ACTIVE BIOMEDICAL MEDIA EXPLORATION
BY MEANS OF SPECTRAL ANALYSIS APPROACHES AND
CHAOTIC SIGNAL ATTRACTOR TRAJECTORIES
INVESTIGATION

Victor F. Dailyudenko, Alexander M. Krot, Elena B. Minervina

Institute of Engineering Cybernetics AS of Belarus
Surganova st., 6. 220012, Minsk, Belarus
E-mail: alxkrot@newman.basnet.minsk.by

Abstract. The mathematical model of nervous pulse propagation in the homogeneous
nervous fibre is constructed on the basis of spectral analysis methods. The results of digitized
cardiosignal investigation on the basis of nonlinear dynamics approach (local - topological
analysis of chaotic attractor trajectories) and spectral analysis methods (fast Fourier
transforming) are represented. It is shown that the local - topological analysis of phase
trajectories allows to estimate a number of freedom degrees of electrocardiosignal and
complexity degree of myocardium dynamics.

Keywords: autowaves, nervous pulse propagation, minimal embedding dimension.

Introduction

Active media represent the basic substance of self-organization complex systems. The examples
of active media are the working substance of a laser, gase plazma in technique; the heart muscle,
eye retina, muscle and nervous fibres in medicine. The active media functioning is
accompanied by propagation of autowaves representing a particular class of nonlinear waves,
which spread in the active media at the expense of the energy stored in the medium [1,2].
Investigations of autowave processes allow to detect many new laws in complex systems
behaviour and create on principle new technologies in signal and image processing. It has been shown that autowave methods
employment allows to create highly parallel algorithms for pattern analysis which increase a
computional speed from 3 to 6 orders of magnitude in comparison with a sequential (von Neumann) computer [3].

Complex systems (CS) behaviour is defined by included active media state. Most recent investigations on physiologic processes in
medical CS such as heart rate, blood pressure, or nerve activity have shown that biomedical signals
vary in a complex and irregular way, even during stable external conditions [4-5]. Chaotic
dynamics of human organ systems offer many functional advantages. Chaotic systems operate
under a wide range of conditions and are therefore adaptable and flexible. In recent years, considerable attention has been devoted to
unifying various aspects of cardiac physiology using nonlinear dynamics, particularly through
methods of topological analysis and fractal geometry [6]. In this paper chaotic dynamics of cardiac activity is investigated. We propose a
method of estimating complexity degrees of heart dynamics by means of electrocardiogram (ECG)
time series exploration on a base of local - topological analysis [7-8] of attractor constructed
from electrocardiosignal. Recently the method has been suggested for a local-topological
analysis of attractor trajectories constructed from chaotic time series (CTS) [7-8]. This method
allows to reduce demanded experimental data quantity and spare computer resources (time,
storage) in comparison with traditional algorithms [9, 10]. Besides, it provides a good
convergence of computation process and obtaining reliable numerical results.

Mathematical modeling of signal propagation
in the active media

A task of great importance is the mathematical modeling of signal propagation in the active
media. Solving this problem is necessary for creating techniques of the control by separate
parts of a complex system and for constructing new technologies in communication. In this paper
we propose a method of modeling active media
excitement and signal propagation along the nervous fibre. The suggested method is based on spectral analysis algorithms (including fast Fourier transformation). The methods proposed in this paper provide essential reduction of computation complexity and high stability of the algorithms.

Let \( x \) be a coordinate in the nervous fibre, the pulse spreading along this coordinate. Then \( u(x,t) \) is a potential difference of the excitation pulse. In accordance with Hodgkin - Huxley model and FitzHugh - Nagumo approach [1, p. 311-330], the nervous fibre as one-dimensional active medium is described by the following nonlinear equation:

\[
\frac{\partial u}{\partial t} - D_u \frac{\partial^2 u}{\partial x^2} = -\frac{1}{C} i(u)
\]

(1)

where \( D_u \) is a diffusion coefficient equals to:

\( D_u = \frac{1}{R C} \); \( R \) and \( C \) are the resistance and capacity of a membrane respectively per unit length of the fibre; \( i \) is an ion current through the nervous fibre membrane that is approximated by a cubic parabola:

\[
i(u) = B u(u-u_1)(u-u_2)
\]

(2)

In the formula (2) \( u_1 \) characterizes the beginning of a refractory period; \( u_2 \) is a difference between the characteristic voltages for Na current; \( B \) is normalizing factor. Cinetic models obtained with FitzHugh - Nagumo approach are often used when investigating autowave processes [11].

The results that are in a good accordance with experiments have been obtained with quazilinear time approximation of the ion current [12]. This approach can be considered as averaged cubic approximation. We consider the case when the pulse spreads along the homogeneous nervous fibre without distortions. In such a case the velocity \( v \) is constant and a "running" variable \( \xi \) can be introduced as follows [1,12]:

\[
\xi = x - vt.
\]

(3)

Then the quazilinear approximation has a form:

\[
i_e \quad \text{when} \quad -\tau \leq \xi < -\nu \Delta t_{ex}
\]

\[
i_r \quad \text{when} \quad -\nu \Delta t_{ex} \leq \xi < 0
\]

\[
0 \quad \text{otherwise}
\]

(4)

\( i_e \) and \( i_r \) are the average values of the direct and inverse membrane currents respectively, \( \tau \) is a pulse length, \( \Delta t_{ex} \) is the length of excitation period. Evidently, this exchange of variables allows to make our consideration invariant over \( x \). Inserting (3) into (1) we obtain for the voltage \( \varphi(\xi) \) of the nervous pulse the following equation:

\[
D \frac{d^2 \varphi}{d \xi^2} + \nu \frac{d \varphi}{d \xi} = \frac{1}{C} i_1(\xi)
\]

(5)

where \( D = D_u \). Further, we apply to (5) Fourier transformation:

\[
\Phi(\omega) = \int_{-\infty}^{\infty} \varphi(\xi) e^{-j\omega\xi} d\xi
\]

(6)

and obtain the equation:

\[
\omega(j\nu - \omega D_{\varphi}) \Phi(\omega) = \frac{j}{\omega C} f_2(\omega),
\]

(7)

where

\[
f_2(\omega) = i_e(1 - e^{-j\omega\Delta t_{ex}}) + i_r(e^{+j\omega\Delta t_{ex}} - e^{-j\omega t})
\]

Consequently, the potential difference Fourier-image of nervous pulse \( \varphi(\xi) \) can be expressed as:

\[
\Phi(\omega) = \frac{j f_2(\omega)}{C \omega^2 (j\nu - \omega D_{\varphi})}
\]

(8)

From the expression (8) the values of real \( \Phi_R(\omega) \) and imaginary \( \Phi_I(\omega) \) parts of nervous pulse spectrum can be obtained. Now one can use to \( \Phi_R(\omega), \Phi_I(\omega) \) any algorithm of fast inverse Fourier transformation [13] and obtain the form of the nervous pulse \( \varphi(\xi) \) in any point of the
nervous fibre. In such approach the result is obtained without solving differential equation (1).

**Electrocardiosignal exploration**

Basic information obtained by experimental investigation of nonlinear dynamic systems (NDS) with the chaotic behaviour is CTS: \( \xi(i) \), where \( i=1,2,...,N \), \( \Delta t \) is the time interval of measurement. The behaviour of NDS can be completely described by means of construction of the chaotic attractor \( R^d \) in Euclidean space \( R^d \). In accordance with Takens method [14], for \( m \leq 2d+1 \) the points of the chaotic attractor \( R^d \subset R^m \) are given by:

\[
\tilde{x}^{(m)} = (\xi(jp), \xi((j+1)p), ..., \xi((j+m-1)p)),
\]

where \( j=1,2,...,L^{(m)} \); \( L^{(m)} = N_p - m + 1 \); \( m \) is embedding dimension, \( p \) is the delay interval. Takens method employment means construction of reduced CTS: \( \tilde{x}_j = \xi(lp) \), where \( l=1,2,...,N_p \); and the value \( N_p \) is given by: \( N_p \approx N/p \).

For the attractor construction we must use the minimal value of \( m \), because in this case we reduce the value of calculations, experimental data quantity and measuring time. The minimal embedding dimension \( m_0 \) characterizes the upper number of NDS freedom degrees and the minimal number of differential equations demanded for mathematical modeling of NDS [15]. Consequently, value of \( m_0 \) is a characteristic of complexity degree of the investigated process and defines the physical state of NDS.

For computing \( m_0 \) many correlative-topological methods are used, among them Grassberger–Procaccia algorithm (GPA) [9] is most conventional. Such methods have large computation complexity and demand long CTS (\( N \approx 10^4 - 10^5 \); \( N_p \approx 2 \times 10^3 - 2 \times 10^4 \)) for their implementation. Besides, it is a common feature of such algorithms that the quantity of required data points increases exponentially with \( m_0 \), resulting in exponentially growing requirements on measuring time, computer time, and data storage capacity [15]. Because of this fact the GPA and similar methods have been applied in most cases only to low-dimensional (typically \( m_0 \leq 10 \)) systems.

In this paper we propose a method of chaotic signals processing and \( m_0 \) determination based on \( R^d \) topological structure analysis. Our method requires much less experimental data quantity and is stable to changing \( m_0 \). The basic idea of our method is following. On the set of \( R^m \) we construct a function \( Z(m) \), that defines a measure of topological instability of the attractor when enlarging phase space dimension \( (R^m \rightarrow R^{m+1}) \). The value of \( Z(m) \) changes monotonously when enlarging \( m \), but if \( m \geq m_0 \), then \( Z(m) = Z_0 \) and does not depend on \( m \) [7-8].

The topological structure of the chaotic attractor \( R^m \) can be defined by computing distances between neighbour points of \( R^m \):

\[
r_{j,j+1}^{(m)} = \left| \tilde{x}_j^{(m)} - \tilde{x}_{j+1}^{(m)} \right|,
\]

where \( j=1,2,...,L^{(m)}-1 \). Distances (10) increase when \( R^m \rightarrow R^{m+1} \), because from (9), (10):

\[
r_{j,j+1}^{(m+1)} = \left[ \sum_{l=0}^{m-1} (\xi_{j+l} - \xi_{j+l+1})^2 \right]^{1/2}
\]

and

\[
r_{j,j+1}^{(m)} = \left[ \sum_{l=0}^{m} (\xi_{j+l} - \xi_{j+l+1})^2 \right]^{1/2} \geq r_{j,j+1}^{(m+1)}
\]

So we suggest to describe changes of topological structure of \( R^d \) by relative distances between attractor points:

\[
\beta_j^{(m)} = \frac{r_{j,j+1}^{(m)}}{r_{j,j+1}^{(m+1)}},
\]

where \( j=1,2,...,L^{(m)}-2 \).

Consequently, dynamics of changes in \( R^d \) topological structure when \( R^m \rightarrow R^{m+1} \) can be represented by the sequence \( \{\beta_j^{(m,m+1)}\} \), the members of that being ratios of relative distances (12) in \( R^m \) and \( R^{m+1} \) respectively.
\[ \gamma_{j}^{(m,m+1)} = \frac{\beta_{j}^{(m)}}{\beta_{j}^{(m+1)}}, \quad (13) \]

where \( j = 1, 2, ..., L^{(m+1)} - 2 \).

Further we average the members of the sequence \( \{\gamma_{j}^{(m,m+1)}\} \) over all \( j \) and obtain the function of instability \( Z(m) \) from the formula:

\[ Z(m) = \frac{1}{L^{(m+1)} - 2} \sum_{j=1}^{L^{(m+1)}-2} \gamma_{j}^{(m,m+1)} \quad (14) \]

The value \( |Z(m) - Z_s| \) is a measure of topological instability of \( R_{\alpha}^{m} \) when transformation \( R^{m} \rightarrow R^{m+1} \). At least, we introduce the coefficient of topological stabilization in \( R_{\alpha}^{m} \) as follows:

\[ \rho(m) = \frac{Z(m+1)}{Z(m)} \quad (15) \]

If the topological stabilization of \( R_{\alpha}^{m} \) is happened (i.e. the topological structure of the chaotic attractor is invariant to transformation \( R^{m} \rightarrow R^{m+1} \)), we have that \( m \geq m_0, \ Z(m) = Z_s \), where \( Z_s \) does not depend on \( m \). Consequently if \( m \geq m_0 \), \( \rho(m) = 1 \) in this case, that is confirmed by results of numerical experiments (see tabl. 2).

For numerical implementation ECG time series with \( N_m = 2500 \) length is investigated, \( \Delta t = 2 \) ms. In accordance with Kotelnikov theorem [16] a maximal frequency value of ECG spectrum equals to \( \frac{1}{2\Delta t} = 250 \) Hz. Consequently, spectrum width is equal 500 Hz. For spectrum computation we take first \( N_{sp} \) points of CTS, \( N_{sp} = 2^{11} = 2048 \). Amplitude spectrum \( A_i \), \( i = 1, 2, ..., N_{sp} \) is computed by means of highly effective algorithm developed in [13] (program RSFFT).

Minimal frequency interval \( \Delta f = \frac{2f_{\pi}}{N_{sp}} = 0.244 \) Hz. At the same time, boundary frequency value of analog-digital transformation device equals to \( f_s = 120 - 125 \) Hz. Consequently only approximately \( N_{sp} = 500 \) points of obtained amplitude spectrum are reliable, that respects \( f_s^* = N_s \Delta f = 122 \) Hz. The amplitude spectrum \( A_i \) with a boundary value \( f_s^*/2 \) with interval \( 2 \Delta f \) (i.e. \( N_b / 4 \) points) is represented in table 1. Our numerical results prove that heart activity dynamics is actually high irregular and displays chaotic behavior features. Corresponding curve of spectrum is displayed in fig. 1.

Fig. 1. ECG signal Fourier amplitude spectrum

As follows from table 1, the amplitude spectrum has some local maximum points near 50 Hz frequency (that corresponds to spectrum values with numbers about \( N_r = 100 - 108 \). This is a result of the external influence of electric power with 50 Hz frequency. As follows from table 1 this kind of external noise doesn't distort ECG signal significantly because the common power of this noise is very small in comparison with common ECG signal power. Nevertheless, we filtered this noise by means of inverse Fourier transforming algorithm [13] and obtained ECG without this hindrance. The reduction of noise level in spectrum points \( A_f \) with numbers \( N_r \) is implemented as follows:

\[ A_f^{(0)} = 10 \sqrt{A_f^{(0)}}. \]

Further, we investigate the topological stabilization of attractor constructed from ECG. For attractor construction Takens method has been used. In our numerical experiments \( N_p = 200, \ 1 < p < 4, \ N = 200 - 800 \). In common ECG length equals to 2500 points and we used only the first part of it. Numerical implementation of local-topological analysis has been made over relationships (11)-(15). The values of coefficient of topological stabilization \( \rho(m) \) are represented in tabl. 2. The numerical results confirm the convergence of used algorithm: the value of stabilization coefficient adopts a constant level when \( m \approx m_0 \). Consequently, the value of \( m_0 \) can be determined from the nature of dependence \( \rho(m) \), represented in the tabl. 2.
We consider that topological stabilization takes place (i.e. \( m = m_0 \)) when \( |\rho(m) - 1| < \varepsilon \). From numerous numerical experiments [7] results we adopt that \( \varepsilon = 0.01 \). From calculated dependence \( \rho(m) \) one can see that \( m_0 = 5 \). This result is in a good coinciding with those obtained by other authors with GPA employment [4]. At the same time, CTS length in our investigations \( N=200 - 800 \), and in [4] \( N=16000 \), that is more than an order longer. Consequently, local-topological method allows to reduce experimental data quantity and spare computer resources. Calculations have been made with computer "Pentium" (tact frequency is 133 MHz, without mathematical coprocessor), computer time for calculating spectral characteristics (as well as one group of topological dependences) being less than 0.3 sec.

At least, we computed \( m_0 \) from various segments of ECS (at the middle and end). The results of \( m_0 \) computation are as well as in tabl.2

<table>
<thead>
<tr>
<th>( N )</th>
<th>( A_i )</th>
<th>( N )</th>
<th>( A_i )</th>
<th>( N )</th>
<th>( A_i )</th>
<th>( N )</th>
<th>( A_i )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>7655</td>
<td>26</td>
<td>2817</td>
<td>51</td>
<td>3313</td>
<td>76</td>
<td>827</td>
</tr>
<tr>
<td>2</td>
<td>8842</td>
<td>27</td>
<td>3244</td>
<td>52</td>
<td>1635</td>
<td>77</td>
<td>302</td>
</tr>
<tr>
<td>3</td>
<td>7931</td>
<td>28</td>
<td>2586</td>
<td>53</td>
<td>925</td>
<td>78</td>
<td>131</td>
</tr>
<tr>
<td>4</td>
<td>5565</td>
<td>29</td>
<td>8477</td>
<td>54</td>
<td>1733</td>
<td>79</td>
<td>803</td>
</tr>
<tr>
<td>5</td>
<td>1458</td>
<td>30</td>
<td>4087</td>
<td>55</td>
<td>1560</td>
<td>80</td>
<td>456</td>
</tr>
<tr>
<td>6</td>
<td>739</td>
<td>31</td>
<td>5611</td>
<td>56</td>
<td>1725</td>
<td>81</td>
<td>344</td>
</tr>
<tr>
<td>7</td>
<td>1963</td>
<td>32</td>
<td>4774</td>
<td>57</td>
<td>2329</td>
<td>82</td>
<td>351</td>
</tr>
<tr>
<td>8</td>
<td>11144</td>
<td>33</td>
<td>832</td>
<td>58</td>
<td>3162</td>
<td>83</td>
<td>432</td>
</tr>
<tr>
<td>9</td>
<td>1495</td>
<td>34</td>
<td>2354</td>
<td>59</td>
<td>1530</td>
<td>84</td>
<td>93</td>
</tr>
<tr>
<td>10</td>
<td>6872</td>
<td>35</td>
<td>2652</td>
<td>60</td>
<td>1686</td>
<td>85</td>
<td>662</td>
</tr>
<tr>
<td>11</td>
<td>9179</td>
<td>36</td>
<td>4907</td>
<td>61</td>
<td>963</td>
<td>86</td>
<td>308</td>
</tr>
<tr>
<td>12</td>
<td>3991</td>
<td>37</td>
<td>2633</td>
<td>62</td>
<td>1172</td>
<td>87</td>
<td>479</td>
</tr>
<tr>
<td>13</td>
<td>1727</td>
<td>38</td>
<td>3046</td>
<td>63</td>
<td>783</td>
<td>88</td>
<td>334</td>
</tr>
<tr>
<td>14</td>
<td>1923</td>
<td>39</td>
<td>6852</td>
<td>64</td>
<td>937</td>
<td>89</td>
<td>437</td>
</tr>
<tr>
<td>15</td>
<td>1706</td>
<td>40</td>
<td>1359</td>
<td>65</td>
<td>1782</td>
<td>90</td>
<td>365</td>
</tr>
<tr>
<td>16</td>
<td>1929</td>
<td>41</td>
<td>5806</td>
<td>66</td>
<td>248</td>
<td>91</td>
<td>571</td>
</tr>
<tr>
<td>17</td>
<td>2570</td>
<td>42</td>
<td>1959</td>
<td>67</td>
<td>1405</td>
<td>92</td>
<td>278</td>
</tr>
<tr>
<td>18</td>
<td>9286</td>
<td>43</td>
<td>463</td>
<td>68</td>
<td>1152</td>
<td>93</td>
<td>411</td>
</tr>
<tr>
<td>19</td>
<td>5128</td>
<td>44</td>
<td>1063</td>
<td>69</td>
<td>1308</td>
<td>94</td>
<td>272</td>
</tr>
<tr>
<td>20</td>
<td>4985</td>
<td>45</td>
<td>175</td>
<td>70</td>
<td>192</td>
<td>95</td>
<td>874</td>
</tr>
<tr>
<td>21</td>
<td>2212</td>
<td>46</td>
<td>4249</td>
<td>71</td>
<td>711</td>
<td>96</td>
<td>632</td>
</tr>
<tr>
<td>22</td>
<td>6595</td>
<td>47</td>
<td>2149</td>
<td>72</td>
<td>449</td>
<td>97</td>
<td>959</td>
</tr>
<tr>
<td>23</td>
<td>3446</td>
<td>48</td>
<td>5044</td>
<td>73</td>
<td>258</td>
<td>98</td>
<td>746</td>
</tr>
<tr>
<td>24</td>
<td>3798</td>
<td>49</td>
<td>1973</td>
<td>74</td>
<td>319</td>
<td>99</td>
<td>297</td>
</tr>
<tr>
<td>25</td>
<td>2751</td>
<td>50</td>
<td>2507</td>
<td>75</td>
<td>833</td>
<td>100</td>
<td>628</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>( m )</th>
<th>( \rho(m) )</th>
<th>( p=1 )</th>
<th>( p=2 )</th>
<th>( p=3 )</th>
<th>( p=4 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( N=200 )</td>
<td>( N=400 )</td>
<td>( N=600 )</td>
<td>( N=800 )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>0.001</td>
<td>0.000</td>
<td>0.553</td>
<td>0.002</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>0.885</td>
<td>0.894</td>
<td>0.946</td>
<td>0.936</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>0.960</td>
<td>0.987</td>
<td>0.990</td>
<td>0.985</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>0.983</td>
<td>0.985</td>
<td>0.987</td>
<td>0.981</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>0.994</td>
<td>0.996</td>
<td>0.999</td>
<td>0.992</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>0.994</td>
<td>0.997</td>
<td>0.996</td>
<td>0.996</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>0.998</td>
<td>0.997</td>
<td>0.998</td>
<td>1.000</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>0.999</td>
<td>1.000</td>
<td>1.000</td>
<td>0.998</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>0.999</td>
<td>0.999</td>
<td>0.998</td>
<td>0.999</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>0.998</td>
<td>0.998</td>
<td>1.000</td>
<td>0.999</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>1.000</td>
<td>0.999</td>
<td>0.999</td>
<td>1.000</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>1.000</td>
<td>0.999</td>
<td>0.999</td>
<td>1.000</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>1.000</td>
<td>0.999</td>
<td>0.999</td>
<td>1.000</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>0.999</td>
<td>0.999</td>
<td>0.999</td>
<td>1.000</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>1.000</td>
<td>1.000</td>
<td>1.000</td>
<td>0.999</td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>1.000</td>
<td>1.000</td>
<td>1.000</td>
<td>1.000</td>
<td></td>
</tr>
<tr>
<td>17</td>
<td>1.000</td>
<td>1.000</td>
<td>1.000</td>
<td>1.000</td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>1.000</td>
<td>1.000</td>
<td>1.000</td>
<td>1.000</td>
<td></td>
</tr>
<tr>
<td>19</td>
<td>1.000</td>
<td>1.000</td>
<td>1.000</td>
<td>1.000</td>
<td></td>
</tr>
</tbody>
</table>
(i.e. \( m_0=5 \)), that one more time proves high reliability of local-topological analysis.

Consequently, this algorithm of the minimal embedding dimension determination essentially increases the efficiency of ECG investigation.

Conclusions

In this paper the mathematical model of nervous pulse propagation in the homogeneous nervous fibre is constructed on the basis of spectral analysis methods. Our method is more suitable for autowave propagation analysis in comparison with traditional that are based on the numerical solving of differential equations [1,17], because it has the following advantages.

1. The method is more robust, i.e. its structure does not depend on a choice of initial conditions and parameters of the active medium.

2. The algorithm suggested provides a good convergence of calculation process with reducing computer resources because there are no complex iteration circles in our method.

3. This method allows to work straightly with experimental data because the variables in (7), (8) can be measured in experiment.

Further, the heart activity dynamics has been investigated. It is shown that cardiac activity is a high irregular process with chaotic behavior features. The local-topological analysis of ECG time series has been made and its results allowed to estimate complexity degree of a cardiac process under investigation. The examination of heart dynamics complexity can provide important physiologic and prognostic information not detected by conventional methods of analysis.

References


5. T.F. Nonnenmacher, G.A. Losa, E.R. Wribel (editors) "Fractals in Biology and Medicine" (Birkhauser - Verlag, 1994.)


