THE MEASURE OF ECG COMPLEXITY BY MATRIX ANALYSIS

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Abstract

The subject of this paper is intensive extraction of information from ECG signals and using it in diagnostics and assessment status of heart function. The aim of this study is presentation of the analytical methods designed for analysis of dynamic interrelations between different ECG parameters. The main idea of this paper is adaptation of Hankel matrix ranks and second order coherence matrices to describe complexity of ECG and relationship between parameters of ECG. The results show that expressing of cardiac signals with Hankel and coherence matrix could be useful for diagnostic purposes.

1. INTRODUCTION

Over the last years there has been growing interest in problems of complexity analysis. There are very interesting research fields including the wide spectrum of tackled problems - from software development to analysis of medical information. The complexity can be described as strength connection between different parts of complex system. It is obvious that human organism is a complex system. There are many excellent methods describing the complexity measure of various physiologic signals. The complexity of electrocardiogram (ECG) signal may reflect the physiological function and healthy status of the heart. For the purpose to characterize the nonlinear complexity of ECG signal the power spectrum, fractal dimensions, wavelet transformation, phase portrait, correlation dimension, the largest Lyapunov exponent, time-dependent divergence exponent, mass exponent spectrum and complexity measure can be used, [1]. The methods verifies the fact that ECG dynamics are dominated by an underlying multi dimensional non-linear chaotic system, whose complexity measure is about 0,7.

Usually in system identification Hankel matrices are formed when is a sequence of output data and realization of an underlying state-space given or hidden Markov model is desired, but in this paper the ranks of the Hankel matrix will be used as features for the system identification purposes.

The ECG signals were recorded and analyzed by means of multi cardio signal analysis system developed in the Kaunas Institute of Cardiology and produced by "Kardiosignalas" Ltd. (Kaunas, Lithuania). All signal analysis techniques used in this paper are implemented on a PC using custom software developed in Matlab R2007b.

The work is divided into three sections. In the first theoretical section the mathematical reasoning of H ranks evaluation and complexity measure estimation are described. In the second section the method for investigation of intro concatenation between two elements of dynamical system based by second order matrix analysis is presented, and conclusions are delivered in the last section.

2. COMPLEXITY FROM THE MATHEMATICAL POINT OF VIEW

In this section the mathematical characterization of complexity will be presented.

Let a dynamical system S be given. This system can be characterized in this way: it consists of *m* components $K_1, K_2, ..., K_m$ and these components $K_r, r = 1,2,...,m$ are related by algebraic relations. Usually these relationships are composed of ordinary sum and product operations, i.e. $S = \alpha_1 K_1 + \alpha_2 K_2 + ... + \alpha_m K_m$. In this case measure of complexity of dynamical system S is noted $cmpl\ S$.

Having proposed interpretation of complexity it is possible to compose the mathematical algorithm of complexity estimation. Suppose that time series $(y_0, y_1, y_2, ...)$ describes dynamical system *S*. Here $y_k, k = 0,1,2,...$ measures are describing the state of dynamical system *S* in time moment *n*. It can be either scalar, or function, or matrix etc.

Then the concept of Hankel rank for these series can be defined. Let a series $(y_0, y_1, y_2, ...)$ be a sequence of real or complex numbers. Then the sequence $(H_1, H_2, H_3, ...)$ of Hankel matrices $H_m, m = 1,2,3,...$ can be formed:

$$H_1 := [y_0],\ H_2 := \begin{bmatrix} y_0 & y_1 \\ y_1 & y_2 \end{bmatrix},\ ...,...$$

and from values of its determinants $\det H_1 := d_1, \det H_2 := d_2, ...$ the sequence of determinants $(d_1, d_2, d_3, ...)$ can be formed.

Frequently the elements $d_r, r = 1,2,3,...$ of this sequence with fixed $\varepsilon > 0$ satisfy special constructed estimation. There exists fixed natural number $m, m \in N$ and such number satisfies inequalities

$$|d_m| \geq \varepsilon, |d_{m+n}| \leq \varepsilon, n = 1,2,3,... \qquad (1)$$

If the system of inequalities (1) hold true for sequence of determinants then the series has $\varepsilon -$Hankel rank equal to natural number m. Besides, this is noted by this way:

$$H_\varepsilon(y_0, y_1, y_2, ...) = m \qquad (2)$$

Then exists a function $f(x)$ which is described by relation

$$f(x) = \sum_{r=1}^{m} Q_r(x) e^{\lambda_r x} \qquad (3)$$

when $Q_r(x)$ is a polynomial and $f(j) \approx y_j, j = 0,1,2,...$.

The primary concepts for Hankel matrices analysis in finding exact, periodic and chaotic solutions of ordinary differential equations were presented in [2].

If the dynamical system S is described by time series with has $\varepsilon -$Hankel rank, then the components K_r can be the functions $Q_r(x)e^{\lambda_r x}$, $r = 1,2,...,m$ it means that complexity of dynamical system S is outlined this way:

$$cmpl\ S = (Q_1(x)e^{\lambda_1 x}, ..., Q_m(x)e^{\lambda_m x}) \qquad (4)$$

The accuracy of expression depends on choose level of ε.

Proposed analysis of time series using Hankel matrices is an alternative method for Fourier analysis which is widely developed. But in proposed method the expression for dynamical systems are finite functions and in most cases it needs less parameters to describe the evaluation of dynamical systems than Fourier methods. For fast classification of dynamical systems and its complexity measure the convolution of Mealy and Moore automaton is practiced [3].

3. INVESTIGATION OF INTERNAL LINKS OF DYNAMICAL SYSTEM

Let a dynamical system *S* be given. Suppose that this system can be described by two (or more) synchronous time series $(y_0, y_1, y_2, ...)$, $(z_0, z_1, z_2, ...)$. Then it is considered that internal links of dynamical system S are relations between two synchronous time series described by mathematical expressions. It must be noticed that usually the couple of series are investigated using statistical methods and there are widely developed analysis of correlation of two series which describes tendency of variation of these series (global type features). But statistical methods are not convenient for investigation of instantaneous features of series variation. The knowledge of such characteristics is none the less important than correlation type properties.

Experience shows that for description of instantaneous features of two time series the algebraic matrix analysis is convenient. In this case the elements y_n and z_n, $n = 0,1,2,...$ are considered as determined. The basis of algebraic matrix analysis is algebraic arrangement of matrices. The discriminant of matrix A or difference of eigen values is outlined by this formula:

$$|\lambda_1 - \lambda_2| = \sqrt{|\text{dsk } A|} \qquad (5)$$

and it shows the „informative degree" of matrix, [4].

The smaller value of $\sqrt{|\text{dsk } A|}$ implies simplicity of dynamical system described by matrix A. When two time series describing dynamical system are given then it is possible to relate to these series one matrix time sequence: $(A_1, A_2, A_3, ...)$ when

$$A_n = \begin{bmatrix} y_n & y_{n+1} - z_{n+1} \\ y_{n-1} - z_{n-1} & z_n \end{bmatrix} \quad (6)$$

Then the features of matrix series sufficiently reflect the interdependence of two series. It shows the variation of discriminates series $(\mathrm{dsk}\ A_1, \mathrm{dsk}\ A_2, \ldots)$. Besides, these series can be considered as analogue of correlation characteristic if the statistical methods in some cases for couple of initial series would be used.

4. THE EXPERIMENTAL RESULTS

The primary step of investigation of physiological systems requires the development of appropriate sensors and instrumentation to transduce the phenomenon of interest in a measurable electrical signal. The next step of the signals analysis, however, is not always an easy task for a physician or life-sciences specialist. The clinically relevant information in the signal is often masked by noise and interference, and the signal features may not be readily comprehensible by visual or auditory systems of a human observer. Processing of biomedical signals is not only directed toward filtering for removal of noise and power-line interference; spectral analysis to understand the frequency characteristics of signals; and modelling for feature representation and parameterization. Recent trends have been toward quantitative or objective analysis of physiological systems and phenomena via signal analysis [1].

Analysis of ECG complexity is implemented by scientific group which contains employees of Kaunas University of Technology, Kaunas University of Medicine and Lithuanian Academy of Physical Education. The physiological state of persons with cardiovascular diseases, elite sportsmen's, elderly people (project GUARANTEE) during various physical tasks is investigating.

The expressing of cardiac signals with Hankel matrix could be useful for diagnostic purposes, because averaged ranks in each RR interval and normalized in one scale separate the "healthy" and "sick" persons groups, [5]. In Fig. 1 the example of these ranks (red line) is presented, when initial data is divided to RR intervals (blue lines).

The higher rank value describes the higher signal complexity in certain interval. It is clearly observable that from numerical relations between ranks and the computation step for describing the higher variation of the signal, the higher rank is needed [6].

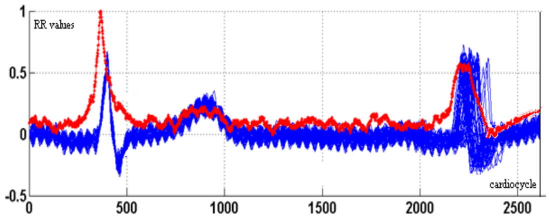

Fig. 1. Example of Hankel matrix analysis

Discriminates for healthy people in normal conditions fluctuate between 0 and 0.2 and grow if physical load is applied, [7]. Results for three different sportsmen (wrestle, stage 10-12 years, 11- 13 place in Europe championship) are shown Fig. 2 (I Rest – 1 min; II – physical load - Rouffier test (30 squats per 45 s); IIIa Recovery (1st minute); IIIb – recovery (2nd minute)).

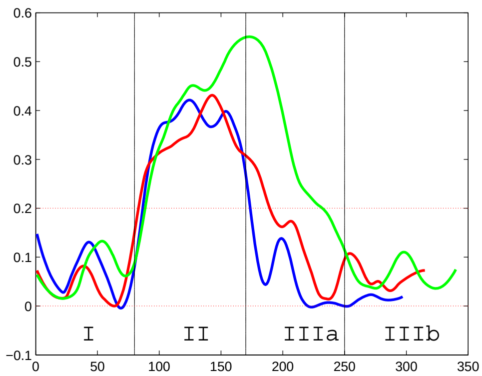

Fig. 2. Example of coherence matrix analysis

5. CONCLUSION

The Hankel matrix ranks and second order coherence matrices for describing complexity of ECG and relationship between parameters of ECG were presented. Such type analysis was applied in evaluation of physiological state for different persons. The increasing amount of studies in this area and application of complex system theory into medicine it is hope to have more detailed and motivated interpretation of intra and interpersonal concatenation and complexity itself.

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