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doi:10.15199/48.2017.03.29

Research of alternative diagnostic features in intelligent computer-based cardiological decision support systems

***Abstract**. The article proposes an alternative system of diagnostic features in electrocardiography. A hodograph is suggested as an alternative to a classic display of an electrocardiograph. The diagnostic value of alternative diagnostic features is analyzed for different premature ventricular contractions. The proposed method of morphological analysis of a biomedical signal with locally concentrated properties improves the accuracy of detection of the structural elements of the ECG in the presence of background noise. A graphical display of an electrocardiogram in the alternative feature space allows the doctor to visually classify different premature ventricular contractions.*

Streszczenie.** W artykule zaproponowano alternatywny sposób przedstawiania cech diagnostycznych sygnału EKG za pomocą hodografu w miejsce klasycznego elektrokardiografu. Wartość diagnostyczna systemu jest oceniona na podstawie szeregu przedwczesnych skurczów komorowych. Zaproponowana metoda polegająca na analizie lokalnie umieszczonych cech poprawia dokładność wykrywania elementów strukturalnych EKG w obecności szumu. Graficzne przedstawienie elektrokardiogramu w alternatywnej przestrzeni cech pozwala lekarzowi na wizualną klasyfikację przedwczesnych skurczów komorowych.* ***Aternatywny sposób przedstawiania cech diagnostycznych sygnału EKG za pomocą hodografu

Keywords: hodograph, electrocardiogram, diagnosis, alternative.
Słowa kluczowe: hodograf, elektrokardiogram, diagnoza, alternatywa.

Introduction

Currently, domestic production of digital electrocardiographic telemetry systems has increased significantly. For example, transtelephonic digital 12-channel electrocardiographic complex „Telecard" developed by „Company TREDEX" (Kharkov) deserves attention [6]. The equipment is designed for the recording and transmission of an electrocardiogram (ECG) to the remote diagnostic host center using any communication channels, in particular, standard phone lines, mobile communication channels, any range radio channels and telephone channels of the DECT standard. The complex uses a digital signal transmission through the acoustic channel which provides guaranteed high quality of an ECG and allows professional diagnosis of any heart disease (coronary artery disease, myocardial infarction, different heart arrhythmias, etc.). Creation of intelligent computerized cardiological decision support systems as part of the electrocardiographic telemetry systems can improve the quality of advice in terms of emergency medical care [5].

Actuality

Traditionally, morphological analysis of an ECG is performed to diagnose the state of the cardiovascular system. In particular electrocardiography is used to determine the frequency and regularity of heartbeats. The most common disorder of heart rhythm is a premature ventricular contraction. A premature ventricular contraction (PVC) is extraordinary excitation (and subsequent reductions) of the heart or its parts resulting from heterotopic excitation of cardiac muscle. The peculiarity of this pathology is that the premature ventricular contraction occur randomly on the background of a large number of normal periods, which requires a long (several hours) ECG monitoring, but automated methods for the detection of „suspicious" periods virtually absent. In practical work and research the ventricular arrhythmia is focus on, since some species of PVCs may indicate the possible development of ventricular fibrillation [3, 4].

An ECG is a biomedical signal (BMS) with locally concentrated properties (LCP). The result of ECG interpretation is the selection of waves and complexes, determination of their amplitude and time characteristics and shape analysis of selected structural elements [10]. To solve the problem of morphological analysis of BMS with LCP, authors proposed a method based on the construction of a multi-channel nonlinear filter [2-4,7]. The task of this method is the detection of structural elements of the given type and their localization on the considered signal [1]. The method is based on the idea of transformation of BMS with LCP into a new feature space using the properties of useful signal model (USM).

The task of providing additional diagnostic information obtained as a result of the morphological analysis of an ECG using the developed method in order to improve the quality of diagnosis of the ventricular arrhythmia is relevant.

Aim of the research

The aim of the research is to provide to cardiologist alternative diagnostic features in human-readable graphic form along with the traditional display of the electrocardiographic signal.

Objectives of research:

1. To design a system of alternative diagnostic features that can be represented in human-readable graphic form.
2. To investigate the diagnostic value of alternative diagnostic features for the ventricular arrhythmia.

Solution

To solve this problem let us consider in more detail the method of morphological analysis of BMS with LCP proposed in [2] (Fig. 1). At the step $S1$ in each channel the corresponding transformation of the input signal $x[t]$ ($t=\overline{0;T_s-1}$, T_s is input signal length) is performed based on the useful signal model (USM). The output of each block $B1_i$ is tuple of parameters for nonlinear filter (the linear size of the aperture, weighting function of the filter, detection signal): $K_i=\langle x_0[t], P_i, f_i(x[t],P_i)\rangle$, where $x_0[t]$ ($t=\overline{0;T_0-1}$) is the signal template (the prototype of the given type structural element); $T_0 << T_s$ is the signal template length; P_i is the set of parameters for the i-th channel; $f_i(x[t],P_i)$ is the signal transformation function within the aperture for the i-th channel.

The linear size of the aperture is equal to the linear size

T_0 of the given template $x_0[t]$ of required structural elements on the time axis.

The step $S2$ is nonlinear filtering. The result of this step is detection of the required structural elements (Fig. 1). In each block $B2_i$ the detection function $\tilde{y}_i[t] \in [0;1]$ of the i-th channel is

(1) $$\tilde{y}_i[t] = \frac{1}{1+\alpha_i D^2(\omega_i^p, \omega_i^t)},$$

where $\alpha_i \in (0;1]$ is the coefficient reflecting sensitivity to variations of the structural elements of required type due to the noise addition and parameter variations $D^2(\omega_i^p, \omega_i^t) = \sum_{j=1}^{Na_i} (y_{ij}^p - y_{ij}^t)^2$ is the square of the distance between the prototype ω_i^p of structural element and a current object ω_i^t within the aperture; $y_{ij}^p = f_i(x_0[t], P_i)$, $y_{ij}^t = f_i(x[t], P_i)$ are coordinates of objects ω_i^p and ω_i^t respectively; $\alpha_i, Na_i, t \in P_i$.

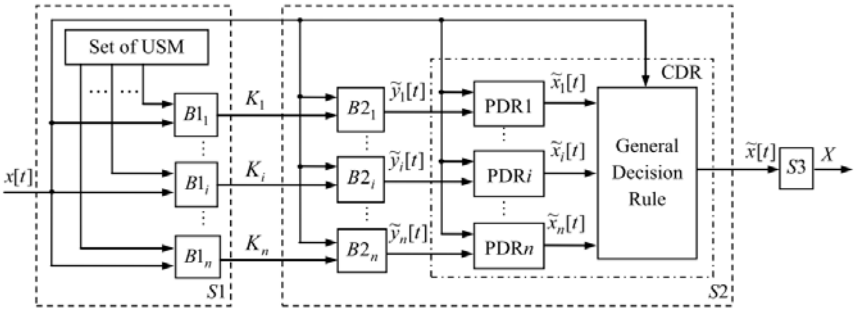

Fig.1. Generalized scheme of morphological analysis of BMS with LCP

Detection of the structural elements of the given type in the i-th channel is performed with private decision rule (PDRi) on the basis of detection function $\tilde{y}_i[t]$:

(2) $$\tilde{x}_i[t] = \begin{cases} x[t] \ \forall t \in [t_{ie}; t_{ie}+T_0], & \textbf{\textit{at}}\ \tilde{y}_i[t_{ie}] > Pd_i; \\ x^0 & \textbf{\textit{at}}\ \tilde{y}_i[t_{ie}] \le Pd_i, \end{cases}$$

where $\tilde{x}_i[t]$ is the private filter response; t_{ie} is point of local maximum of the function $\tilde{y}_i[t]$ such that $\tilde{y}_i[t_{ie}] \ge \tilde{y}_i[t]$ $\forall t \in \dot{\mathbf{M}}(t_{ie})$; $\tilde{y}_i[\cdot]$ is detection function (1) for the i-th channel; $\dot{\mathbf{M}}(t_{ie}) = \mathbf{M}(t_{ie}) \setminus \{t_{ie}\}$ is deleted neighborhood of the point t_{ie}; $\mathbf{M}(t_{0ij})$ – neighborhood of the point t_{ie}; *j* – index of local maximum; Pd_i – threshold of PDRi; $x^0 = const$ – constant that determines the signal level corresponding to the absence structural elements of given type at the current signal fragment (e.g., isoline level of an ECG).

Then private decision rules are united into collective of decision rules (CDR), the result is the signal $\tilde{x}[t]$ containing structural elements of the given type.

At the step $S3$ the characteristics of found structural elements are calculated from the signal $\tilde{x}[t]$. These characteristics are the components of the set X. The components of the set X are the traditional diagnostic features used to diagnose the state of the cardiovascular system with an ECG.

According to the private decision rule (2), not all objects ω_i^t are subject to classification but only those objects $\tilde{\omega}_i^e$ are classified for which the detection function $\tilde{y}_i[t]$ has local maxima ($\{\tilde{\omega}_i^e\} \subset \{\omega_i^t\}$). Those each classified object $\tilde{\omega}_i^e$ is the part of signal $x[t]$ with length T_0 that starts at the point t_{ie}.

In its turn $\{\tilde{\omega}_i^e\} = \Omega_1 \bigcup \Omega_2$, $\Omega_1 \bigcap \Omega_2 = \varnothing$, where Ω_1, Ω_2 are set of the desired structural elements and set of all other objects respectively. In addition, each object $\tilde{\omega}_i^e$ can be described both amplitudes $x[t]$ of said signal part in the original feature space and coordinates $\tilde{y}_{ij}^e$ calculated with the functions $f_i(x[t], P_i)$ in the alternative feature space. It should be noted that only objects of the set Ω_1 coincide with the structural elements accepted in medical practice. But objects of the set Ω_2 are abstract, and their properties aren't analyzed at conventional diagnosis of cardiovascular system with an ECG. However, since at the step $S1$ of the input signal conversion is performed based on the useful signal model, in the new feature space the structural elements are described diagnostic features adapting to the useful signal model and maximally taking into consideration the properties of the considered BMS with LCP. Therefore, it is advisable to consider the relative position of objects of sets Ω_1 and Ω_2 in the alternative feature space in order to obtain additional diagnostic information [8].

Most clearly the relative position of objects of sets Ω_1 and Ω_2 can be represented graphically. Thus it is necessary that the number of coordinates in the alternative space is $Na_i \le 3$ and the coordinate values $\tilde{y}_{ij}^e$ are normalized.

The properties of detection function can be used to normalize coordinates of objects $\tilde{\omega}_i^e$. The normalized distance $D'^2(\omega_i^p, \omega_i^t) \in [0;1]$ between objects ω_i^p and ω_i^t can be determined using detection functions $\tilde{y}_i[t]$ as follows:

(3) $$D'(\omega_i^p, \omega_i^t) = \sqrt{1-\tilde{y}_i[t]} = \sqrt{1-\frac{1}{1+\alpha_i D^2(\omega_i^p, \omega_i^t)}} =$$

$$= D(\omega_i^p, \omega_i^t)\sqrt{\frac{\alpha_i}{1+\alpha_i D^2(\omega_i^p, \omega_i^t)}} = D(\omega_i^p, \omega_i^t)\sqrt{\alpha_i \tilde{y}_i[t]}.$$

Then, taking into account the expression (3) normalized and centered with respect to the prototype ω_i^p alternative diagnostic features $\widetilde{y}_{ij}^{\prime e}$ of the i-th channel are determined with the following expression:

(4) $\widetilde{y}_{ij}^{\prime e} = (y_{ij}^p - \widetilde{y}_{ij}^e)\sqrt{\alpha_i \widetilde{y}_i[t]}$,

where $\widetilde{y}_{ij}^{\prime e}$, $\widetilde{y}_{ij}^e$ are normalized and non-normalized coordinates of objects $\widetilde{\omega}_i^e$ in an alternative space features.

It's obvious that $\widetilde{y}_{ij}^{\prime e} \in [0;1]$ and $\widetilde{y}_{ij}^{\prime e} = 0$ if the object $\widetilde{\omega}_i^e$ is the same as the prototype ω_i^p , i.e. $y_{ij}^p = \widetilde{y}_{ij}^e \;\; \forall j = \overline{1, Na_i}$. Then, the more the object $\widetilde{\omega}_i^e$ is similar to the prototype ω_i^p of an alternative feature space, the closer to the origin this object should be located. And the most dissimilar objects should be located at the boundary of the unit circle.

As previously noted, viewed BMS with LCP are quasi periodic signals. The smaller is the variability of heart rate and structural elements (waves and complexes) of an ECG, the greater is the density of object groups in the alternative feature space (AFS). Conversely, the greater is the variability of the structural elements, the smaller is the density of object groups in the alternative feature space [11]. A series of experiments for the detection of QRS complexes of the normal ECG and the ECG with different types of ventricular arrhythmia are performed to validate this statement. QRS complex of lead I of the normal ECG averaged over the 50 periods is selected as the prototype. Morphological analysis is performed using one channel of designed nonlinear filter (Fig. 1), so the following description of experiments the index i is not indicated. To describe the prototype ω^p in the alternative feature space the finite difference one-order is used as a conversion function $f(x[t], P)$ [9], through which the left and right slope of the QRS complex are described (corresponding to portions between the peaks of Q, R waves and R, S waves are shown in Fig. 2), so the number of coordinates is $Na = 2$.

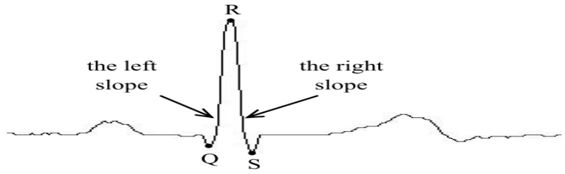

Fig. 2. The typical QRS complex of lead I of the normal ECG

Fig. 3 a typical location of objects in the alternative feature space (AFS) with respect to QRS-complex prototype ω^p of the lead I of the normal ECG is shown. Fig. 3a shows that classes Ω_1 and Ω_2 are compact sets, and the class Ω_2 are divided into three clusters. In addition the authors propose another display of the objects in the AFS as a hodograph (Fig. 3b). Let call this hodograph ECG-hodograph. The ECG-hodograph for the normal ECG is a figure of the triangle type (Fig. 3b).

In the case of ventricular arrhythmia the typical location of objects in the AFS has the form shown in Fig. 4a-10a. It is easy to notice that the location of objects of the class Ω_2 differs from the corresponding view for the normal ECG. Objects of the class Ω_2 are not grouped into three separate clusters, while the configuration of points are different for distinct types of ventricular arrhythmia (Fig. 4a-10a). In addition, various additional figures are formed on the ECG-hodographs except triangles characteristic for the normal ECG. The individual ECG-hodograph points are attached to the time axis, that enables to find those periods of ECG („suspicious" periods), where the objects are different from similar objects of the normal ECG.

It should be noted that the location of the objects of the class Ω_2 in the AFS for the most dangerous „R-on-T" PVCs (Fig. 6a, 9a) significantly differs from the corresponding display of objects for other PVCs (Fig. 4a, 5a, 7a, 8a, 10a). An even more pronounced pattern is observed on the corresponding ECG-hodograph (Fig. 6b, 9b and Fig. 4b, 5b, 7b, 8b, 10b).

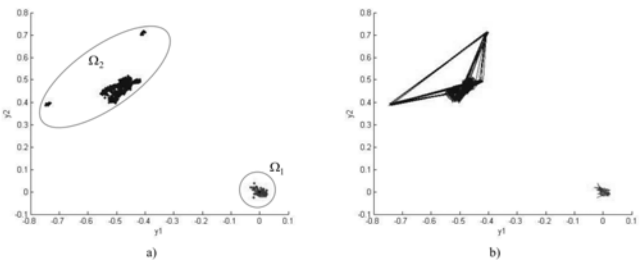

Fig.3. Display of the normal ECG in the AFS: a) the location of objects relative to ω^p (marked by *); b) the ECG-hodograph

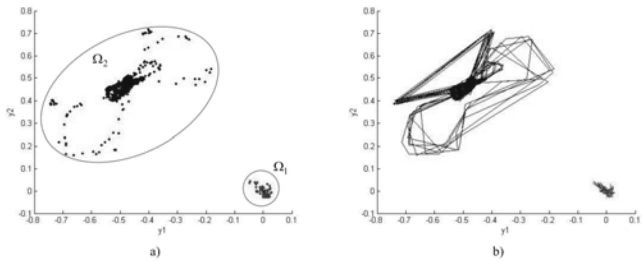

Fig.5. Display of the ECG with early PVC left in the AFS: a) the location of objects relative to ω^p (marked by *); b) the ECG-hodograph

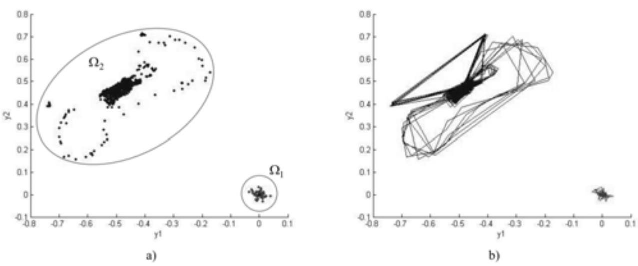

Fig.4. Display of the ECG with PVC left in the AFS: a) the location of objects relative to ω^p (marked by *); b) the ECG-hodograph

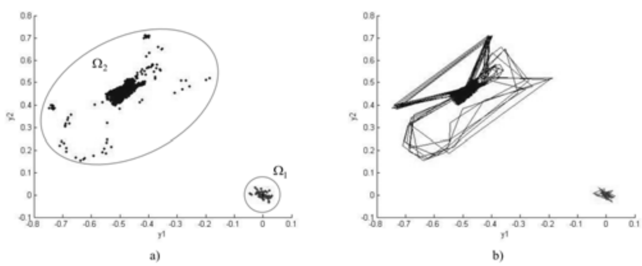

Fig.6. Display of the ECG with „R-on-T" PVC left in the AFS: a) the location of objects relative to ω^p (marked by *); b) the ECG-hodograph

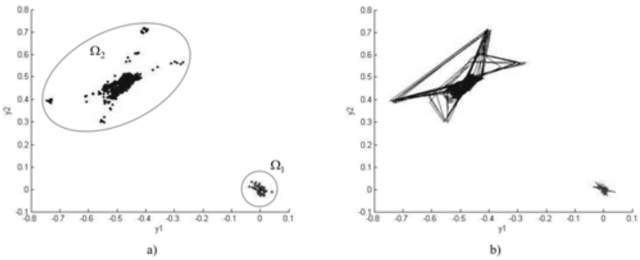

Fig.7. Display of the ECG with PVC right in the AFS: a) the location of objects relative to ω^p (marked by *); b) the ECG-hodograph

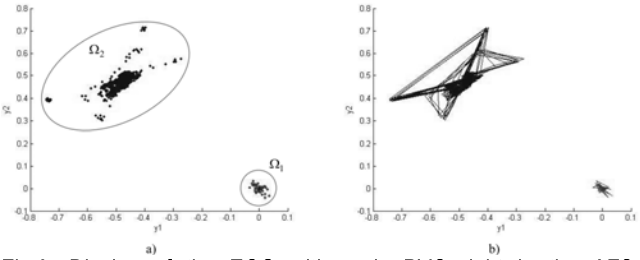

Fig.8. Display of the ECG with early PVC right in the AFS: a) the location of objects relative to ω^p (marked by *); b) the ECG-hodograph

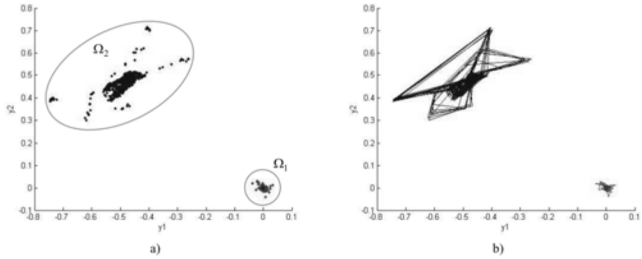

Fig.9. Display of the ECG with „R-on-T” PVC right in the AFS: a) the location of objects relative to ω^p (marked by *); b) the ECG-hodograph

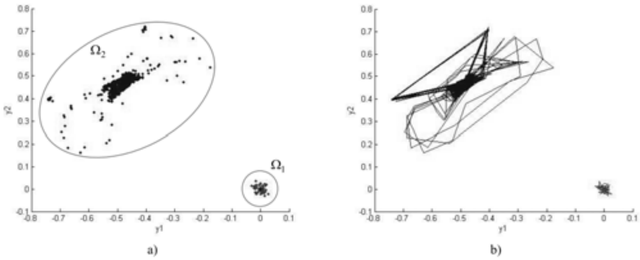

Fig.10. Display of the ECG with multifocal PVC in the AFS: a) the location of objects relative to ω^p (marked by *); b) the ECG-hodograph

Conclusions

1. The system of alternative diagnostic features is designed. Dependence of proposed alternative diagnostic features from the selected useful signal model and the detection function of the non-linear filter of the developed method of morphological analysis of BMS with LCP is shown. Display of the ECG in the alternative feature space is suggested as the ECG-hodograph.

2. The diagnostic value of alternative diagnostic features is analyzed for different PVCs. Differences of the ECG-hodographs for the normal ECG and the ECG with different PVCs are shown.

3. The proposed method of morphological analysis of BMS with LCP improves the accuracy of detection of the structural elements of the ECG on the background noise, and a graphical display of the ECG in the AFS allows the doctor visually to classify different PVCs that increases the diagnostic confidence combined with a classic analysis of „suspicious” ECG periods on the time axis.

4. Further research focuses on the study of the AFS for other types of pathologies, as well as on the development of numerical diagnostic characteristics of ECG-hodographs.

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