GRAPHICAL METHODS FOR NON-LINEAR ANALYSIS OF ELECTROCARDIOGRAPHIC DATA

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Abstract:

Introduction: One of the most widely used methods for studying the bioelectric activity of the heart is the electrocardiogram (ECG). An important diagnostic parameter that can be determined by the ECG is heart rate variability (HRV), which takes into account the difference between successive strokes of the heart. Changing HRV can be an indicator of a number of disease states, such as low HRV levels can show poor health that is not only associated with cardiovascular disease but also with other diseases such as internal, nervous, mental, and other disorders.

Objectives: The subject of this article is the study of 24-hour ECG signals by applying non-linear graphical methods for HRV analysis. The non-linear graphical methods aim at obtaining graphical and quantitative information on the cardiovascular status of the study groups to complement the information obtained from traditional linear methods of analysis.

Methods: For the non-linear analysis of HRV, graphical methods were used: Poincaré plot and Recurrence plot were used, which are suitable for the examination of electrocardiographic signals. Two groups of people were investigated: 20 healthy controls and 20 patients with arrhythmia.

Results: Based on the nonlinear analysis of RR time series, the graphs of a healthy subject and a patient with arrhythmia were constructed using the Poincare plot. The graph of the healthy subject has the shape of a comet, while the graph of the patient with arrhythmia has the shape of a fan. The quantitative characteristics of patients with arrhythmia significantly change compared to the healthy subjects. The SD1 ($p < 0.003$) and SD2 ($p < 0.0001$) values decreased in patients with arrhythmia compared to the healthy controls. This reduction leads to reduction of the areas of the ellipse in the patients with arryhthmia. The ratio of SD1/SD2 ($p < 0.05$) is lower for the healthy controls. The graphs obtained by the Recurrence plot of the investigated signals differ in healthy subjects and in patients with arrhythmia. For a healthy subject, the graph has a diagonal line and fewer squares showing a higher HRV. The graph of a patient with arrhythmia contains more squares, indicating periodicity in the investigated signal. The Recurrence Quantification Analysis showed that the values of the investigated parameters DET% ($p < 0.0001$), REC% ($p < 0.0001$) and ENTR ($p < 0.001$) in patients with arrhythmia are increased.

CONCLUSIONS: The importance of the graphical nonlinear methods used for the analysis of HRV consists in forming a parametric and graphical assessment of the patient's health status.

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Keywords: Poincaré plot, Recurrence plot, ECG, HRV, RR-interval series.

Introduction

The mathematical analysis of electrocardiogram data is of interest to many researchers. Heart rhythm is an objective characteristic of the functional state of the human organism and depends on a number of factors: age, gender, environmental conditions, mental and physical stress of the organism, diseases and others (Ernst, 2014). An important diagnostic parameter that can be determined by digital electrocardiograms is heart rate variability (HRV) taking into account the difference between successive heartbeats (RR time intervals) (Kumar et al., 2013). The heart rate variability is related to the need to adapt the body to the changing conditions of the external and internal environment and reflects the work of the whole organism, not just the cardiovascular system (Pfeifer et al., 1982). Changing HRV may be an indicator of a number of disease states, such as low HRV levels can show poor health (Mirza et al., 2012). The widespread prevalence of HRV as a non-invasive diagnostic method of analysis functioning of the cardiovascular system is a fundamentally important trend in modern cardiology. Considering the importance of this method, in 1996, the European Cardiological and North American Electrophysiological Society gave recommendations for the clinical use of the HRV method (Malik, 1996). As a result of the introduced new standard, the analysis of heart rate variability has become a rapidly evolving field in cardiology, in which is realized the use of mathematical methods of analysis in the diagnosis of a number of diseases. The advantage of this new direction is the possibility of detecting the most subtle variations in cardiac activity, so mathematical methods of HRV analysis are particularly useful in assessing the general functional capabilities of the body in normal and early abnormalities that, in the absence of the necessary preventive procedures can progressively develop into a more serious illness (Smith et al., 2009).

The mathematical methods for the analysis of HRV are two main classes: linear and non-linear (Ernst, 2014). The quantitative dimensions of the studied parameters in the use of linear mathematical methods of analysis have a significant clinical application because the norm-pathology limits are

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known according to the standard introduced (Malik, 1996). Recently, the non-linear methods of HRV analysis such as graphical, fractal, multifractal and wavelet analysis methods have been increasingly used, since cardiac signals are non-stationary and have both periodic and non-periodic components (Acharya et al., 2007). The application of these new mathematical methods for HRV analysis provides additional information on the physiological state of the patient as well as generates new knowledge on the diagnosis, prognosis and prevention of pathological conditions in cardiovascular diseases.

The purpose of this article is to show the results of the mathematical analysis of digital electrocardiographic data (RR) using the graphical methods: Poincaré plot and Recurrence plot.

Methods of graphical analysis and data

Poincaré plot

Poincaré plot is a relatively new technique for analyzing non-linear dynamics of HRV (Khandoker et al., 2013). It is a geometric model in which each RR interval is presented as a function of the previous interval and is applied to the coordinate system (Tayel et al., 2015). Each pair of RR intervals (previous and next) has coordinates (x, y), where x is the RR_n interval, and y is the value of $RR_{n+1.}$ In the formation of the graph a cloud of points is created, such as the center is located on the line of identity (Piskorski et al., 2005). The line of identity is a graph of the function x=y ($RR_n=RR_{n+1}$). If the point is above the identity line, it means that x<y ($RR_n<RR_{n+1}$). Accordingly, if the dot is located below the line of identity, this indicates that the interval RR_{n+1} is shorter than the RR_n interval. Therefore, the form of the cloud of points (RR_n; RR_{n+1}) on the Poincaré graph reflects the change in the length of the RR intervals, i.e. the dispersion (Golińska, 2013).

If an ellipse with a longitudinal and transverse axis is placed on the graph constructed using the Poincaré plot, the following indicators can be derived: ellipse length (SD2 [ms] parameter); ellipse width (SD1 [ms] parameter); SD1/SD2 ratio; area of the ellipse - the area of the ellipse S = (SD1*SD2*pi)/4.

The main features used for HRV visual analysis by using the Poincaré method are: the shape, size, and location of the main cloud of points, localization, and symmetry of cloud points.

- The shape of the cloud is categorized for the different functional states of a person (Khandoker et al., 2013) :
    - The healthy subject's graph has one main cloud of points to which extra points can be evenly scattered. The main cloud has the shape of a comet with a narrow lower part and gradually expanding towards the top.
    - The chart of the diseased subject is in the form of a torpedo, fan or complex form (consisting of several clouds) depending on the type of disease.
- Localization of the cloud points. If there are more than one cluster in the graph, which are essentially separate from the cloud, an arrhythmia may be expected. As a rule, these clusters indicate the presence of extrasystoles (Piskorski et al, 2007).
- The symmetry of the cloud points is determined against the identity line. Symmetry shows the absence of rhythm disturbances, and the asymmetry back - for the presence of such.
- Location of the main cloud. The position of the main cloud in the graph suggests which Autonomic Nervous System department has a greater impact on the HRV.
    - The location of the main cloud in the lower left corner of the graph shows the predominance of the sympathetic nervous system.
    - The location of the main cloud in the top right corner indicates the predominance of the parasympathetic system (Pfeifer et al.,1982).

Recurrence plot

The Recurrence plot method allows a non-linear process to be analyzed visually according to its graphical image (Marwan et al., 2007). It is a powerful tool for exploring the non-linear properties and detecting hidden dependencies in observed time series (Acharya et al, 2006). The basis of the method lies in the drawing and analysis of a recurrent diagram. The recurrent diagram is a graphical representation of the matrix (Acharya et al., 2007):

$$R_{i,j}(\varepsilon_i, m) = \theta(\varepsilon_i - \|X_i(m) - X_j(m)\|). \qquad (1)$$

Where:

- $X_i(m)$ is the phase trajectory of the dynamic system in the m-dimensional phase space;
- $\theta(.)$ is the Heaviside function;
- $||X_i(m) - X_j(m)||$- the distance between the points;
- ε_i (which determines the proximity of adjacent points i).

The matrix, which is presented as a graph is a two-dimensional set of points in accordance with equation (1). The matrix consists of zeros and ones, such as the nearby (recurrent) points are depicted in black, and the distant points are white in the case of a black and white graphic. The proximity of the adjacent points is determined by the parameter ε_i.

The diagram topology analysis allows the observed processes to be classified, such as (Thiel at al., 2004):

- Determination of homogeneous processes with independent random values;
- Determination of processes with slow changing parameters;
- Determination of periodic or oscillating processes corresponding to non-linear systems, etc.

The numerical analysis of the recurrence diagrams allows calculation of the complexity measures of structural-recurrent diagrams (Turianikova et al, 2014). The following indicators are used to assess the recurrence: REC% (level of recurrence) DET% (determinism) ENTR (Shannon entropy) and others.

Recurrence rate (REC) - reflect the density of recurrence points by counting them. This parameter indicates the probability of finding a recurrence point in the time series (probability of repeating the status).

$$REC\% = \frac{1}{N^2}\sum_{i,j=1}^{N} R_{i,j} \tag{2}$$

Determinism (DET) - is a feature of predictability of the system. This parameter is defined as a ratio between the number of recurrence points present on the diagonal lines and the total number of recurrence points.

$$DET\% = \frac{\sum_{l=l_{min}}^{N} lP(l)}{\sum_{i,j}^{N} R_{i,j}}, \tag{3}$$

where:

- l_i is the length of the i-th diagonal line;
- $P(l)=\{l_i,\ i=1,\ldots,N_l\}$ is the frequency distribution of the diagonal lines lengths in the recurrent diagram;
- N_l is the number of diagonal lines.

Entropy (ENTR) – this parameter is associated with Shannon's entropy.

$$ENTR = -\sum_{l_{min}}^{N} p(l)\ln\big(p(l)\big), \tag{4}$$

where:

$$p(l) = \frac{P(l)}{\sum_{l_{min}}^{N} P(l)} \tag{5}$$

The recurrence quantification analysis (RQA) allows us to determine the level of recurrence, determinism of the time series studied.

Data

In this article two groups of signals are analyzed: RR time series of 20 healthy subjects and 20 patients with cardiovascular disease (arrhythmia). These signals are consisting of around 100 000 data points, corresponding to 24-hour Holter ECG monitoring.

Statistical analysis

The results are presented as mean ± standard deviation (mean±SD). Differences between the parameters of the groups are tested with an ANOVA test. A p-value of <0.05 was regarded as statistically significant.

The results shown in the article were obtained through software developed in Matlab.

Results and discussion

This article shows the results of the non-linear analysis of HRV by applying the Poincare plot and Recurrence plot methods.

Based on the nonlinear analysis of RR time series, the graphs of a healthy subject and a patient with arrhythmia were constructed using the Poincaré plot. The diagram of the healthy subject (Figure 1-left) has the shape of a comet with a sharpened lower part, which gradually expands towards the top. The graph (Figure 1-right) of a patient with cardiovascular disease has the form of a fan (arrhythmia). For each diagram an ellipse with longitudinal and transverse axis is built. In the healthy patients, the shape of the ellipse is pronounced, whereas in the patients with cardiovascular diseases the length and width of the ellipse are approximately equal, and the ellipse approaches a circle.

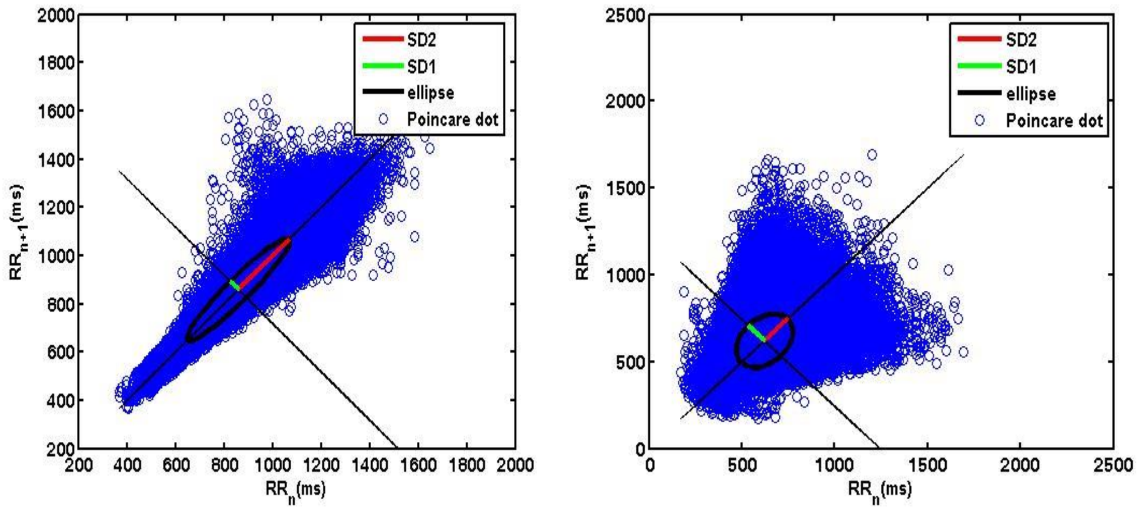
The quantitative characteristics determined by the Poincaré method are significantly altered in patients with cardiovascular disease compared to healthy subjects. In Table 1 are shown the values of parameters SD1 and SD2, the relationship between them and the area of the ellipses of the study groups. SD1 decreased in patients with arrhythmia (Group 2) as compared to the healthy controls (Group 1). This decrease was statistically significant ($p<0.05$). The SD2 value is decreased almost double in patients compared to healthy controls, this decrease being statistically significant ($p<0.0001$). Lower values of SD1 and SD2 parameters in patients with arrhythmia lead to reduced HRV. The SD2/SD1 ratio is lower in healthy subjects and is statistically significant ($p=0.05$). Decreasing the SD1 and SD2 parameters results in a reduction in area of the ellipse for the patients with arrhythmia.

Table 1: Parameters obtained by the Poincaré plot for Group 1 (healthy subjects) and Group 2 (patients with arrhythmia)

Parameter	**Group 1 n=20 mean±sd**	**Group 2 n=20 mean±sd**	**p-value**
SD_1 [ms] (Poincare Plot)	61.2±10.3	44.5±14.8	0.003
SD_2 [ms] (Poincare Plot)	258.1±26.1	69.3±12.1	0.0001
SD_1/SD_2 (Poincare Plot)	0.31±0.7	0.65±0.3	0.05
S [ms^2] (Poincare Plot)	12 052±62	3 121±91	0.0001

Source: Author

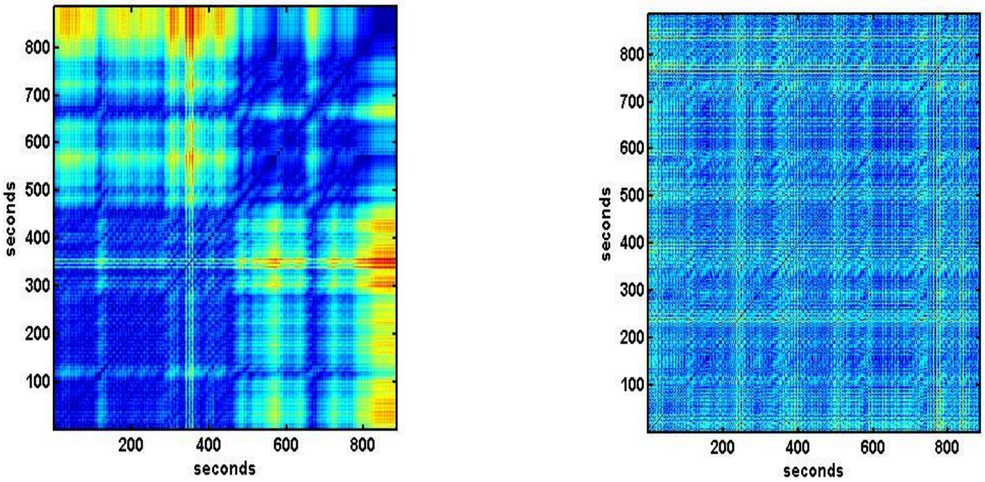
Figure 1: Poincaré plot of healthy subject and patient with arrhythmia



Source: Author

The graphical method, such as Recurrence plot is suitable for investigation of the electrocardiographic signals. Changing the RR intervals dynamics is led to a significant change in the shape of the recurrent chart. Figure 2 shows the graphs obtained by the Recurrence plot for the first 10 minutes of a 24-hour Holter recording for a healthy subject (the graph on the left) and a patient with arrhythmia (the graph on the right). For a healthy subject, the graph has a diagonal line and had fewer squares showing a higher HRV. An anomaly such as an arrhythmia has more squares in the graph indicating the periodicity of the investigated signal. In the second case, the HRV decreases. Similar results are reported in (Acharya et al., 2007). The visual evaluation of recurrent diagrams allows for quick information on the behavior of the investigated process. Reducing the complexity of the process (heart rhythm) and switching to periodicity is indicative of a pathological change in the regulation of heart rhythm. Cardiovascular diseases significantly influence the dynamics of RR intervals, with HRV reduced.

Figure 2: Recurrence plot of healthy subject and patient with arrhythmia



Source: Author

The results of the Recurrence Quantification Analysis are reported in Table 2. The values of the studied parameters are increased in patients with arrhythmia, their statistical significance is p <0.005.

Table 2: Parameters obtained by the Recurrence plot for Group 1 (healthy subjects) and Group 2 (patients with arrhythmia)

Parameter	**Group 1 n=20 mean±sd**	**Group 2 n=20 mean±sd**	**p-value**
DET [%] (Recurrence Plot)	96.3±0.5	99.7±0.1	0.0001
REC[%] (Recurrence Plot)	36.3±0.7	43.4±0.5	0.0001
ENTR (Recurrence Plot)	3.1±0.5	3.6±0.4	0.001

Source: Author

Recurrence plot and Recurrence Quantification Analysis are accessible tools for investigating the dynamics of complex systems, such as RR-time intervals.

Conclusion

Visual analysis of HRV based on non-linear methods, such as the Poincare plot and Recurrence plot, provide important information about the physiological state of patients.

The Poincare plot allows doctors to see the entire 24-hour ECG record at a glance and quickly detect cardiovascular abnormalities, if there are any. This is due to the fact that the shape of the cloud of points is categorized for the different functional states of a person. The Recurrence plot is also a useful tool for investigating nonlinear properties and detecting hidden dependencies in observed RR time intervals. The graphical results of the Recurrence plot studies indicate that a decrease in the complexity of the heart rhythm is the result of a pathological change in the regulation of the heart rhythm.

The quantitative characteristics determined by the Poincaré method are significantly altered in patients with cardiovascular disease compared to healthy subjects. The numerical analysis of recurrence diagrams allows calculation of the complexity measures of structural-recurrence diagrams.

The significance of the graphical non-linear methods used consists in forming of a parametric and graphical assessment of the patient's health status. Studies using such methods are not numerous and therefore the results described in this article may be of interest.

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