

A New T-wave Frequency Based Index for Discrimination of Abnormal Repolarization

Corrado Giuliani¹, Laura Burattini¹

¹Polytechnic University of Marche, Ancona, Italy

Abstract

Aim of the present study was to propose an innovative TCE_{10} index (defined as the T-wave cumulative normalized energy at 10 Hz, in %) as a useful tool to characterize the T wave in terms of its frequency content, and to test the TCE_{10} ability to discriminate abnormal cases of repolarization. To this aim, ECG recordings (X, Y, Z leads and vector-magnitude signal, VMS) of 23 control healthy (CH) subjects and 23 antero-septal acute myocardial infarction (ASAMI) patients were analysed. Abnormal repolarization was identified when TCE_{10} was below a threshold value, defined as the 25th percentile of the TCE_{10} distribution over the CH population. Results indicate that the ASAMI population was characterized by lower TCE_{10} values than the CH population (X: $93.9 \pm 5.9\%$ vs. $98.2 \pm 1.2\%$; Y: $95.2 \pm 4.5\%$ vs. $97.8 \pm 1.4\%$; Z: $97.4 \pm 1.6\%$ vs. $99.1 \pm 1.5\%$; VMS: $95.7 \pm 2.8\%$ vs. $97.9 \pm 1.3\%$; $P < 0.01$). Moreover, the ASAMI patients were discriminated from the CH subjects with a lead-independent specificity of 74% and a lead-dependent sensitivity of 78%, 61%, 87% and 57% for lead X, Y, Z and VMS, respectively. In conclusion, compared to the CH subjects, the ASAMI patients show increased high-frequency spectral energy and were discriminated from the former with satisfactory values of sensibility and specificity.

1. Introduction

Sudden cardiac death (SCD) remains one of the leading causes of death in developed countries [1-2]. Among the possible causes of SCD there are the abnormalities in the repolarization phase of the heart, which are known to be associated to susceptibility to malignant ventricular arrhythmias [3-4].

The digital electrocardiogram (ECG) has been widely used to evaluate and diagnose cardiovascular diseases. In particular, the number of studies on the T wave, representing the cardiac repolarization on the ECG tracing, have been constantly growing in the last decades, and several noninvasive T-wave based predictors of SCD

have been proposed in the literature [5]. Among these predictors, the inverted T wave [6], the QT interval [7-8] and the T-wave alternans [9-10] are of particular interest, even though they do not provide satisfactory values of sensitivity and specificity.

Abnormalities in the repolarization morphology are reflected, in the frequency domain, in a variation of the T-wave frequency content. Still, as far as we know, no SCD predictor is based on this feature. Thus, aim of the present study was to investigate the T-wave frequency content of ECG recordings, and to design an innovative index which could be used to highlight differences between healthy and pathological conditions. Performances of such index was tested using ECG recordings of a healthy population and of patients affected by acute myocardial infarction.

2. Methods

2.1. Study Population and clinical data

Our study population consisted of 23 control healthy subjects (CH) and 23 antero-septal acute myocardial infarction (ASAMI) patients, matched in terms of gender and age (Table 1), who underwent a short (30 s to 2 min), 3-lead (orthogonal Frank's XYZ) ECG recording (sampling frequency, f_s : 1 KHz). All ECG tracings are available at the Physionet database (Physionet PTB Diagnostic Database; www.physionet.org).

2.2. T-wave frequency content evaluation

From each subject ECG recording, a 10-s window was randomly extracted to be processed in order to evaluate the T-wave frequency content. The former was independently estimated for the three orthogonal Frank's XYZ ECG leads and for the vector magnitude signal (VMS), obtained by their combination as in Eq. 1:

$$VMS = \sqrt{X^2 + Y^2 + Z^2} \quad (1)$$

Before being processed, each tracing (either lead or VMS) was prefiltered for high frequency noise removal

and baseline subtraction (by means of a band-pass filter with passing band between 0.5 Hz and 35 Hz), and R peak and T-wave endpoints detection [11-12].

Then, the T-wave frequency content evaluation was performed on the tracing-dependent T-wave signal (TWS), obtained by zero padding everything outside the T-wave windows (Fig.1). More specifically, the Fourier transformation was used to compute the power spectrum ($PS_{TWS}(f)$) and, subsequently, the energy signal ($E_{TWS}(f)$). The latter, after computation of the total energy, was normalized and expressed as percentage ($E_{TWS}\%(f)$), respectively; Eq.2).

$$E_{TWS}\%(f) = \frac{E_{TWS}(f)}{\sum_{f=0}^{f_c/2} E_{TWS}(f)} \cdot 100 \quad (2)$$

2.3. Definition of a new T-wave frequency index for discrimination of subjects with abnormal repolarization

A new TCE_{10} index, representing the T-wave cumulative normalized energy at 10 Hz (Fig. 2), was defined as in Eq. 3:

$$TCE_{10} = E_{TWS}\%(10) \quad (3)$$

A subject presented abnormal T-wave frequency content if his/her TCE_{10} was below a threshold value, THR, defined as the 25th percentile of TCE_{10} distribution over the CH subjects.

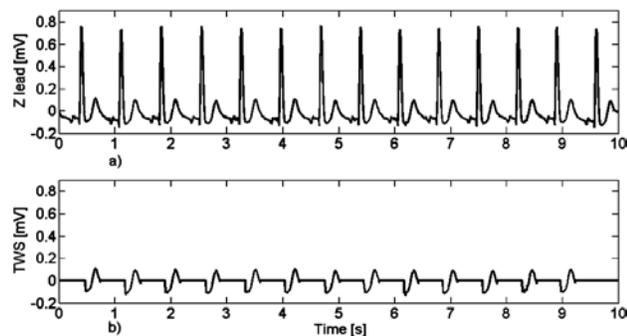


Figure 1. Z-lead ECG signal (panel a) of an ASAMI patient and corresponding T-wave signal (TWS; panel b).

2.4. Statistics

Age, heart rate and four values of TCE_{10} (one for each lead and one for the VMS) were reported for each subject of either populations. Mean and standard deviation (SD) values (over each population) of each clinical parameter were also reported. To be independent of normality, comparison between distributions relative to the ASAMI patients and the CH subjects was performed by means of the Wilcoxon rank sum test for equal medians. The ability of our THR to discriminate abnormal repolarization was evaluated computing sensitivity (Se), specificity (Sp) and area under the ROC curve (AUC) values. In all cases, statistical significance was set at 0.05 level.

3. Results

Clinical parameters relative to our CH subjects and ASAMI patients are reported in Table 1, which shows that the two populations differed significantly in terms of mean heart rate (which was lower for the CH than the ASAMI).

Analysis of frequency content of the TWS showed that most of the T-wave frequency content of leads X, Y, Z and VMS was included within 10 Hz in both populations. However, the ASAMI population was consistently characterized by lower TCE_{10} values than the CH population (Table 2). This finding indicates that the ASAMI patients have more frequency components than the CH subjects at high frequencies, as shown in Fig.3 where typical $PS_{TWS}\%(f)$ signals for an ASAMI patient and for a CH subject are shown. Consequently, the ASAMI mean $E_{TWS}\%(f)$ curve was significantly under the CH mean $E_{TWS}\%(f)$ curve for frequencies greater than 10 Hz, as represented in Fig. 4.

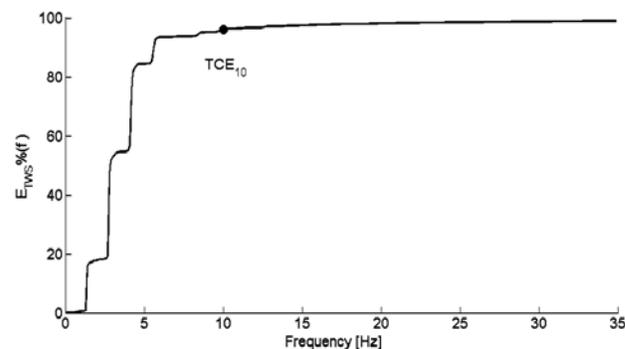


Figure 2. Graphical representation of the TCE_{10} index (black dot) defined as the T-wave cumulative normalized energy at 10 Hz.

THR values (X: 98.1%, Y: 97.2%, Z: 99.1%, VMS: 97.4%; defined as in Methods) were used to identify TCE₁₀ normality region out of which abnormal cases of repolarization are expected to fall (Fig.5). Such THR values allowed a discrimination of the ASAMI patients from the CH subjects with values of Se, Sp and AUC, as reported in Table 3. Z was found to be the optimum lead for discrimination of abnormal repolarization (Se=87%, Sp=74%; AUC=0.85).

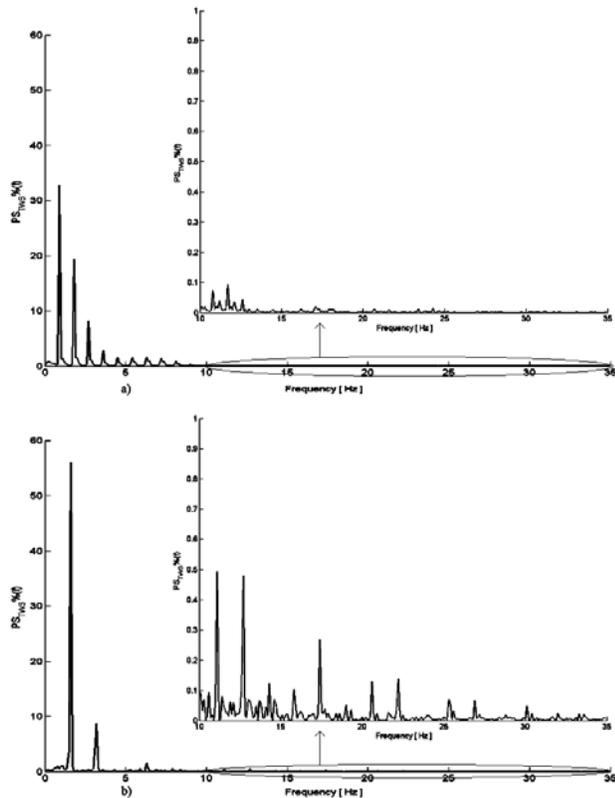


Figure 3. Typical PS_{TWS}%(f) signal for a CH subject (panel a) and for an ASAMI patient (panel b).

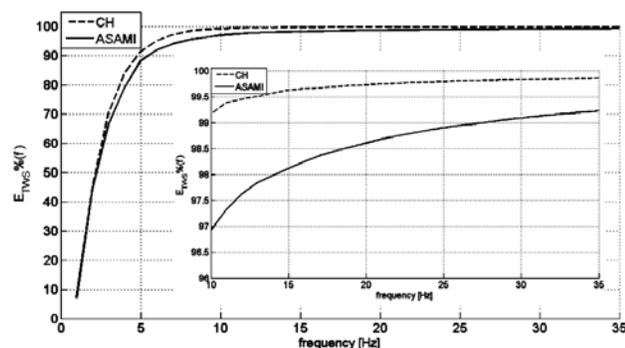


Figure 4. E_{TWS}%(f) curve over the CH subjects and the ASAMI patients for the Z lead.

4. Discussion and conclusions

This study proposed a new TCE₁₀ index, which represents the T-wave cumulative normalized energy at

Table 1. Mean±SD values of clinical parameters relative to the CH and ASAMI populations. NS: Not statistically significant.

	CH (N=23)	ASAMI (N=23)	P
Male	18 (78%)	18 (78%)	NS
Age (years)	52±14	61±12	NS
HR (bpm)	71±11	87±15	<10 ⁻⁵

Table 2. Mean±SD values of TCE₁₀ values for the CH and ASAMI populations.

	CH (N=23)	ASAMI (N=23)	P
X	98.2±1.2%	93.9±5.9%	<0.01
Y	97.8±1.4%	95.2±4.5%	<0.01
Z	99.1±1.5%	97.4±1.6%	<0.01
VMS	97.9±1.3%	95.7±2.8%	<0.01

Table 3. Sensibility (Se), specificity (Sp) and area under the ROC curve (AUC) values for the X,Y,Z and VMS.

	Se	Sp	AUC
X	78%	74%	0.79
Y	61%	74%	0.75
Z	87%	74%	0.85
VMS	57%	74%	0.73

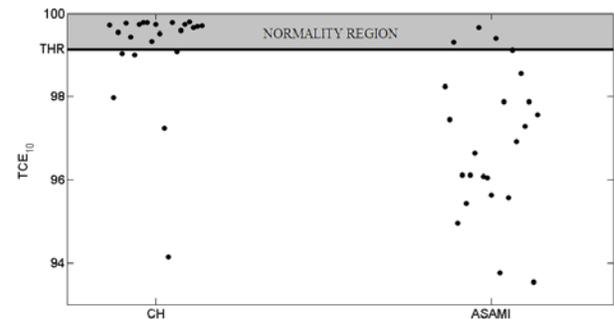


Figure 5. TCE₁₀ values for the CH subjects and the ASAMI patients in the Z lead. The THR is the value delimiting the TCE₁₀ normality region.

10 Hz, for discrimination of abnormal repolarization based on the T-wave frequency content, and tested the TCE₁₀ performance on CH subjects and ASAMI patients.

According to our results both CH and ASAMI populations have a T-wave frequency content mostly included within 10 Hz, as indicated by TCE₁₀ values greater than 93% (thus indicating that no more of the 7% of the spectrum is located in the 10-f_s/2 Hz frequencies range). However, compared to the CH subjects, the ASAMI patients show a significant increment of the high-frequency (greater than 10 Hz) components, as highlighted by significantly lower values of TCE₁₀ measured in all leads. Such difference between populations is only marginally due to a higher heart rate characterizing the ASAMI patients, which still has the effect to slightly shift their ECG spectrum toward the high frequencies. Indeed, an unpublished study from ourselves performed on the same ECG tracings used here but after heart-rate normalization (i.e. with heart rate forced to be 60 bpm to eliminate its effect on the T-wave frequency content evaluation) provided results statistically analogous to those obtained in the present study. Thus, the significant increment of the high-frequency components in the ASAMI patients, compared to the CH subjects, which is highlighted by the lower TCE₁₀ values measured in the former population, is essentially due to a more fragmented repolarization characterizing subjects with cardiomyopathy.

The definition of a THR as 25th percentile of the TCE₁₀ distribution over the CH population allowed the identification of a normality region which, by definition, is able to discriminate abnormal cases of repolarization with a specificity of 74% in all leads. Such value of specificity is a consequence of the THR definition and of the number of subjects in the CH population, which being less than 100, does not allow specificity to reach 75%. The sensitivity, instead, was lead dependent. In our ASAMI population lead Z appears as the optimum (showing a sensitivity of 87%), but it is possible that other leads could be optimal for patients discrimination when these were affected by acute myocardial infarction in other locations or by other diseases. Instead, the X, Y and Z lead combination in the VMS seems to significantly reduce the TCE₁₀ ability to discriminate abnormal cases of repolarization.

In conclusion, the CH subjects and the ASAMI patients have the T-wave frequency components differently distributed along the spectrum. Such differences can be highlighted by our innovative TCE₁₀ index, which is significantly lower for the ASAMI patients, thus indicating an increment of the high-frequencies (greater than 10 Hz) components. Eventually, the TCE₁₀ index provided satisfactory values of sensibility and specificity when used to discriminate abnormal cases of repolarization.

References

- [1] Reddy KS, Yusuf S. Emerging epidemic of cardiovascular disease in developing countries. *Circulation* 1998; 97:596-601.
- [2] Priori SG, Aliot E, Blomstrom-Lundqvist C, Bossaert L, Breithardt G, Brugada P, et al. Task Force on Sudden Cardiac Death, European Society of Cardiology. *Europace* 2002; 4:3-18.
- [3] Derval N, Simpson CS, Birnie DH, Healey JS, Chauhan V, Champagne J, et al. Prevalence and characteristics of early repolarization in the CASPER registry: cardiac arrest survivors with preserved ejection fraction registry. *Journal of the American College of Cardiology* 2011; 58:722-28.
- [4] Oosterhoff P, Tereshchenko LG, van der Heyden MA, Ghanem RN, Fetis BJ, Berger RD, et al. Short-term variability of repolarization predicts ventricular tachycardia and sudden cardiac death in patients with structural heart disease: a comparison with QT variability index. *Heart Rhythm* 2011 8:1584-90.
- [5] Hlaing T, DiMino T, Kowey PR, Yan GX. ECG repolarization waves: their genesis and clinical implications. *Annals of Noninvasive Electrocardiology*, 2005; 10:211-23.
- [6] Walder LA, Spodick DH. Global T wave inversion: long-term follow-up. *Journal of the American College of Cardiology* 1993; 21:1652-56.
- [7] Zhang Y, Post WS, Blasco-Colmenares E, Dalal D, Tomaselli GF, Guallar E. Electrocardiographic QT interval and mortality: a meta-analysis. *Epidemiology* 2011; 22:660-70.
- [8] Noseworthy PA, Havulinna AS, Porthan K, Lahtinen AM, Jula A, Karhunen PJ, et al. Common genetic variants, QT interval, and sudden cardiac death in a Finnish population-based study. *Circulation: Cardiovascular Genetics* 2011; 4:305-11.
- [9] Yu H, Pi-Hua F, Yuan W, Xiao-Feng L, Jun L, Sen L, et al. Prediction of sudden cardiac death in patients after acute myocardial infarction using T-wave alternans: a prospective study. *Journal of Electrocardiology* 2012; 45:60-65.
- [10] Leino J, Verrier RL, Minkinen M, Lehtimäki T, Viik J, Lehtinen R, et al. Importance of regional specificity of T-wave alternans in assessing risk for cardiovascular mortality and sudden cardiac death during routine exercise testing. *Heart Rhythm* 2011; 8:385-390.
- [11] Burattini L, Bini S, Burattini R. Automatic microvolt T-wave alternans identification in relation to ECG interferences surviving preprocessing. *Medical Engineering and Physics* 2011; 33:17-30.
- [12] Burattini L, Zareba W, Moss AJ. Correlation method for detection of transient T-wave alternans in digital Holter ECG recordings. *Annals of Noninvasive Electrocardiology* 1999; 4:416-424.

Address for correspondence.

Corrado Giuliani
Department of Information Engineering
Polytechnic University of Marche
60131 Ancona, Italy
c.giuliani@univpm.it