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High-resolution Multichannel Measurement and Analysis of Cardiac Repolarization

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Time and spatial inhomogeneity of the repolarization phase is considered to be an important, noninvasive indication of sudden cardiac death in patients after myocardial infarction. Analysis of spatial variability of the repolarization phase was carried out on signals recorded with the 64-channel system for measurement of high-resolution ECG. The lead position on the torso, according to the University of Amsterdam lead system, was used. A new parameter, called the *T*-wave shape index and the distribution function method, as a method sensitive to shape variations, were applied to examine spatial variability of the *T*-wave shape in HR ECG maps.
A group of 14 healthy volunteers and a group of 12 patients after myocardial infarction were studied.
The diversity of spatial distributions of the parameters connected to the shape of the *T*-wave is clearly noticeable in the group of patients after myocardial infarction. The similarity of spatial distributions of proposed parameters in the group of healthy subjects is observed. The obtained results confirm the hypothesis that the spatial heterogeneity of the repolarization phase increases after myocardial infarction.

K e y w o r d s: high-resolution ECG, repolarization phase, shape variability, myocardial infarction

1. Introduction

Noninvasive examination of the heart electrical activity is essential for clinical diagnosis of many cardiac diseases. However, some features of the ECG are not well understood, i.e. the *T* wave shape changes [1]. The *T* wave in ECG reflects the repo-

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larization phase (i.e. the diastole of heart ventricles, in particular the left ventricle). The shape of *T* wave is a function of many parameters, including size and shape of the ventricle, heart rate and action potential distribution [2]. The widely used parameter describing the repolarization phase is the QT interval. Its dispersion, in 12-lead ECG, is a measure of the repolarization inhomogeneity. The inhomogeneity of the repolarization phase correlates with re-entry phenomena causing development of life threatening ventricular arrhythmia [3–6]. In particular, it concerns a large group of patients after myocardial infarction and patients with left ventricular hypertrophy [4, 7]. However, in clinical practice accurate and reproducible measurement of the QT dispersion has been limited by difficulties with reliable identification of the *T*–wave offset [8]. There are some data that indicate that the shape of the QT complex, in which the *T* wave is the most important factor, much more important in pathogenesis of the repolarization inhomogeneity than the QT interval dispersion [7, 8]. Therefore, it is essential to find such parameters that could characterize the shape of the *T*-wave.

The purpose of this study was to investigate the spatial changes of the repolarization phase, in particular, the *T*-wave shape in a high-resolution ECG recording. Two different parameters quantifying the *T*-wave shape and shape differences were applied: parameter TSI (T-wave Shape Index) based on the length of the *T*-wave curve and integral of the ECG amplitude in the *T*-wave segment [9] and a new parameter calculated from the distribution function method, which allows to detect the small differences of the signal shapes [10].

2. Material and Methods

The preliminary analysis of the repolarization phase in the HR-ECG was performed on a set of data of 14 normal subjects and 12 post-infarction patients. The examination was carried out in an electrically shielded room using a 64 channel high-resolution ECG measurement system [11].

2.1. System

The system consists of 64 low noise (c.a. 1 μV) amplifiers with 16-bit A/D converters *(BIOSEMI, the Netherlands*). The ECG signals are acquired with 4096 Hz sampling frequency, digitized and recorded at least through 300 seconds. The digital signals are converted to the serial optical format and then transferred to a computer via an optical fiber. The data acquisition is controlled by the LabView measurement software. Electrode locations on the surface of the torso according to the University of Amsterdam lead system was used. The system includes 32-lead Lux optimal set [12,13], six standard ECG leads and three orthogonal X,Y,Z leads. The low resistance Ag/AgCl pediatric electrodes LFR-310 (*Bio-Lead-Lok, Poland*) are applied in the form of strips and as single electrodes.

2.2. Methods

The signals analyzed in this work are averaged by the cross-correlation method, which results in a very low noise data, approximately 0.1–0.7 μV RMS.

In the study two methods describing the *T*-wave shapes are compared: the the TSI parameter and the distribution function method. The *T*-wave Shape Index (TSI), is a quantitative measure of the individual *T*-wave shape and is defined as follows:

$$TSI = \frac{\int_{Ton}^{Toff} V(t)dt}{Tcurve\_length} \tag{1}$$

The parameter is a ratio of the integral of ECG amplitudes in the *T*-wave segment and the total length of the *T*-wave curve.

The distribution function method defined in [10] has been proposed to measure the shape similarity between the two positive signals. For the signal $s(x)$ and its normalized integral $S(x) = \int_{-\infty}^{x} s(t)dt \,/\, \int_{-\infty}^{+\infty} s(t)dt$ it is known that $S(x)$ remains invariant for any transformation of *s(x)* of the type:

$$s(x) \to v(x) = ks(f^{-1}(x))\frac{d}{dx}f^{-1}(x)\,, \tag{2}$$

where ($k > 0$) and f is an increasing continuous function.

On the other hand it is often held that two signals s and v have the same shape if their profiles are taken from one another by means of the scale change on the ordinate and a linear transformation on the abscissa, i.e., v is taken from s by shape relationship:

$$v(x) = k's\left(\frac{x-b}{a}\right),\ (k',\, a) > 0 \tag{3}$$

which is analogous to the relationship (2) using

$$k' = ka \quad \text{and} \quad f(t) = at + b \ \ (a > 0).$$

Normalized distribution functions $S(x)$ and $V(x)$ of signals $s(x)$ and $v(x)$ are equal at points x and y related by $y = f(x)$.

$$S(x) = V(y) = (V \circ f)(x). \tag{4}$$

Therefore the functions S and V are related by $S = V \circ f$ which, is equivalent to

$$f(x) = (V^{-1} \circ S)(x) \,. \tag{5}$$

Function $f(x)$ is a linear relationship only if the signals are identical in the above described meaning. The difference between signals $s(x)$ and $v(x)$ shapes is characterized by a standard deviation of the relationship $f(x)$ from a fitted linear function $y(x)$.

$$\Delta = \sqrt{\sum_{t=1}^{t=N} \left(f(x) - y(x) \right)^2 / N} \,. \tag{6}$$

Parameter Δ is a quantitative measure of the similarity of shapes. Successive steps in the calculation process of the distribution function parameter are presented in Fig. 1.

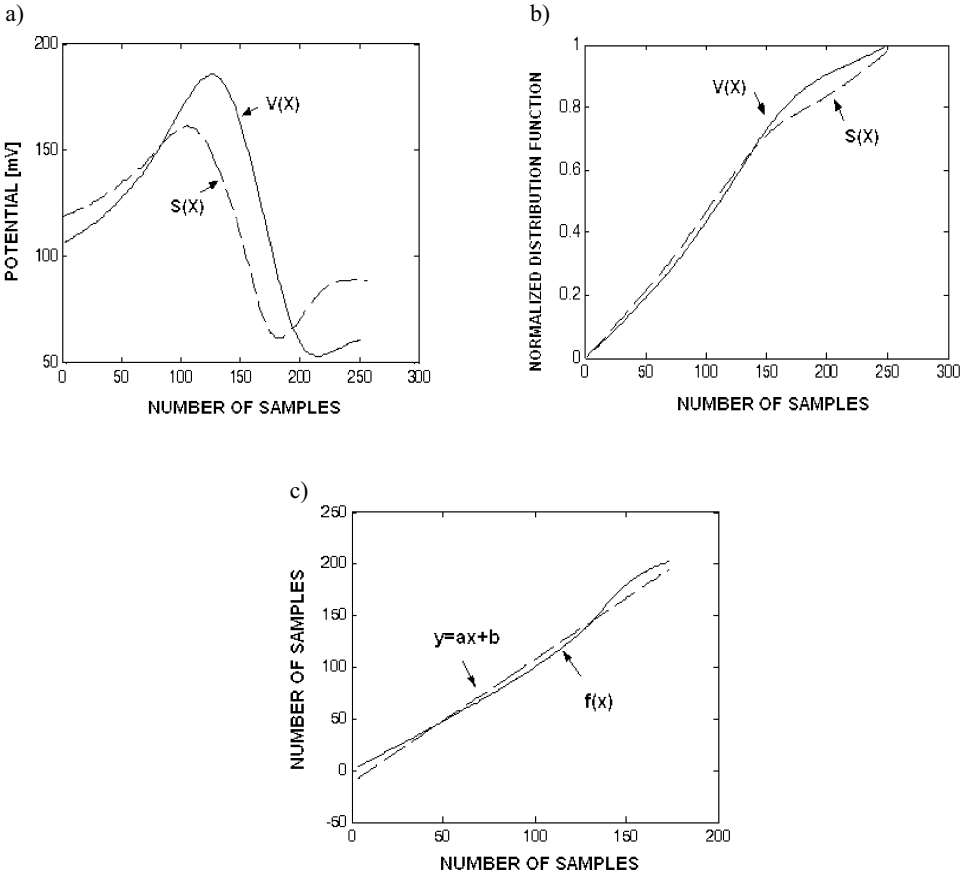

Fig. 1. Successive steps in Δ parameter calculations: a) Comparison of two signals – *T* waves $v(x)$ and $s(x)$, b) Distribution functions $V(x)$ and $S(x)$ of compared signals, c) Comparison of $f(x)$ relationship with linear fitted function $y(x)$

In the distribution function method, it is necessary to have a reference signal for each lead. In this study the reference was calculated for each lead as the average T wave in the group of the healthy subjects. However, it is difficult to calculate the average signals from the leads located far from the precordial area. Two examples of the T waves obtained from the different lead positions i.e. from the lead placed over the heart and the lead placed on the right side of the chest in the group of healthy subjects are shown in Fig. 2.

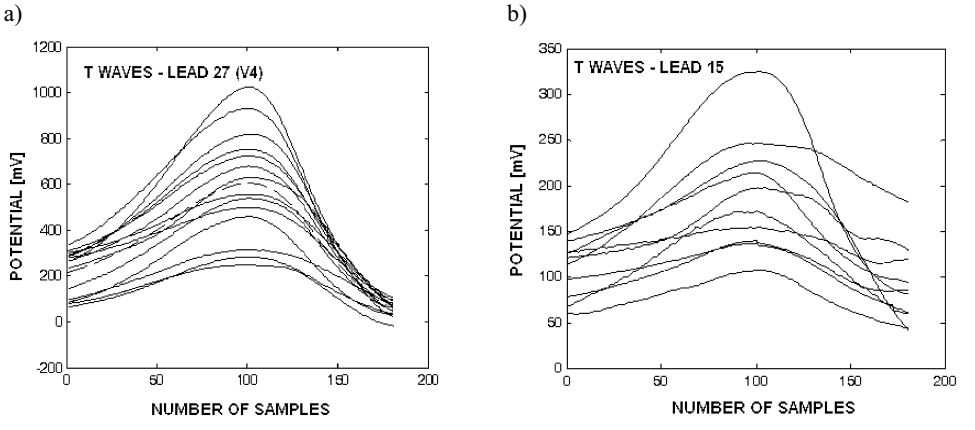

Fig. 2. Examples of *T* waves: a) from lead placed over the heart; b) from lead placed on right side of the chest

The proposed TSI parameter and Δ parameter were calculated for all the surface ECG signals of each subject and presented as iso-amplitude maps. For the TSI parameter, the absolute values of differences between the normalized TSI parameter of each subject and the mean normalized TSI parameter calculated in the group of healthy subjects, are analyzed (DIFF_TSI).

3. Results

The obtained results show that in certain areas on the torso surface, differences of the *T*-wave shapes between the healthy subjects and the post-infarction patients can be clearly noticed. The maps of DIFF_TSI parameter of patients are very miscellaneous in contrast to the maps of DIFF_TSI parameter of healthy subjects which are very similar and its values are low. The Δ parameter gives similar results for the patients group and for healthy subjects but only in the precordial area. In the peripheral leads, a large dispersion of Δ parameter is observed in the control group. In Figure 3 the examples of maps of DIFF_TSI parameter and the maps of Δ parameter are presented.

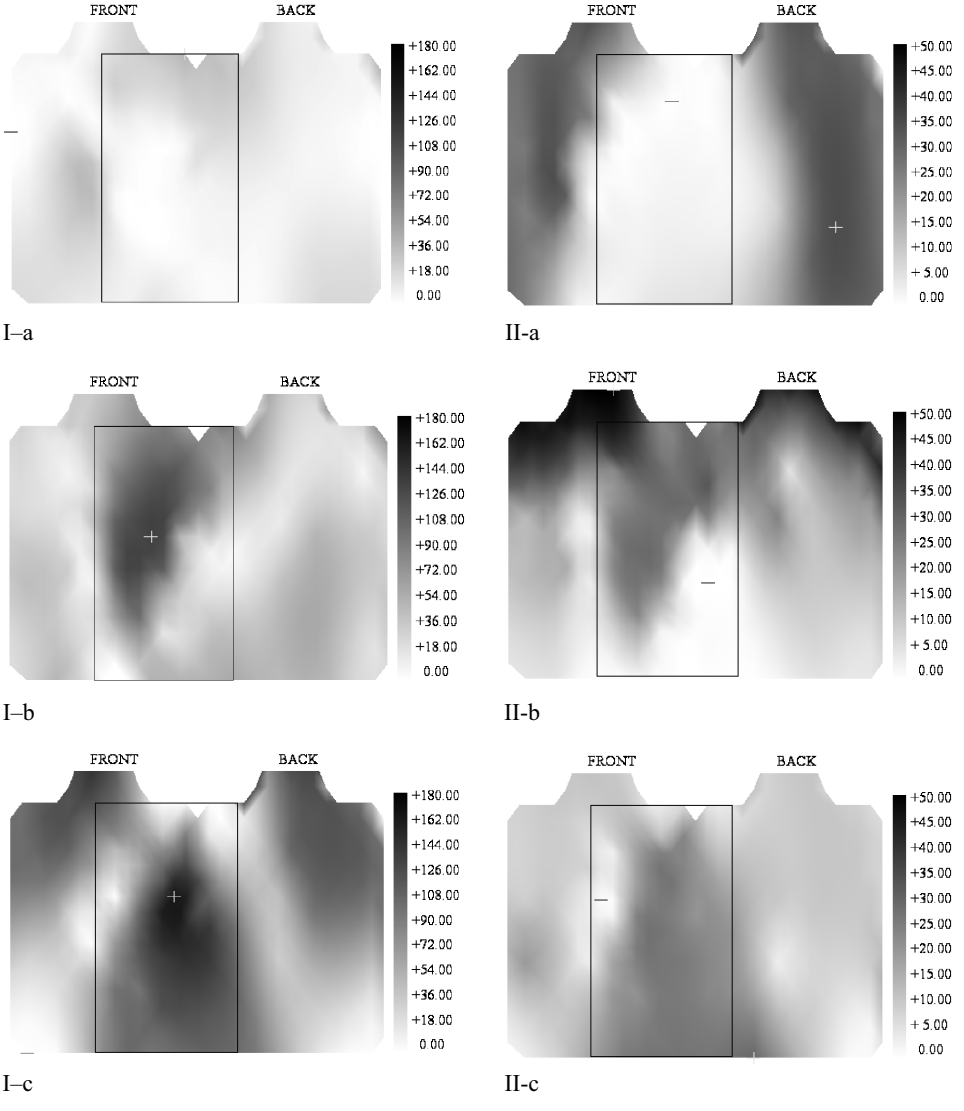

Fig. 3. Examples of maps. In columns: I – difference maps of TSI parameter, II – maps of Δ parameter; in rows: a – control subject, b – patient after anterior infarction, c – patient after anterolateral and inferior infarctions

The precordial area in each map is indicated with a rectangle. The maps of parameters of the same subject are placed one above the other to facilitate comparison. Values of both parameters are very small in maps of control subject, within rectangular area, whereas, the values of both parameters in maps of patients are much larger and their spatial distributions are similar, within rectangular areas. The regions of the

highest values of both parameters in the patients' maps might indicate the infracted area of the heart muscle [14].

In Figure 4, the values of both parameters as functions of the lead numbers are shown. With grey colour, the area of the values for the normal group, i.e. mean ± 2SD, is indicated and black lines represent the values of parameters of individual patients after myocardial infarctions.

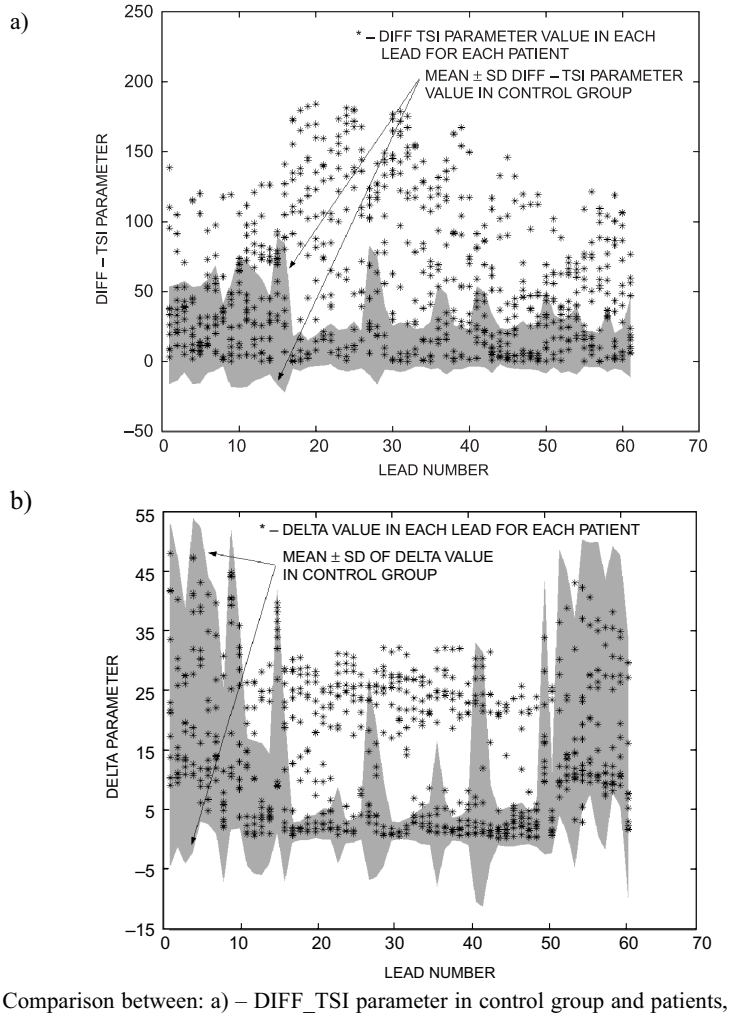

Fig. 4. Comparison between: a) – DIFF_TSI parameter in control group and patients, b) – Δ parameter in control group and patients

The values of both parameters in patient group are outside the area of values calculated in the control group, especially in the precordial area in case of Δ parameter.

4. Discussion and Conclusion

In this work the TSI parameter, based on the *T*-wave integral and the *T*-wave curve length, quantifying the *T* wave shape, has been calculated as well as, for the first time, the distribution function method (Δ parameter) has been used to quantify the *T* wave shape differences. Both the proposed parameters are independent of the accuracy of the *T*-wave on- and offset detections. Only amplitude changes in the same established time interval for all the leads are taken into account. The spatial heterogeneity of the values of both parameters has been found to be larger in the examined patients with cardiac insufficiency than in normal subjects. Moreover, the spatial distributions of the values of both parameters show similar patterns, especially in the precordial area, which could indicate the infracted regions of the heart in patients after myocardial infarction. The obtained results show that spatial variability of both parameters might be a good marker of variability of the *T*-wave morphology and could reflect the spatial repolarization dispersion. Further study on larger group of patients with cardiac insufficiencies is still required.

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