DOI 10.1007/s10527-018-9796-x
Biomedical Engineering, Vol. 52, No. 2, July, 2018, pp. 120-124. Translated from Meditsinskaya Tekhnika, Vol. 52, No. 2, Mar.-Apr., 2018, pp. 37-40. Original article submitted October 23, 2017.

Wavelet Analysis of Cardiac Electrical Activity Signals

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To solve important problems of cardiovascular monitoring, effective algorithms for computer processing of electrocardiogram signals (ECS) should be developed on the basis of nonlinear dynamic analysis. ECS can be represented as electric excitation of the conducting nerve network of the heart (CNNH) in the form of solitons of different sizes, taking into account their polarization along the main CNNH branches. Detailed information on the electrical activity in all parts of the four-chamber heart is contained in the self-similar fractal scale-invariant CNNH structure. With the help of wavelet transform, it is possible to represent the structure of the process of excitation of CNNH segments as a system of local extrema of the wavelet diagram of ECS. The wavelet spectrum of ECS has a fractal structure in the form of self-similar waves with scaling 1/f. Each of these waves reflects the excitation of the corresponding CNNH segment. Wavelet representation of the ECS can be used as a tool for detecting various cardiovascular diseases by visualizing skeleton functions of the ECS wavelet transform.

Introduction

Cardiovascular monitoring is, to this day, based mainly on a phenomenological approach to diagnosis. The physical and physiological aspects of data obtained from biological signals are often ignored, despite the fact that these complex quasi-chaotic signals bear information on the dynamics of biological processes. Development of adequate nonlinear models and techniques for fractal structure analysis of the conducting nerve network of the heart (CNNH) is an important problem of modern cardiovascular diagnostics. There is an important link between the communication systems of the human body and the structure of biological signals organized as self-similar fractal biological systems with scaling $1/f$ [1]. The nervous and vascular systems of the heart can be considered as examples of such structures.

Methods

Detailed information on the electrical activity in all parts of the four-chamber heart in the process of excitation of all CNNH segments can be obtained by consideration of the nonlinear character of these processes and the self-similar fractal scale-invariant CNNH structure with scaling $1/f$ (ECS also has a $1/f$ Fourier spectrum).

Thus, the ECS shape and spectrum reflect the fractal structure of neural networks of the heart (Fig. 1, a and b). The frequency and power of electrofluctuations correspond to the system topology: maximum fluctuations in larger branches harmonically decrease in length and power and increase in frequency in the process of Fibonacci branching, which leads to formation of a harmonic $1/f$ Fourier spectrum of the ECS (Fig. 1b).

Hermann Helmholtz and his pupils had shown in 1850 that nervous impulse propagates as a bell-shaped solitary wave resembling a particle moving at a constant rate of ~30 m/s [2]. This is a typical soliton in the modern sense of the word – a self-reinforcing auto-wave propagating in active medium. Cardiac pacemaker excitation propagates through the CNNH as solitary waves (solitons):

$$S_i(x, t_i) = u_i ch^{-2}[(x - ct_i)/\Delta]; \; ch = e^z + e^{-z}/2;$$

$$c = u_i/3; \; \Delta = (12/u_i)^{1/2}, \quad (1)$$

where u_i is the excitation amplitude; $i = 1, ..., n$; n is the number of CNNH branches.

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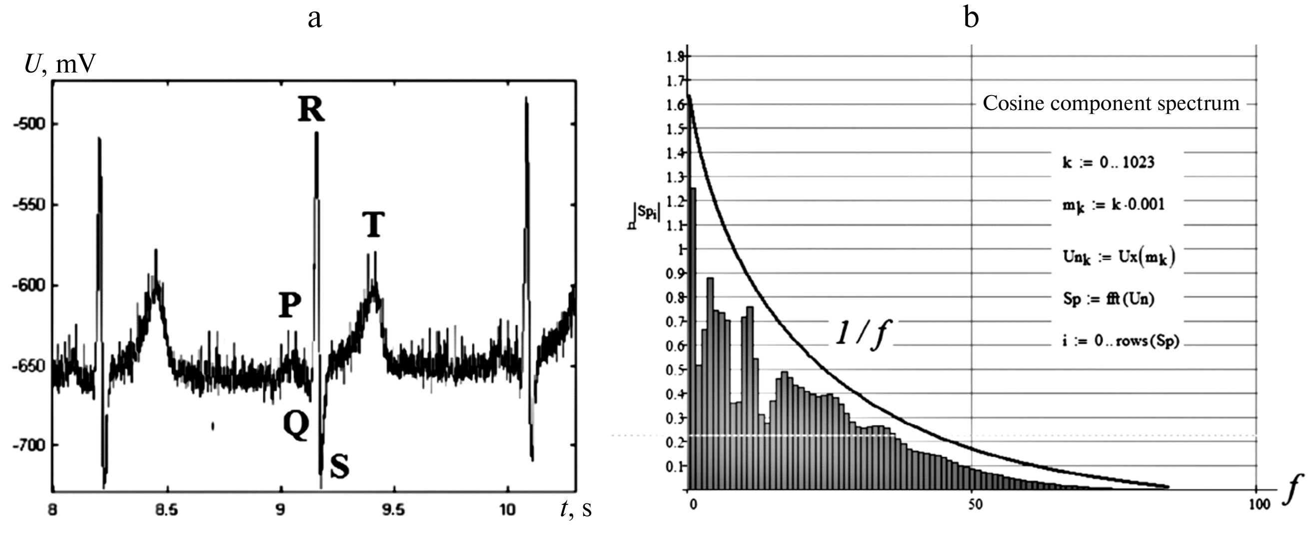

Fig. 1. Experimental ECS (a) and its Fourier spectrum (b).

The excitation wave propagates from the pacemaker to the right and then to the left atrium and reaches the atrioventricular node. Then, the wave propagates over the interventricular septum through the His bundle. Upon propagating through the right and left branches of the His bundle, the wave branches out into the Purkinje fibers in the left and right ventricular myocardium, leading thus to ventricular contraction [3].

Helmholtz had experimentally shown that ECS can be represented as electric excitation of the CNNH in the form of solitons of different sizes, taking into account their polarization along the main CNNH branches (Fig. 2).

Thus, excitation waves can be described by the following equation:

$$U(x,t) = S_1(t_1) + S_2(t_2) + S_3(t_3) + S_4(t_4) + \\ + S_5(t_5) + S_6(t_6) + S_7(t_7) + S_8(t_8), \quad (2)$$

where $S_i(t_i)$ is the soliton at t_i (Fig. 1b); $U(x, t)$ is the resulting biopotential of ECS.

$$U(t) = e^{\frac{-\left(t-\frac{T}{1000}\right)^2}{2\left(\frac{5}{1000}\right)^2}};$$

TABLE 1. Parameters of Auto-wave ECS Model

T_i	φ_i	S_i	u_i	Description
65	0	10	0.2	Right atrium (excitation)
90	40	10	0.2	Left atrium (excitation)
175	0	8	–0.2	Right atrium (repolarization)
177	40	8	–0.2	Left atrium (repolarization)
180	0	7	1.35	His bundle excitation
185	80	5	0.1	Left posterior bundle, Purkinje fibers
201	170	11	0.15	Left bundle, Purkinje fibers (excitation)
190	–170	5	0.15	Right bundle, Purkinje fibers (excitation)
300	80	25	0.4	Left posterior bundle (repolarization)
370	–170	20	–0.25	Left bundle (repolarization)
350	170	25	–0.25	Right bundle (repolarization)

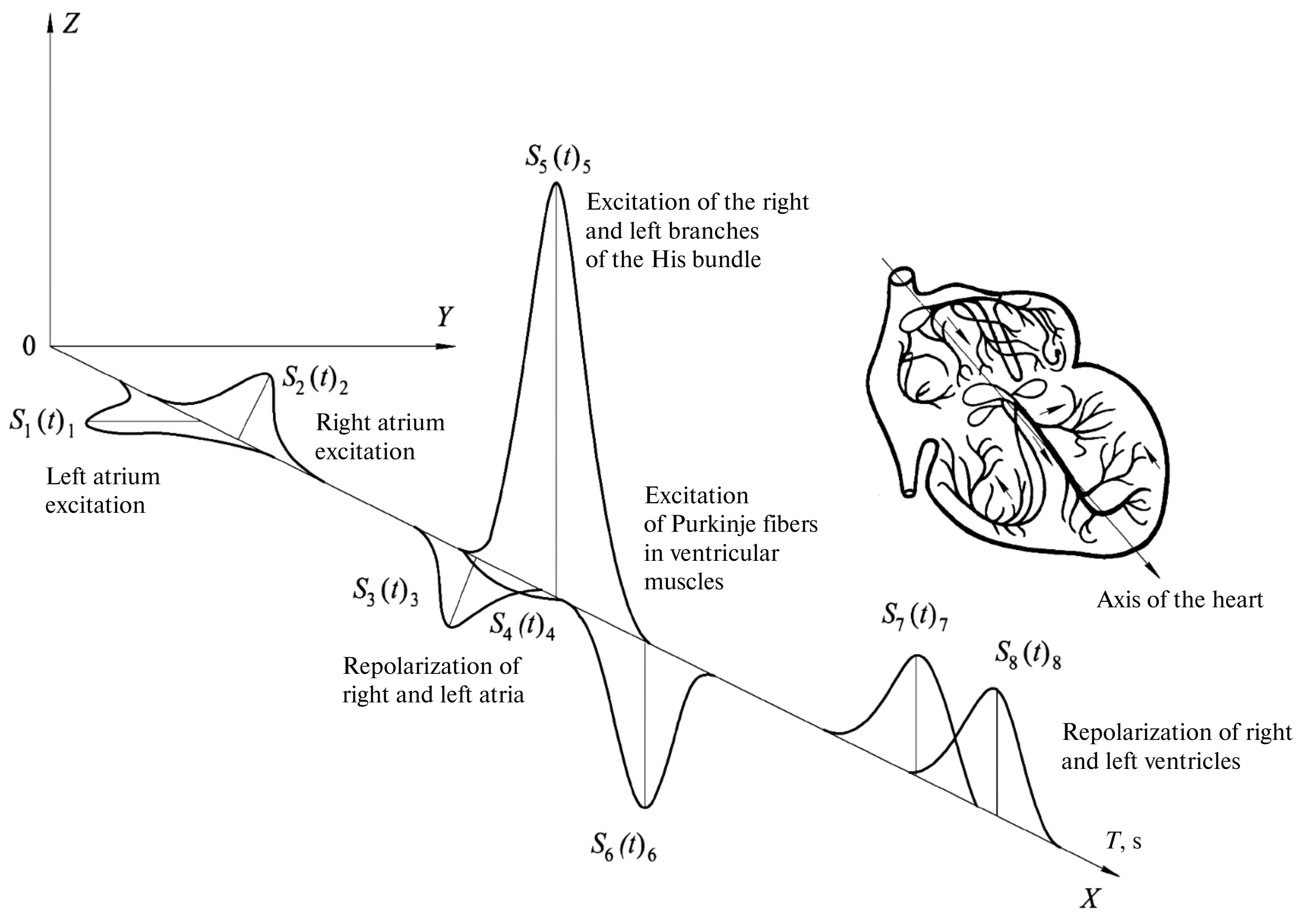

Fig. 2. ECS soliton polarization in CNNH.

$$U_{x(t)} = \Sigma_i[U(t)_i \cdot x_i \cdot u_i];$$

$$U_{y(t)} = \Sigma_i[U(t)_i \cdot y_i \cdot u_i], \quad (3)$$

where $i = 0,1...10$; $y = \sin(\varphi)$; $x = \cos(\varphi)$.

It is important to take into account changes in the direction of polarization in CNNH segments.

A two-dimensional auto-wave model of ECS was developed in Mathcad to simulate CNNH disorders (Fig. 3). The model parameters are given in Table 1.

In Table 1, u_i is the excitation amplitude; $i = 1, ..., n$; n is the number of CNNH branches.

A method providing high time and frequency resolutions is required to analyze such signals. Wavelet analysis meets these requirements. Biological signals are usually soliton-like. Thus, it is expedient to use wavelet functions based on Gaussian function derivatives as the mother wavelet [4].

A hardware–software system (HSS) based on the MKM-11 recorder was developed to implement CNNH wavelet introscopy as a means of cardiovascular monitoring.

The accumulated ECS and photoplethysmogram (PPG) records are transmitted via Bluetooth to smartphone and processed to determine the parameters of cardiovascular activity in online mode [5, 6]. The HSS software includes modules for HRV diagnosis and structural wavelet analysis. These modules provide data processing for determination of the cardiovascular activity parameters; in particular, they provide detection of latent ECG and determinaion of the CNNH state.

Discussion

Wavelet spectrum of ECS has a self-similar fractal structure with scaling $1/f$. Each of the self-similar waves represents propagation of excitation through the respective CNNH segment [6]. The structure of the process of CNNH excitation can be represented using wavelet transform as a system of local extrema of the wavelet diagram. For example, the latent structure of the P and R waves represented using wavelet transform shows the amplitude–phase spatial pattern of excitation propagation through the CNNH segments in the form of corresponding waves in the wavelet spectrum.

In current medical practice, the complex structure of the P wave, QRS complex, and T wave is ignored. Wavelet transform provides time and frequency data on ECS; it can be used to detect waves of excitation of the left and right atria, waves in the left and right ventricular myocardium, and complex repolarization of the CNNH during the T-wave phase.

Wavelet transform of ECS is an adequate spatiotemporal representation of the excitation phases and amplitudes in the CNNH. Comparison of the CNNH nodes and the corresponding (in terms of phase and time) waves of the wavelet diagram spectrum makes it possible to obtain a latent electrocardiogram representing the entire process of excitation propagation in the form of solitons from the pacemaker through all CNNH segments [7].

The P wave structure is observed as a sum of left and right atria waves (Fig. 4). It represents the actual propagation of excitation over the left and right ventricular myocardium. The moments of initiation of the QRS complex and the R wave are shown in Fig. 4. The QRS complex is representative of the excitation wave propagating over the ventricles in different directions and time moments and resulting in formation of Q, R, and S waves.

An ordinary ECG does not represent formation of the R wave in the process of excitation propagation over the left and right ventricular myocardium. The wavelet transform represents the phases of formation of the R wave and inversion of the direction of excitation propagation from the interventricular septum to the Purkinje fibers in the left and right ventricles.

Atrial repolarization coincides with ventricular depolarization. As a consequence, atrial repolarization cannot be detected in ECG, being absorbed by the complex representing ventricular depolarization.

The T wave (Fig. 4) is representative of the repolarization process (return of ventricles into the initial state). The wavelet transform represents the order of repolarization of the left and right ventricles. Wavelet data can be used to represent on PC monitor the entire process of sig-

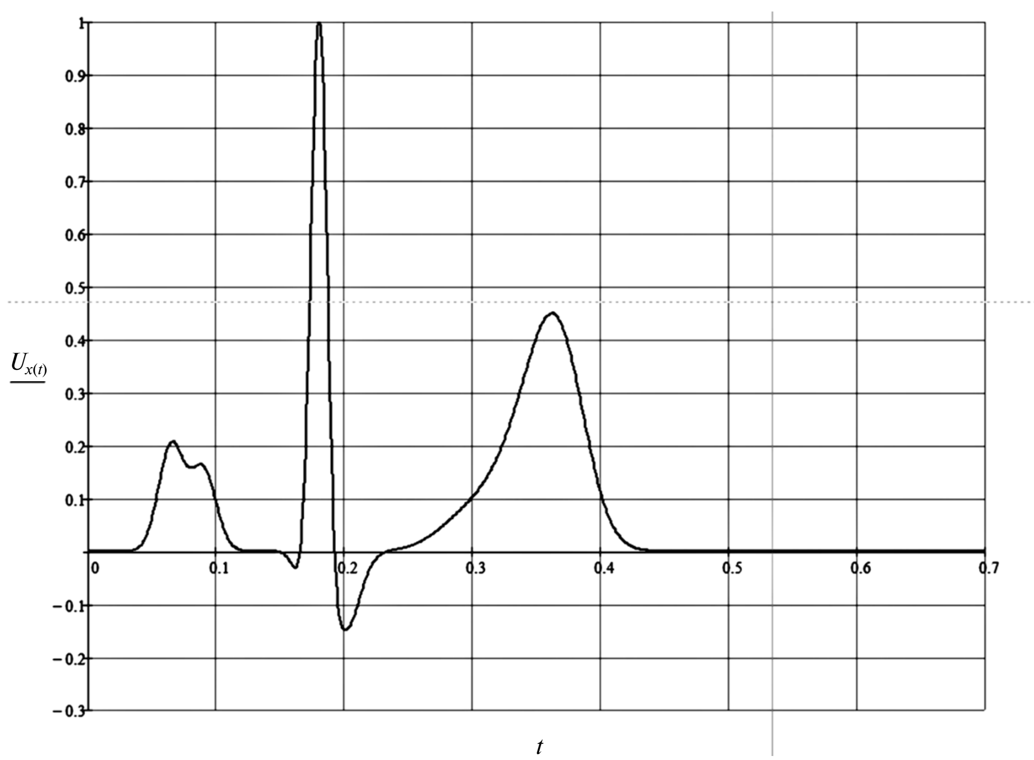

Fig. 3. Auto-wave model of ECS.

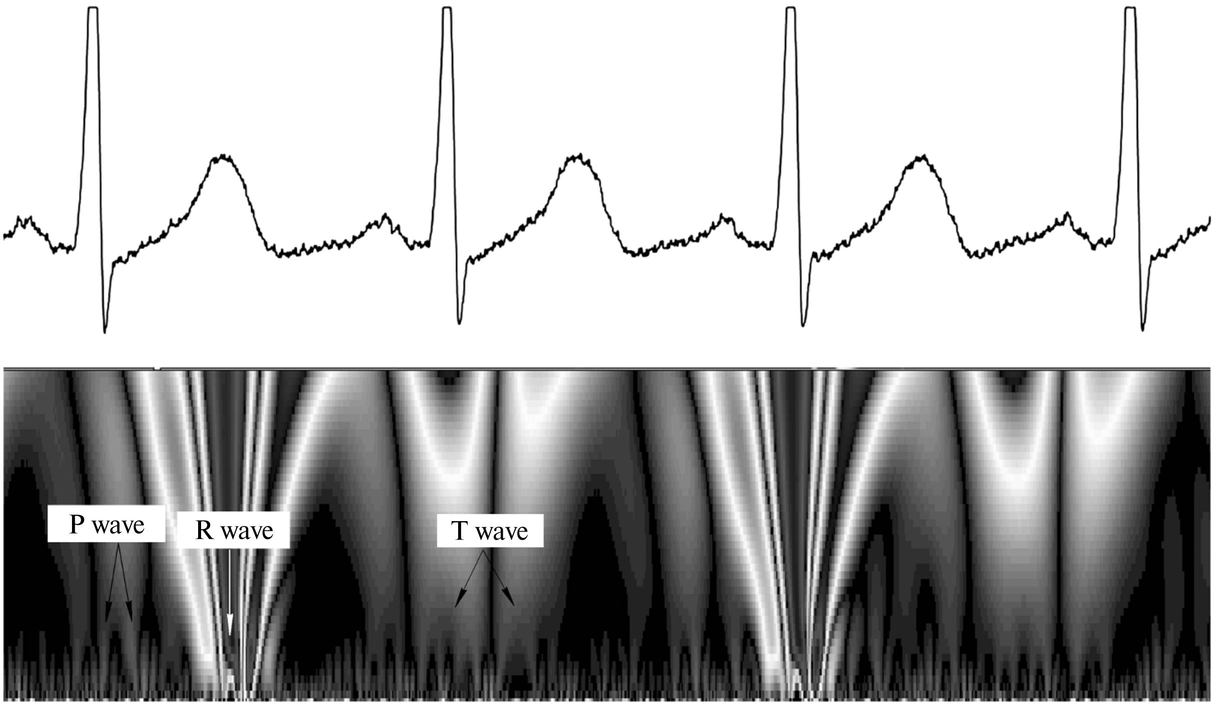

Fig. 4. Wavelet representation of P wave, R wave, and T wave.

nal propagation from the pacemaker through CNNH branches.

Conclusions

All elements of the wavelet diagram reflect the structure of processes in the conduction system of the heart and the phase and amplitude relationships in all parts of the four-chamber heart. Wavelet representation of the ECS can be used as a tool for detecting various cardiovascular diseases by visualizing skeleton functions of the ECS wavelet transform. However, interpretation of the wavelet diagram as a source of information on ECS and cardiovascular pathologies requires more detailed study.

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