Volume 4, Issue 12, December 2014 ISSN: 2277 128X
International Journal of Advanced Research in Computer Science and Software Engineering
Research Paper
Available online at: www.ijarcsse.com

Graphical Methods for Nonlinear Analysis of ECG Signals

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Abstract— In this paper are presented the current results of scientific research of heart rate variability (HRV) analysis based on digital electrocardiograms (ECG). This analysis is a non-invasive and effective technique to reflect the autonomic nervous system regulation of the heart. HRV is used to diagnose and estimate of alterations in heart rate by measuring the variation of RR intervals (time intervals between two consecutive heart beats). The RR intervals are obtained from 24-hour digital Holter ECG records of healthy and unhealthy subjects. In the presented research work are used two graphical methods for nonlinear analysis of RR time series: Poincaré plot and Rescaled adjusted range Statistics plot (R/S). The obtained results show that these methods are suitable for diagnostic, forecast and prevention of the pathological statuses.

Keywords— graphical methods, nonlinear analysis, ECG signal, Poincaré plot, Rescaled adjusted range Statistics plot (R/S), RR interval, Heart Rate Variability (HRV).

I. INTRODUCTION

The cardiovascular disease is among the top 10 causes of death in the world. Ischemic heart disease, stroke, chronic obstructive lung have remained the top major killers the past decade. The latest scientific researches have shown that cardiovascular diseases can be mathematically analyzed and predicted by cardiac screening for early detection of possible complications to prevent disease and to improve the quality of life. The diagnostic parameter, which can be defined by the electrocardiograms (ECG) is heart rate variability (HRV) by measuring the time between heartbeats. In 1996, the European Society of Cardiology and North American Society of Pacing and Electrophysiology, are given recommendations on clinical usage of the HRV method for the evaluation of the risk for cardiology disease as: myocardial infarction (heart attacks), sudden cardiac death, etc [1]. HRV measurements are nonlinear and nonstationary and considerable part of information is coded in the dynamics of their fluctuation in the different time periods [2]-[4]. Through implementation of conventional (linear) mathematical methods part of the important characteristics of signal dynamics are missed. The investigations, development and implementation of new nonlinear mathematical methods and knowledge, based on the fractal theory will allow discovering new reasons for HRV fluctuations. These nonlinear methods are based on the invention, that the series of HRV possess characteristics, connected with the basic terms of fractal geometry, as: self-similarity, scalability, fractal dimension, long-range dependence [5]-[6]. The actuality of these researches is of extremely importance because the results of analysis of the cardiac data with these methods can give not only detailed information for physiological status of the patients, but create a possibility for generation of new knowledge concerning the diagnostics, prognosis and prevention of pathology of cardiovascular disease. The prevention in medicine is important not only for every person, but for the society as whole. The nonlinear analysis of cardiology data is especially new scientific approach, giving new concept for the dynamics of the heart activity.

The main objective of this article is to investigate the HRV signals by measuring the variation of RR intervals. The RR time series are extracted from 24-hour Holter ECG signals of healthy and unhealthy subjects. The analysis of HRV time series is based on the following two graphical methods: Poincaré plot and Rescaled adjusted range Statistics plot (R/S).

II. SUBJECTS AND METHODS

A. *Subjects*

In this article are analyzed three groups of signals: RR time series of 5 healthy persons, 5 patients with atrial fibrillation and 2 patients with congestive heart failure. The investigated signals of every patient consist about 100 000 data points, corresponding to 24-hour records of ECG RR time intervals. The data are taken from the Department of Cardiology of Multiprofile District Hospital for Active Treatment "Dr. Stefan Cherkezov" AD, town of Veliko Tarnovo, Bulgaria.

B. *Poincaré plot*

The Poincaré plot analysis is a graphical nonlinear method to assess the dynamic of HRV. This method provides summary information as well as detailed beat-to-beat information on the behavior of the heart. It is a graphical representation of temporal correlations within the RR intervals derived from ECG signal. The Poincaré plot is known as a return maps or scatter plots, where each RR interval from time series RR = {RR1, RR2, …, RRn, RRn+1} is plotted against next RR interval.

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The Poincaré plot parameters used in this paper are SD1, SD2 and SD1/SD2 ratio. SD2 is defined as the standard deviation of the projection of the Poincaré plot on the line of identify (y=x) and SD1 is the standard deviation of projection of the Poincaré plot on the line perpendicular to the line of identify. These parameters can be defined by following equations [6], [7]:

$$x = \{x1, x2, \dots, xn\} = \{RR1, RR2, \dots, RRn\} \quad (1)$$

$$y = \{y1, y2, \dots, yn\} = \{RR2, RR3, \dots, RRn+1\} \quad (2)$$

$$SD1 = \sqrt{var(d_1)} \quad (3)$$

$$SD2 = \sqrt{var(d_2)} \quad (4)$$

$$Ratio = \frac{SD1}{SD2} \quad (5)$$

Where:

- i = 1, 2, 3, …, *n* and *n* is the number of points in the Poincare plot which is one less than the length of the R time series;
- var(d) is the variance of d;
- $d_1 = \frac{x - y}{\sqrt{2}}$;
- $d_2 = \frac{x + y}{\sqrt{2}}$.

SD1 has been correlated with high frequency power, while SD2 has been correlated with both low and high frequency powers. The ratio SD1/SD2 is associated with the randomness of the HRV signal. It has been suggested that the ratio SD1/SD2, which is a measure of the randomness in HRV time series, has the strongest association with mortality in adults.

C. Rescaled adjusted range Statistics plot (R/S plot)

The rescaled range is a statistical measure of the variability of a time series introduced by British hydrologist Harold Hurst [8]. Closely associated with R/S method is the Hurst exponent. Based on the Hurst exponent value, the following classifications of time series can be realized:

- H=0.5 indicates a random series;
- 0<H<0.5 – the data in the signal are anti-correlated;
- 0.5<H<1 – the data in the signal are long-range correlated.

The R/S for the time series X(n) is asymptotically given by a power law:

$$\frac{R(n)}{S(n)} \propto n^H . \quad (6)$$

Where:

- R(n) is the range which is the difference between the minimum and maximum accumulated values;
- S(n) is the standard deviation estimated from the observed data X(n);
- H is the Hurst exponent.

To estimate the Hurst exponent is plotted R(n)/S(n) versus n in log-log axes. The slope of the regression line approximates the Hurst exponent [9].

III. RESULTS AND DISCUSSION

The results of the Poincaré plot analysis of RR time series for healthy and unhealthy subjects and their histograms are shown on Fig.1, Fig.2 and Fig.3. The Poincaré plot for healthy subject (Fig.1-a) is a cloud of points in the shape of an ellipse (‘comet’ shaped plot). On the other hand, plots for patient with atrial fibrillation (Fig.2-a) and congestive heart failure (Fig.3-a) are a cloud of points in the shape of a circle (‘complex” shaped plot). The geometry of these plots has been shown to distinguish between healthy and unhealthy subjects. Fig. 1-b, Fig.2-b and Fig.3-b show histograms of healthy and unhealthy subjects. In the histograms, each column corresponds to the number of RR intervals specified time range. For the healthy subject, the variability of RR intervals is significantly higher than subjects with atrial fibrillation and congestive heart failure.

The obtained Poincaré plot parameters in this paper are directly related to the physiology of the heart. The parameter SD1 is the length of the semi-minor axis of the ellipse and it is the reflection of short term variability of heart rate. The parameter SD2, the length of the semi-major axis, is the measure of long term variability. The values of SD1, SD2 and their ratios of the analyzed signals are presented in Table 1. Since the values of the SD1 and SD2 parameters depend on the RR intervals, the ratio of SD1 to SD2 is used to make comparison among Poincaré plots from different subjects. From Table 1 it is seen that the values of SD1 are lesser in normal subjects comparatively to the atrial fibrillation and congestive heart failure subjects. The SD1/SD2 values over time in atrial fibrillation and congestive heart failure subjects suggest a higher level of randomness.

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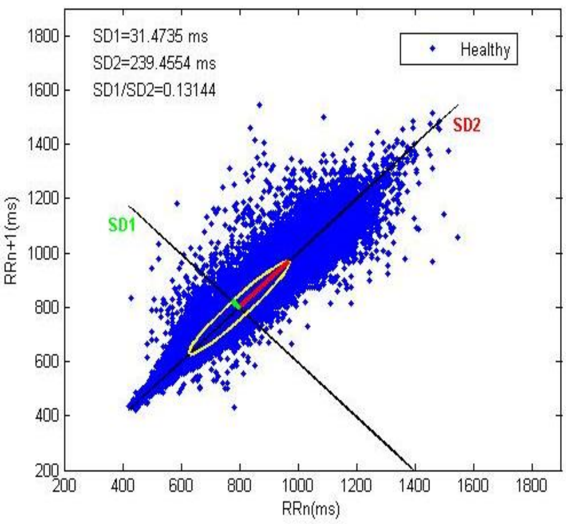
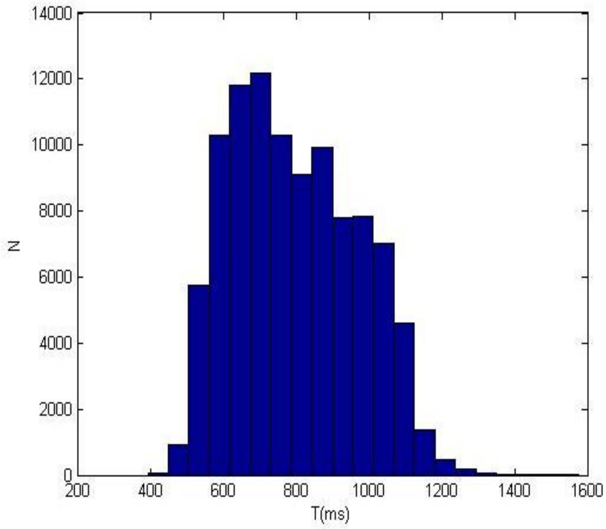
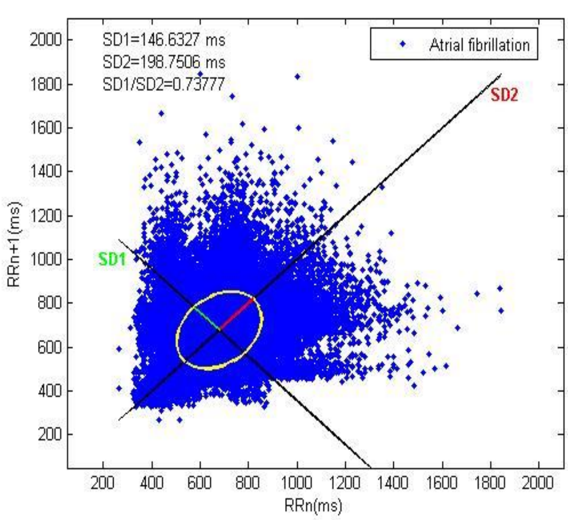
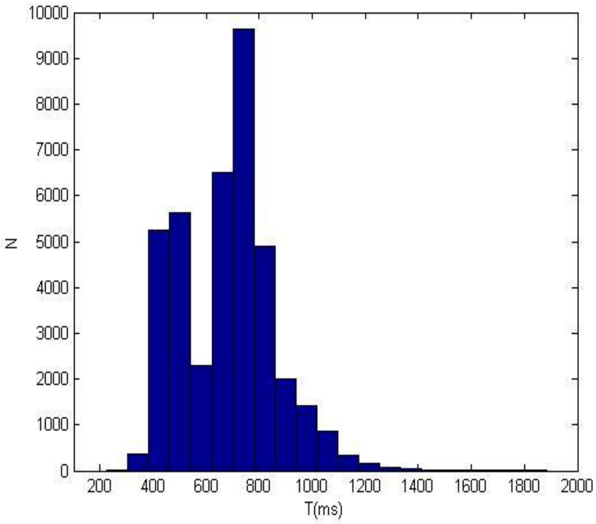




(a) (b)

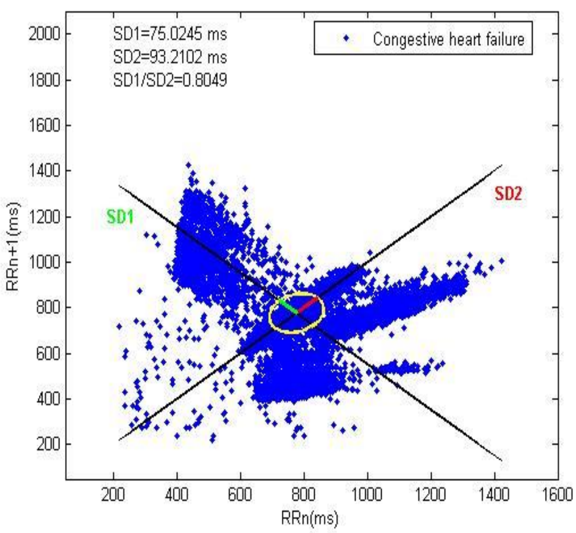
Fig. 1 Poincaré plot (a) and Histogram plot (b) of RR time intervals of a healthy person

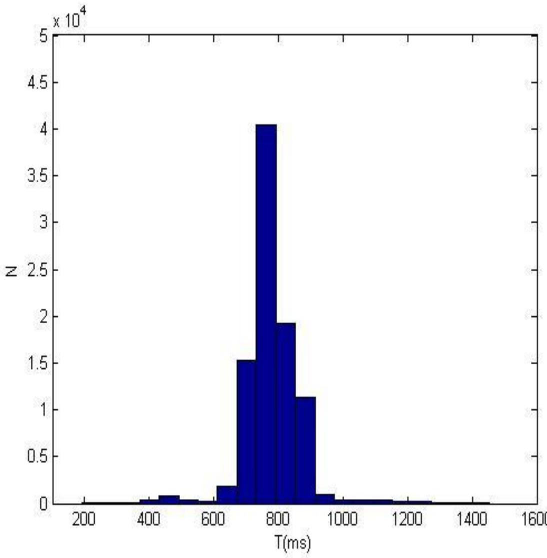




(a) (b)

Fig. 2 Poincaré plot (a) and Histogram plot (b) of RR time intervals of an atrial fibrillation subject





(a) (b)

Fig. 3 Poincaré plot (a) and Histogram plot (b) of RR time intervals of a congestive heart failure subject

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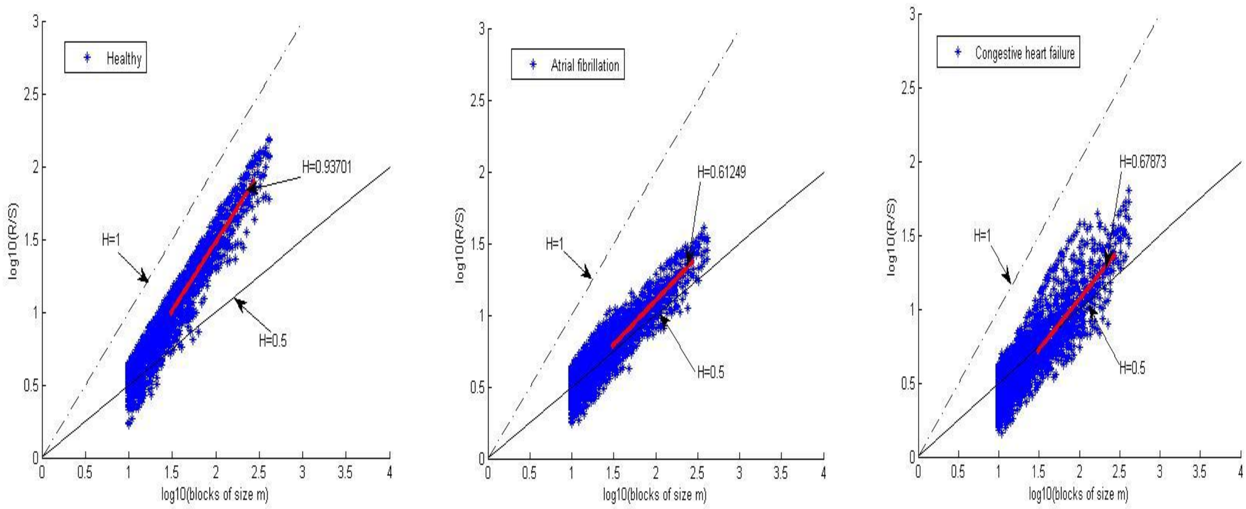
TABLE I The Values of Poincaré Plot for Healthy and Unhealthy Subjects

RR intervals of subjects	SD1(ms)	SD2(ms)	SD1/SD2 ratio
Subject 1-healthy	31.4735	239.4554	0.13144
Subject 2-healthy	20.2030	172.7411	0.11696
Subject 3-healthy	22.8663	138.988	0.16452
Subject 4-healthy	46.3933	295.2948	0.15711
Subject 5-healthy	18.2378	139.9263	0.13034
Subject 6-unhealthy (atrial fibrillation)	146.6327	198.7506	0.73777
Subject 7-unhealthy (atrial fibrillation)	125.0066	173.939	0.71868
Subject 8-unhealthy (atrial fibrillation)	202.5862	271.8955	0.7449
Subject 9-unhealthy (atrial fibrillation)	126.0803	182.1317	0.6922
Subject 10-unhealthy (atrial fibrillation)	122.051	177.0883	0.6892
Subject 11-unhealthy (congestive heart failure)	74.9388	110.0461	0.68098
Subject 12-unhealthy (congestive heart failure)	75.0245	93.2102	0.80490

The results of the R/S method applied to the three studied signals to determine the value of the Hurst exponent are shown in Fig.4. The determined values of the Hurst exponent are presented in Table 2.

The obtained results show that three RR time series are correlated, i.e. they are fractal time series. The values of the Hurst exponents of the patients with congestive heart failure and atrial fibrillation are significantly smaller than these of the healthy subjects. The presented scientific research determine that the Hurst exponent decrease in cases of atrial fibrillation and congestive heart failure of unhealthy subjects. The investigation of dependence between the value of the Hurst exponent and cardiology status could be used for diagnosis and prognosis of cardio disease.



a) b) c)

Fig. 4 R/S method for analysis of RR intervals for healthy (a), atrial fibrillation (b) and congestive heart failure (c) subjects

TABLE IIThe Values of Hurst Exponent for Healthy and Unhealthy Subjects

RR intervals of subjects	Hurst exponent
Subject 1-healthy	0.8563
Subject 2-healthy	0.9370
Subject 3-healthy	0.7590
Subject 4-healthy	0.9265
Subject 5-healthy	0.9179
Subject 6-unhealthy (atrial fibrillation)	0.6125
Subject 7-unhealthy (atrial fibrillation)	0.6936
Subject 8-unhealthy (atrial fibrillation)	0.6480
Subject 9-unhealthy (atrial fibrillation)	0.7342
Subject 10-unhealthy (atrial fibrillation)	0.7026
Subject 11-unhealthy (congestive heart failure)	0.7539
Subject 12-unhealthy (congestive heart failure)	0.6787

The described graphical methods are realized by the original MATLAB software developed in research project for nonlinear analysis of ECG signals.

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IV. CONCLUSION

The Poincare plot and R/S plot are valuable HRV analysis graphical methods due to is ability to display nonlinear aspects of the interval signals. Applications of these methods for analysis of RR intervals may lead to new diagnostics for patients at high risk of cardiac desire and they are suitable non invasive methods of diagnostics, forecast and prevention of the pathological statuses.

The developed application software for graphical methods for nonlinear analysis of ECG signals is implemented as additional mathematical tool for prevention of pathological status of patients by medical doctors.

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