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Optimal ECG Lead System for Arrhythmia Assessment with Use of TCRT Parameter

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The aim of the study was to evaluate diagnostic value of TCRT (spatial QRS-T angle) parameter in different sets of ECG leads and to select the ECG lead set, for which the TCRT parameter would have the best sensitivity and specificity in identifying patients threatened by ventricular tachycardia (VT pts). Two groups of patients after myocardial infarction were studied: 13 non VT pts and 30 VT pts. The TCRT parameter values differentiated VT pts group from non VT pts group for all analyzed sets of ECG leads. Considering sensitivity of the TCRT parameter in identifying VT patients the best set of ECG leads was selected.

K e y w o r d s: arrhythmia, vectorcardiography, risk factors

1. Introduction

Diseases of heart and cardiovascular system are nowadays a major health problem. In European countries, cardiovascular mortality represents around 40% deaths of people at age below 74 years [1]. The most frequent cause of death among people with circulatory failure is sudden cardiac death (SCD), which is defined as: ‘natural death due to cardiac causes heralded by abrupt loss of consciousness within one hour of the onset of acute symptoms’ [2, 3]. The most common electrophysiological mechanism leading to SCD is rapid acceleration of cardiac rhythm called ventricular tachycardia (VT). It often evolves into ventricular fibrillation (VF).

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Lack of effective, noninvasive, diagnostic methods for the SCD prediction stimulates intensive searching of new tools for early detection of cardiac disorders. One of important risk markers of the ventricular tachycardia is a new parameter representing the total angle between QRS complex and T wave in electrocardiogram called TCRT (total cosine R to T). It was proposed for assessment of cardiac arrhythmia by Turkish scientist Burak Acar et al. in 1999 [4]. The TCRT parameter allows to assess homogeneity of electrical phenomena in cardiac muscle by examination of concordance between direction of depolarization wave propagation and direction of repolarization process. In normal physiological terms direction of depolarization should not significantly differ from direction of repolarization (the TCRT parameter close to one). The repolarization sequence in this case replicates the depolarization sequence in the opposite direction. It means that cells that depolarize last repolarize first. The abnormalities in the physiological synchronization between depolarization and repolarization of ventricles (the TCRT parameter close to minus one) lead to arising of the additional source of high frequency pulses which might cause arrhythmia incidents.

The TCRT parameter was originally calculated from 8 standard ECG leads. Many studies on body surface potential mapping have proved its superiority over standard ECG lead system in detecting cardiac insufficiencies [5–8, 11]. The results of our analysis [5] confirmed the diagnostic value of the TCRT parameter determined in that way. It was shown that sensitivity and specificity of the TCRT parameter were higher when 64 leads ECG system was used [5].

However, the application of many electrodes is cumbersome what causes difficulties with application of this technique as a clinical routine test. The compromise could be achieved when number of the ECG leads and its location on the body surface would be found in a way allowing reliable detection of various cardiac pathologies. In work of Fereniec et. al [9] three subsets of optimal 12 and 16 ECG leads from 64 surface ECG leads were chosen for diagnostics of ischemic heart disease and myocardial infarction.

The aim of this study was to evaluate the diagnostic effectiveness of the TCRT parameter calculated from the sets of ECG leads proposed in our previous work [9]. Another objective was selection of a set of optimal leads for VT assessment using the TCRT parameter with the best sensitivity and specificity.

2. Materials and Methods

The study was carried out on the group of 43 men, patients after myocardial infarction (MI) in age of 24 to 74 years (mean age 52.0 ± 13.4 years). The study group consisted of 30 patients with ventricular tachycardia (VT) and 13 without arrhythmia episodes in long term follow-up.

The ECG signals were recorded in the electrically shielded room using the high-resolution 64-lead ECG measurement system. The lead location corresponded to the

University of Amsterdam lead system [10, 11] where 61 electrodes were located on the torso and 3 ones on limbs. The ECG signals were sampled with frequency of 4096 Hz and amplitude resolution of 16 bits. To improve signal-to-noise ratio the ECG signals with a noise level about 6 to 8 μV were decimated to 1024 Hz [12] and averaged in time with use of cross correlation method [13]. The number of averaged heart beats was 100–300 beats depending on the noise level in the measured signal.

The values of TCRT parameter were calculated for subsets of the optimal ECG leads selected in our previous study [9] for ischemia and myocardial infarction diagnosis. To identify the best 12 and 16 ECG lead location on the body surface the Discriminant Index (DI) [14] and Sequential Selection Algorithm (SSA) [11] were used.

The Discriminant Index allows for the selection of ECG leads with the largest differences in ECG waves' shapes between the group of healthy subjects and the group of MI patients. This optimization of ECG leads focuses on finding of the optimal number and distribution of the ECG leads allowing to increase sensitivity and specificity of diagnostic methods using chosen leads subsets.

The Sequential Selection Algorithm proposed by Lux [11] was used for the determination of the smallest number and placement of the ECG leads, which would allow for the best approximation of ECG potentials distribution on the surface of the body received from system with large amount of leads. In the algorithm the correlation coefficients between all leads are determined from the covariance matrix estimated using all ECG signals from all subjects. The lead that had the highest correlation coefficient ("information content") with all other ones was selected sequentially. Finally sets of 12 and 16 optimal leads were selected.

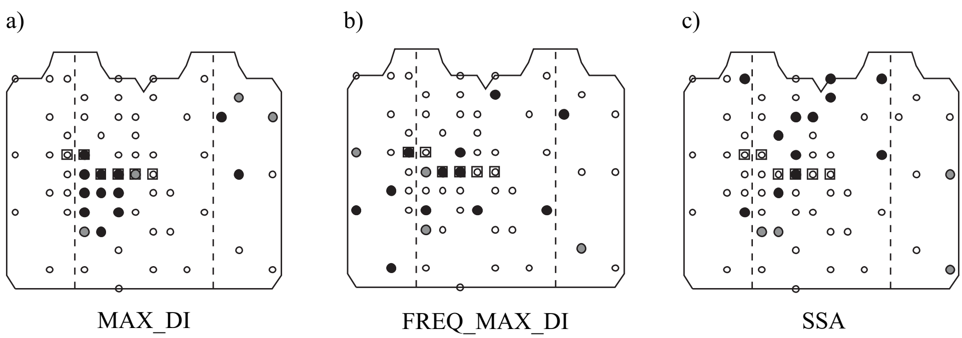

Fig. 1. Optimal locations of 12 and 16 ECG leads around thorax, a – chosen in respect of maximal value of the Discriminant Index (MAX_DI), b – chosen in respect of the most frequently occurrence of the maximal value of the Discriminant Index (FREQ_MAX_DI), c – the leads selected using sequential selection algorithm (SSA). Unfilled squares (□) stand for precordial leads (from left V_1, V_2, V_3, V_4, V_5, and V_6), black circles (●) represents the set of 12 optimal ECG leads, and filled grey circles (●) are 4 additional leads added to form the set of 16 optimal ECG leads

The selected sets of optimal ECG leads are shown in Fig. 1. The first 12 and 16 ECG leads were selected according to the maximal values of DI (Fig. 1a – MAX_DI). The ECG leads with the largest differences between the ECG signals averaged in group of healthy subjects and the ECG signals averaged in group of MI patients were chosen. The second subsets of optimal ECG leads were selected according to the most frequently occurrence of the maximal value of Discriminant Index (Fig. 1b – FREQ_MAX_DI) calculated individually for each patient. The third sets of optimal ECG leads were chosen using the Sequential Selection Algorithm (Fig. 1c – SSA).

To calculate the TCRT parameter, the singular value decomposition (SVD) was applied to the data matrix M (mxn), in which m is the number of analyzed ECG channels, n is the number of samples in each channel (m>n). It is expressed by the following formula:

$$M = U \Sigma V^T \tag{1}$$

where:

U – *mxm* orthogonal matrix, ortonormal basis of columns of M,

V – *nxn* orthogonal matrix, ortonormal basis of rows of M,

Σ – diagonal matrix mxn of singular values ($\sigma_{ij} = 0$ if $i \neq j$ and $\sigma_{11} \geq \sigma_{22} \geq \cdots \geq 0$).

The first column of both U and V matrixes includes *k* the most important components of data matrix M, thus the matrix M can be approximated as:

$$M_k \sim U_k \Sigma_k V_k^T \quad (\text{where } k >= 1) \tag{2}$$

As a result of a projection of the matrix M onto three first columns of the matrix U (u_1,u_2,u_3), three independent components of the ECG signals (three orthogonal signals – S_1, S_2, S_3) were obtained and ordered according to their significance. In further analysis the signals containing most information about measured data (99% of ECG energy [15]) were used.

The ECG characteristic points (onsets and offsets of both depolarization and repolarization waves) were determined according to procedure described by Acar et al. [4].

The TCRT parameter was defined as an average of cosines of the angles between consecutive R-wave loop vectors located in a subspace U and the main T-wave loop vector.

$$TCRT = \frac{1}{\Delta t_R} \int_{i=1}^{\Delta t_R} \cos\left[\angle\left(t_v, r_v\left(i\right)\right)\right], \tag{3}$$

where:

t_v –T-wave vector,

$r_v(i)$ – vectors creating R-wave,

Δt_R – duration of R-wave.

The examples of orientation of R-wave loop and T-wave loop for two analyzed patients after myocardial infarction are shown in Fig. 2: with ventricular tachycardia (Fig. 2a) and without VT (Fig. 2b). For most cases the angles α between the main direction of the R-wave and the T-wave for VT patients were larger than for patients who did not have episode of arrhythmia. The TCRT parameter measures differences between the main orientations of depolarization and repolarization waves thus it could separate VT pts group from non-VT pts group.

a) b)

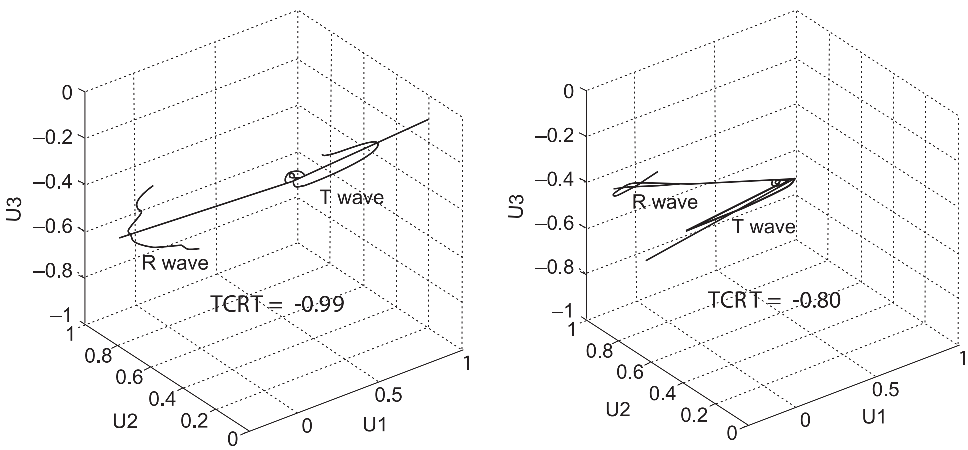

Fig. 2. The orientation of R-wave loops and T-wave loops are shown for MI patients with ventricular tachycardia (a) and without episode of arrhythmia in long term follow-up. Note that directions of the depolarization and the repolarization waves are close to each other in a case of non-VT patient (b), whereas they are far from each other in case of VT patient (a). The negative values of the TCRT parameter correspond to large difference between orientation of R-wave and T-wave

Range of physiological (normal) and pathological (proarrhythmic) values of angles between directions of the main T-wave and R-wave vectors were determined according to Kardys et al. [16]: physiological range from 0° to 130° ($-0.64 < \text{TCRT} \le 1$), pathological from 130° to 180° ($-1 \le \text{TCRT} \le -0.64$).

3. Results

The results of study are shown in Table 1 and Table 2. They are compared with results obtained in our previous analysis on the same group of patients performed using 61 leads and a set of 8 standard leads [5].

The distinct differences in the values of TCRT parameter were observed between group of patients with ventricular tachycardia (VT pts.) and group of patients without ventricular tachycardia for all sets of ECG leads (Table 1).

Table 1. Mean values of the TCRT parameter (± STD) calculated using different sets of ECG leads

Algorithm of selection	Number of ECG leads	VT pts.	non VT pts.
	61 leads	–0.80 ± 0.27	0.27 ± 0.46
	8 standard leads	–0.80 ± 0.22	0.28 ± 0.49
MAX_DI	12 optimal leads	–0.71 ± 0.37	0.18 ± 0.69
	16 optimal leads	–0.72 ± 0.34	0.22 ± 0.68
FREQ_MAX_DI	12 optimal leads	–0.67 ± 0.36	0.27 ± 0.61
	16 optimal leads	–0.73 ± 0.31	0.13 ± 0.64
SSA	12 optimal leads	–0.55 ± 0.44	0.35 ± 0.59
	16 optimal leads	–0.58 ± 0.42	0.34 ± 0.58

The best sensitivities were obtained in a case of 61 leads as well as for 12 and 16 sets of optimal ECG leads selected in respect to maximal value of the Discriminant Index (MAX_DI). There was no difference in values of sensitivity for the sets of leads chosen with MAX_DI method. A little bit worse result of the TCRT sensitivity for detection of VT patients were obtained in a case of the sets of optimal ECG leads selected with FREQ_MAX_DI method and for standard ECG leads.

The result of the TCRT sensitivity calculation (worse than 60 %) was unsatisfactory in the case of set of leads selected using Sequential Selection Algorithm (SSA). The values of specificity were better than 80 % for all analyzed sets of the ECG leads.

Table 2. The sensitivity and specificity of TCRT parameter

Algorithm of selection	Number of ECG leads	Sensitivity of TCRT parameter [%]	Specificity of TCRT parameter [%]
	61 leads	76	100
	8 standard leads	72	100
MAX_DI	12 optimal leads	76	85
	16 optimal leads	76	85
FREQ_MAX_DI	12 optimal leads	69	92
	16 optimal leads	72	85
SSA	12 optimal leads	52	100
	16 optimal leads	59	100

The result of TCRT parameter calculation on the group of MI patients with ventricular tachycardia and without VT is shown in Fig. 3. The set of 12 optimal ECG leads chosen in respect of the maximal value of Discriminant Index (MAX_DI) was used in the calculation. The sensitivity of TCRT for this set of leads was the same as for the set of 61 leads. The specificity of TCRT was also acceptable.

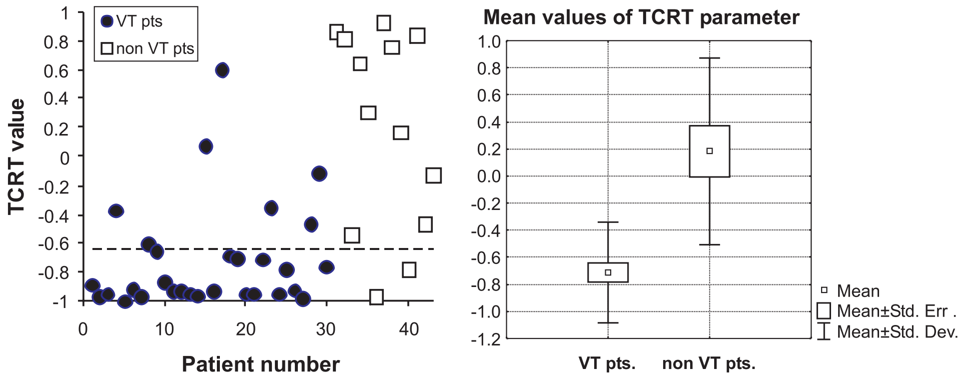

Fig. 3. Values of TCRT parameter calculated from the set of 12 ECG leads chosen in respect of the maximal value of Discriminant Index (MAX_DI)

4. Discussion and Conclusions

The sets of ECG leads characterized by the best sensitivity and specificity of the TCRT parameter in indentifying patient threatened by ventricular arrhythmia were searched.

The six optimal ECG leads' subsets of 64 surface ECG leads system selected in our previous study [9] were used in the calculations. The four sets of 12 and 16 ECG leads chosen using the Discriminant Index show the best differences in morphology of ECG signals between the group of MI patients and the group of healthy volunteers. The next two analyzed sets of ECG leads selected using the Sequential Selection Algorithm allow the best approximation of ECG potentials' distribution on the surface of the body, received from 64 ECG leads system.

The results of analysis performed in this study confirmed the diagnostic value of the TCRT parameter in identifying patients threatened by ventricular tachycardia. Selection of the optimal 12 ECG lead set for the TCRT parameter calculation chosen on basis of the maximal value of Discriminant Index [9] seems to be a good solution. For this lead system the sensitivity of the TCRT parameter in identifying VT patients was the same as for 61 leads set. Specificity of TCRT parameter in case of this subset of optimal ECG leads was also satisfactory. This 12 lead set could be applied during ECG tests with use of standard electrocardiographs. High prognostic value of the TCRT parameter gives rise to statement, that it might be an effective marker helpful in a qualification process to implantable cardioverter-defibrillator therapy of MI patients. Further analysis, especially with larger number of patients after myocardial infarction, is required.

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