The Research of Fractal Characteristics of the Electrocardiogram in a Real Time Mode

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Abstract: The article presents the results of recent investigations into Holter monitoring of ECG, using non-linear analysis methods. It is shown that one of the most precise characteristics of the functional state of biological systems is the dynamical trend of correlation dimension and entropy. On the basis of this it is suggested that a complex programming apparatus be created for calculating these characteristics on line. A similar programming product is being created now with the support of RFBR. The first results of the working program, its adjustment, and further development, are also considered in the article.
Keywords: Holter monitoring, E C G, correlation dimension, Fractal analysis of temporary rows, non-linear dynamics of heart rate

1 Introduction

In 1996 the European Cardiological Society and the North American Electrophysiological Society gave recommendations on the clinical usage of the heart rate variability method (HRV) [11], and it is presently being carried out by different methods (fig. 1). Most of the HRV investigations are based on the linear measurement of cardio-rhythm (standard deviation of interval duration between sinusoidal contraction (SDNN), standard deviation of average values RR-intervals (SDANN), indicators of the autonomous regulation contour (RMSSD, pNN50), triangulation index, power values in different frequency ranges, low-high frequency spectral components, their ratio ((ULF, VLF, LF, HF, LF/HF) etc.) These indicators are now used in clinical practice. However, the interest of investigators is attracted by non-linear mathematical methods, using, for example, postulates from the theory of determinated chaos. So, in [2] the investigation was into the supposition that a non-linear component HRV might show periodical structure in a 24 hour period, which was partially proved. There are contradictory data of the influence on non-linear components of breathing. The authors in [4] have not discovered reliable differences in forced and free breathing in the non-linear component HRV. Just the opposite is stated in [3] concerning the expressed non-linear component HRV in forced breathing. In [7] it is shown that

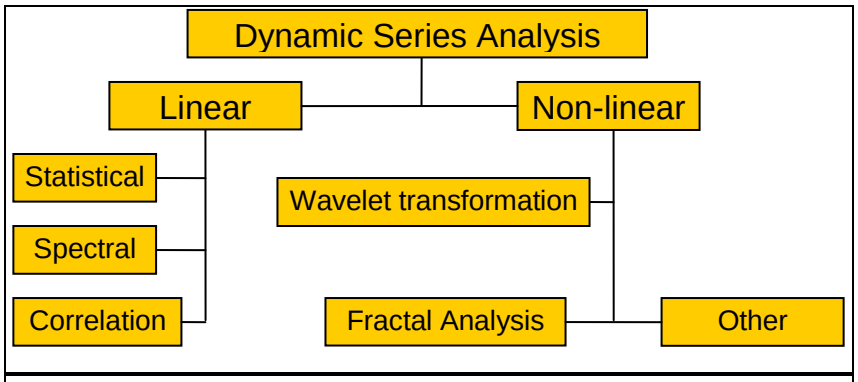

Fig. 1. Modern methods of investigation and analysis of processing

methods based on the analyses of non-linear dynamics VCR can better discover patients with the risk of sudden death. In [6] the VCR changes are investigated in 92 episodes of the paroxysmal fibrillation of the auricle. The non-linear methods include such indicators as entropy approximation (ApEn). The authors conclude that the reduction of non-linear criteria reflects the changes of the sympatho-vagus regulation before the paroxysmal fibrillation of the auricle. In [5] it is also noted that methods of HRV evaluation based on non-linear analysis are better than standard methods in discovering changes in patients before the beginning of the ventricle fibrillation [13].

However, non-linear VCR analysis demands the prolonged formation of a data base for building a restored attractor, the dimension trend evaluation of which might last for several hours, which is not acceptable in conditions of urgent cardiology, and demands the transition from RR-intervals to complete ECG. This transition certainly makes the task more complicated, but at the same time enhances the reliability of entropy evaluation [8]. In [9] and [16] it is shown that there are currently no indicators satisfactorily describing the reactions of the cardio-vessel system to different external influences (physical uploads, stress, etc). In [10], based on the complete ECG, it is proved that the functioning of the heart of a healthy person is not regular.

2 The method of fractal analysis

The method of fractal analysis consists of the transition from the signal to the restored attractor for the numeric characteristics of which probable (fractal) dimensions are used, expressed by the equation dimensions of Renyi:

$$D_q = \lim_{\varepsilon \to 0} \lim_{\tau \to 0} \lim_{m \to \infty} [\frac{\ln I_q(\varepsilon)}{\ln(1/\varepsilon)}], I_q = \frac{\sum_{i=1}^{M(\varepsilon)} p_i^q}{1-q}$$

at q=0 this is a well known dimension of Kolmogorov-Hausdorff:

$$D_F = \lim_{\varepsilon \to 0} \frac{\ln M(\varepsilon)}{\ln(1/\varepsilon)}$$

However, to characterize the attractor not only metric qualities are necessary, but also the probability of finding a point on the attractor. Usually for this purpose informational dimension and related informational entropy is used, as well as correlation dimension and correlation entropy:

$$D_C = \lim_{\varepsilon \to 0} \frac{\ln(\sum_{i=1}^{M(\varepsilon)} p_i^2)}{\ln(\varepsilon)} = \lim_{\varepsilon \to 0} \frac{\ln(C(\varepsilon))}{\ln(\varepsilon)}, I_C = \ln \frac{C(r,N)}{C(r,N+1)}$$

$$C(\varepsilon) = \lim_{m \to \infty} \frac{1}{m^2} \sum_{i,j=1}^{m} \theta(\varepsilon - \rho(x_i, x_j)), C(r) = \sum_{i=0}^{m-2} \sum_{j=i+1}^{m-1} \frac{\theta(\varepsilon - \rho(x_i, x_j))}{m(m-1)/2}$$

$$\theta(\alpha) = \begin{cases} 1, \alpha \geq 0 \\ 0, \alpha < 0 \end{cases}$$

For finding the characteristics of the attractor we need a definite number of points, that could be evaluated with the well-known equations of Eckmann or Nerenberg:

$$D_{\max} = \frac{2\ln M}{\ln(1/r)}, r = \frac{\varepsilon}{\varepsilon_{\max}};$$

$$M \geq M_{\min} = 10^{2+0.4D}$$

For giving the phase space, the method of progressive differentiation is usually used or the method of Takens delay:

$$\vec{x}(t) = (a(t), \frac{da(t)}{dt}, ..., \frac{d^{n-1}a(t)}{dt^{n-1}});$$

$$\vec{x}(t) = (a(t), a(t + \tau\Delta t), ..., a(t + \tau(N-1)\Delta t))$$

The delay parameter in the last case is usually calculated as the first zero of the autocorrelation function, or as the first minimum of the function of mutual information:

$$B(\tau) = \frac{1}{m} \sum_{k=0}^{m-1} (a_k - \bar{a})(a_{k+\tau} - \bar{a}), m = M - (N-1)\tau;$$

$$I(\tau) = \sum_{a_k} P(a_k, a_{k+\tau}) \ln(\frac{P(a_k, a_{k+\tau})}{P(a_k)P(a_{k+\tau})})$$

The methods of calculation of the correlation dimensions and correlation entropy are presented here:

$$C(r) \sim r^{D_2}$$

$$\ln C(r) \sim D_2 \ln r$$

$$C(r,N) \sim r^{D_2} \exp(-N \cdot I_2)$$

$$I_2 = \ln \frac{C(r,N)}{C(r,N+1)}$$

According to the well-known Takens theory the dimension of the phase space should be evaluated like this:

$$N \leq 2D_2 + 1$$

3 Firmware complex

Unfortunately, the Holter monitor is a three-channel static device, allowing the processing of the signal only after the device has been removed. But our practical interest lies in predicting the changes of the fractal characteristics. That is why our current software which is presently being developed, though working with the static records, still calculates the characteristics on-line, progressively shifting the window width on the required number of points.

So currently the complex calculates on-line:

- the histogram of variability
- low and high frequency spectral components ULF, VLF, LF, HF
- autocorrelation function
- correlation dimensions
- correlation entropy

and also builds graphs of a two / three dimensional attractor with their successive updating. The interface of the complex is shown in fig. 2

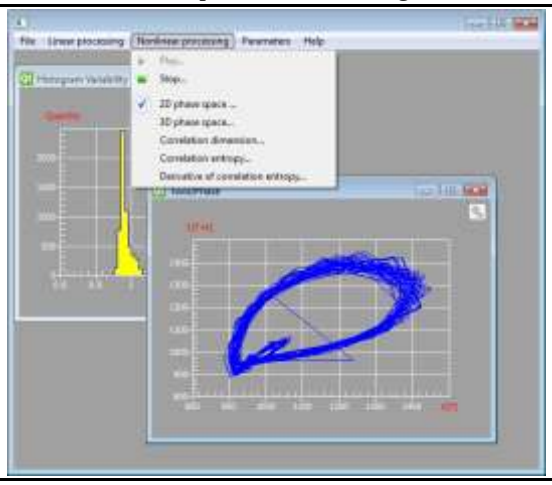

Fig. 2. Interface of the firmware complex

4 Results

According to the above-described method with the specially elaborated software, the correlation dimension is evaluated every second for the whole period of the cardiogram measurement. The adjustments of the program parameters allow the playback of the initial mass with any given speed. On the basis of the calculated data the dynamic trend is built.

The results of the program work are shown here for patients with different diseases, such as patients recovering from stroke (fig .3), vegetative conditions (fig. 4), pneumonia (fig. 5) and the most interesting - life-threatening sciatical risk (fig .6)

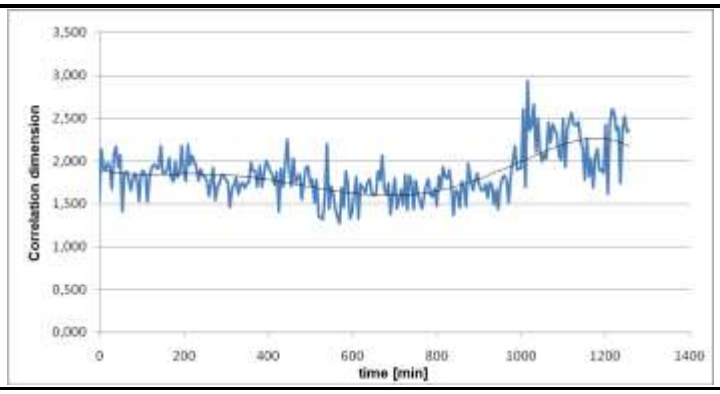

Fig. 3. Recovering after stroke

In this graph the significant change of the correlation dimension (more than 1) is clearly seen.

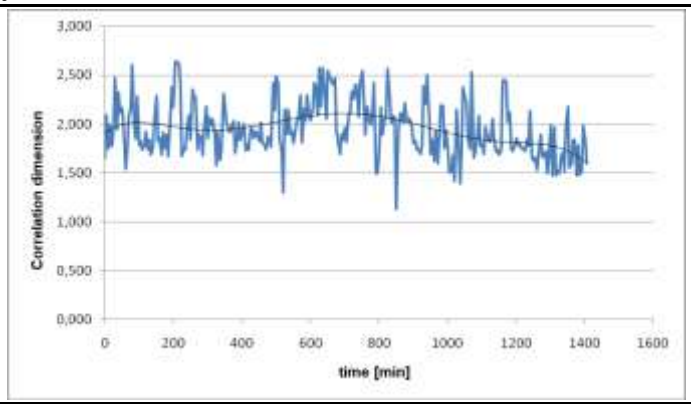

Fig. 4. Vegetative condition

In the vegetative condition the changes are much smaller and predictable (approximately 0.5)

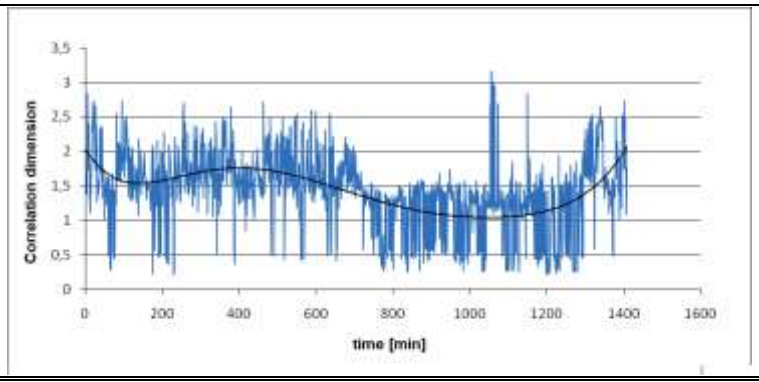

Fig. 5. Pneumonia

In the severe pneumonia condition the trend changes of the correlation dimension reach approximately 2 during the day. Finally, in the near-death state (fibrillation of ventricles), for a period of time the trend stays permanent (fig .6). However,

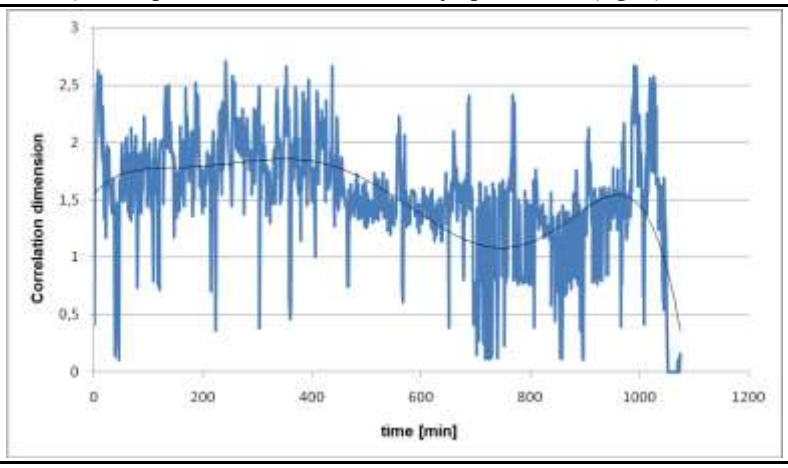

Fig. 6. Changing of cardio-rhythm with the risk of death.

further on, sharp fluctuations start, followed by a rapid dropping down to zero (case of death). It is noted that this dropping down is observed for several minutes. However, it is hoped that prediction can be made of the dropping down of the trend due to the sharp increase after a long period of calm-condition of the system. In this case an attempt will be made to reconstruct such a signal with the help of the non-linear system of differential equations with right sides as polynomials:

$$\begin{cases} \dot{x}_1 = f_1(x_1, x_2 \ldots x_N) \\ \dot{x}_2 = f_2(x_1, x_2 \ldots x_N) \\ \ldots \\ \dot{x}_N = f_N(x_1, x_2 \ldots x_N) \end{cases} \quad f_j = \sum_{l_1, l_2, \ldots, l_N = 0}^{\nu} C_{j, l_1, l_2, \ldots, l_N} \prod_{k=1}^{N} x_k^{l_k}, \sum_{k=1}^{N} l_k \le \nu$$

And also finding the unknown coefficients, for example, with the method of least squares.

5 Conclusion

Unfortunately, nowadays for the purpose of functional diagnosis of the body condition, the linear indicators used are taken from a patient's biomedical signals. The latest work in different aspects of cardio-rhythm studies in normal condition and in pathology shows that, apart from the classical methods of analysis in the time and frequency field, there is a recurring tendency to explore the cardio-rhythm from the point of view of non-linear analysis. Various influences, including the neurohumoral mechanisms of higher vegetative centres, cause the non-linear character of the cardio-rhythm changes, for the description of which special methods are necessary (graphs of the attractor, correlation dimensions, entropy etc). All these methods are of great interest for researchers; however, the practical application is not clear and as a result not limited.
However, it is necessary to emphasise the qualitative character of the changes in such indicators. The software currently elaborated here will significantly improve the efficiency of investigations made into the topic.
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