}. For baseline frequency similar to that of TWA, this was overestimated and detected even though not present. Finally, for baseline frequency higher than $f_{TWA,}$ TWA was never detected, even though it was present.

Application of both AMF and TOS to AMI data (RR=899±152 msec) gave the results shown in Fig. 1 and Table 3. TWA-positive patients identified with AMF processing were two, while all ten patients resulted TWA-positive after application of the TOS (Fig.1). As reported in Table 3, the number of TWA-positive patients detected with AMF processing was much lower (p<0.05) but characterized by a larger number of alternating T waves (p<0.05), and a greater TWA magnitude (p<0.05). No significant differences were found in the TWA episodes mean duration and TWA mean amplitude.

Table 1. TWA detection from simulated data after application of our AMF technique.

Simulated data	#AT	# TWA E	TWA E L	TWA A (mV)	TWA M (mV)
0.30 Hz Baseline					
TWA00	0	0	0	0	0
TWA50	128	1	128	50	6400
0.67 Hz Baseline					
TWA00	128	1	128	381	48768
TWA50	128	1	128	428	54784
1.50 Hz Baseline					
TWA00	0	0	0	0	0
TWA50	128	1	128	72	9216

#AT: number of alternating T waves. #TWA E: number of TWA episodes. TWA E L: TWA episodes mean length. TWA A: TWA mean amplitude. TWA M: TWA mean magnitude.

Table 2. TWA detection from simulated data after application TOS technique.

Simulated data	#AT	# TWA E	TWA E L	TWA A (mV)	TWA M (mV)
0.30 Hz Baseline					
TWA00	0	0	0	0	0
TWA50	128	1	128	50	6400
0.67 Hz Baseline					
TWA00	128	1	128	108	13824
TWA50	128	1	128	158	20224
1.50 Hz Baseline					
TWA00	0	0	0	0	0
TWA50	0	0	0	0	0

#AT: number of alternating T waves. #TWA E: number of TWA episodes. TWA E L: TWA episodes mean length. TWA A: TWA mean amplitude. TWA M: TWA mean magnitude.

Table 3. TWA detection from Holter ECGs of AMI patients.

AMI data	#AT	# TWA E	TWA E L	TWA A (mV)	TWA M (mV)
AMF+ (2)	85±16	11±1	8±0	50±35	4512±380
TOS+ (10)	35±19*	5±3*	7±1	35±22	983±375*

#AT: number of alternating T waves. #TWA E: number of TWA episodes. TWA E L: TWA episodes mean length. TWA A: TWA mean amplitude. TWA M: TWA mean magnitude. AMF+, TOS+: TWA-positive patients after AMF and TOS processing, respectively; Means with asterisk in the TOS+ row are significantly lower that the corresponding means in the AMF+ row (Student t-test, $p<0.05$).

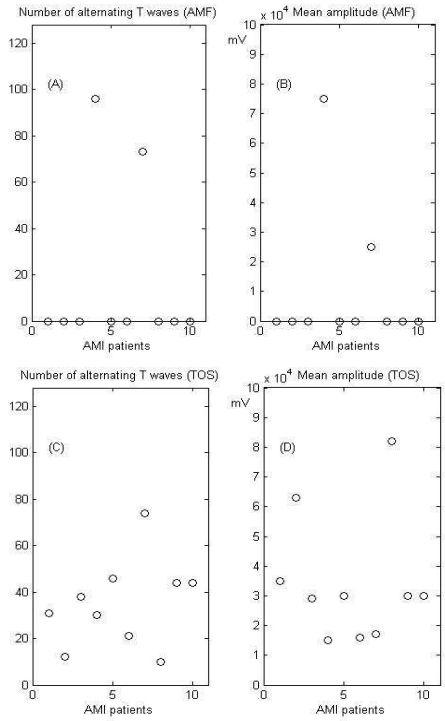

Figure 1. Number of alternating T waves and TWA mean amplitude when baseline removal was performed by AMF (panels A and B) and by TOS (panels C and D) techniques.

4. Discussion and conclusions

In the last ten years, efforts have been put in setting up computerized procedures that allow detection of TWA from standard Holter ECG recordings, thus making available a non-invasive and clinically useful marker of cardiac instability [8,14].

Baseline fluctuations may prevent TWA detection from ECG recordings [13-15]. Consequently, baseline removal is always required when analyzing TWA. Baseline fluctuations may depend on 'internal' (respiration and muscular electric noise) as well as 'external' (electrical interferences) causes [13,16,18] that make it hard to determine its frequency components. To improve the effectiveness of TWA detection algorithms, in a recent study [16] we proposed an adapting match filter (AMF) that emphasizes the TWA signal by filtering out the baseline and any other ECG component but the TWA itself. The effectiveness of this new approach was compared with that of a third-order spline interpolation (TOS), a traditional technique [13-14] with an implicit theoretical limitation that allows removal of only baseline fluctuations at frequencies lower than heart rate (HR).

Indeed, oscillations are estimated by interpolating a fiducial point every beat, and the estimated maximum frequency is, by definition, HR. As baseline frequency approximates it, the accuracy of isoelectric line estimation reduces. Thereafter, the TOS is not suitable to remove baseline with frequency components higher than HR. Considering that f_{TWA}=HR/2, the spline interpolation appears theoretically useful only to remove baseline frequency components at lower frequency than f_{TWA}.

These theoretical considerations were confirmed by the results of our applications to simulated data. The TOS allowed TWA detection only for baseline frequency components lower than f_{TWA} (Table 2). By contrast, application of our AMF allowed TWA detection almost independently of baseline frequency components, when different from TWA own frequency (Table 1).

Search of TWA in Holter ECGs from our 10 AMI patients by the AMF- and the TOS-based procedures yielded significantly different results. AMF application identified only 2 TWA-positive cases, whereas, all 10 patients were TWA-positive according to the TOS-based procedure. Moreover, the two patients that resulted TWA positive after AMF application were characterized by a larger number (p<0.05, Table 3) of beats involved in the TWA episodes, than the number detected by the TOS.

The issue as to which procedure is more reliable is still open. However, based on our simulation study and on the clinical observation that, at least in its visible form, TWA is an infrequent phenomenon (and thus unlikely to be found in every patient, even if AMI), our AMF-based method appears more reliable because it allows more precise identification of TWA almost independently of baseline frequency components. By contrast, TOS performance strongly depends on the baseline frequencies, and its application seems to introduce some distortions that may cause false-positive (see experimental data) as well as false-negative (see simulated data) detections of TWA.

References

[1] Schwartz PJ, Malliani A. Electrical alternation of T wave: clinical and experimental evidence of its relationship with the sympathetic nervous system and with the Long QT Syndrome. Am Heart J 1975; 89(1):45-50.

[2] Zareba W, Moss AJ, Le Cessie S, Hall WJ. T wave Alternans in idiopathic Long QT Syndrome. J Am Coll Cardiol 1994; 23(7):1541-1546.

[3] Adam DR, Smith JM, Akselrod S, NybergS, Powell AO, Cohen RJ. Fluctuations in T-wave morphology and susceptibility to ventricular fibrillation. J Electrocardiol 1984; 17(3):209-218.

[4] Smith JM, Clancy EA, Valeri CR, Ruskin JN, Cohen RJ. Electrical alternans and cardiac electrical instability. Circulation 1988; 77: 110-121.

[5] Nearing BD, Huang AH, Verrier RL. Dynamic tracking of cardiac vulnerability by complex demodulation of the T wave. Science 1991; 252(5004):437-440.

[6] Rosenbaum DS, Jackson LE, Smith JM, Garan H, Ruskin JN, Cohen RJ. Electrical alternans and vulnerability to ventricular arrhythmias. N Engl J Med 1994; 330(4):235-241.

[7] Rosenbaum DS, Albrecht P, Cohen RJ. Predicting sudden cardiac death from T wave alternans from the surface electrocardiogram: promises and pitfalls. J Cardiovasc Electrophysiol 1996; 7(11):1095:1111.

[8] Burattini L, Zareba W, Rashba EJ, Couderc JP, Konecki J, Moss AJ. ECG features of microvolt T-wave alternans in coronary artery disease and Long QT Syndrome patients. J Electrocardiol 1998; 31: 114-120.

[9] Klingenheben T, Zabel M, D'Agostino RB, Cohen RJ, Hohnloser SH. Predictive value of T-wave alternans for arrhythmic events in patients with congestive heart failure. Lancet 2000; 356(9230): 651-652

[10] Ikeda T, Saito H, Tanno K, Shimizu H, Watanabe J, Ohnishi Y, Kasamaki Y et al. T-wave alternans as predictor for sudden death after myocardial infarction. Am J Cardiol. 2002; 89(1): 79-82.

[11] Bloomfield DM, Steinman RC, Namerow PB, Parides M, Davidenko J, Kaufman ES, Shinn T et al. Microvolt T-wave alternans distinguishes between patients likely and patients not likely to benefit from implanted cardiac defibrillator therapy: a solution to a multicenter automatic defibrillator implantation trial (MADIT) II conundrum. Circulation 2004; 110(14): 1885-1889.

[12] Richter S, Duray G, Hohnloser S. How to analyze T-wave alternans. Heart Rhythm 2005; 2(11):1268-1271.

[13] Burattini L: Electrocardigraphic T-wave alternans detection and significance. Doctoral thesis, University of Rochester, 1998.

[14] Burattini L, Zareba W, Moss AJ. Correlation method for detection of transient T-wave alternans in digital ECG recordings. Annals of Noninvasive Electrocardiol 1999; 4(4):416-424.

[15] Bloomfield DM, Hohnloser SH, Cohen RJ. Interpretation and classification of microvolt T-wave alternans tests. J Cardiovasc Electrophysiol 2002; 13(5): 502-512.

[16] Burattini L, Zareba W, Burattini R. Automatic Detection of Microvolt T-Wave Alternans in Holter Recordings: Effect of Baseline Wandering. Biomedical Signal Processing and Control 2006; in press

[17] Akselrod S, Norymberg M, Peled I, Karabelnik E, Green MS. Computerized analysis of the ST segment changes in ambulatory electrocardiograms. Med Biol Eng Comput 1987; 25(5): 513-519.

Address for correspondence

Prof. Roberto Burattini
Department of Electromagnetics and Bioengineering
Polytechnic University of Marche
Via Brecce Bianche, 60131, Ancona, Italy
e-mail address: r.burattini@univpm.it