Illuminating of Premature Ventricular Contractions of Heart using Fractal Dimension and Poincaré plot methods

Md Meganur Rhaman, Md Rezwan Islam, Tanzia Afrin Haque

Abstract- Premature ventricular contractions (PVC) are premature heartbeats originating from the ventricles of the heart. These heart beats occur before the regular heartbeat. PVC in patients with heart diseases (heart attacks, heart failure, diseases of the heart valves) may be associated with increased risks of developing ventricular tachycardia. A technique of nonlinear analysis, the fractal analysis is most mathematical models produce intractable solutions. Fractal is a mathematical analysis for characterizing complex, repeating geometrical patterns at various scale lengths. Due to the self-similarity in the heart's electrical conduction mechanism and self-affine behaviour of heart rate (HR), fractal analysis can be used to analyze HR time series data. Some studies tried to apply the fractal dimension to quantify of cardiac abnormality like PVC. Total of 14 set of ECG recordings, 7 with normal rhythm, 7 of premature ventricular contraction (PVC). Based on FD change, we can identify and classify different abnormalities present in ECG. Presents the uses of Poincaré plot indexes of heart rate variability (HRV) from short term ECG recordings as a screening tool for PVC. A clear reduction of standard deviation (SD) projections in Poincaré plot patterns is observed in the healthy group with a significant difference of SD between healthy and PVC subjects. The results show that Poincaré plot patterns of HRV can be used in identifying PVC. Finally a comparison is shown for FD and Poincare plot parameters.

Index Terms- ECG, FD, HP, HRV, PVC, Poincaré plot, SD.

1 INTRODUCTION

Premature ventricular contractions (PVC) are early or extra heartbeats that commonly occur and usually harmless in normal hearts, but can cause problems in hearts with pre-existing diseases. PVC may be perceived as a "skipped beat" or felt as palpitations in the chest. In a normal heartbeat, the ventricles contract after the atria have helped to fill them by contracting, in this way the ventricles can pump a maximized amount of blood both to the body and to the lungs [1]. The ventricle electrically discharges prematurely before the normal electrical discharges. These premature discharges are due to electrical "irritability" of the heart muscle of the ventricles and can be caused by heart attacks, electrolyte imbalances, lack of oxygen, or medications. Immediately after PVC, the electrical system of the heart resets, this resetting causes a brief pause in heartbeat and some patients report feeling the heart briefly stopping after PVC. PVC may be more common among older persons, patients with high blood pressure, and patients with heart diseases. PVC can also occur in young healthy individuals without known heart diseases or high blood pressure. Patients with three or more consecutive PVC in a row may develop ventricular tachycardia [1]. Conventionally used time and frequency domain parameters of HRV [5], [6] are not always suitable for analysis because of the non-stationary characteristic of the ECG. The visual analysis of variability of the Poincaré plot [7] for quantification of the unpredictability and complexity of the heart rate.

Fractal is a mathematical investigation for characterizing complex, replicating geometrical patterns at different scale lengths [2]. Fractal behaviour is exhibited by the heart in electrocardiogram signals and by the brain in electroencephalogram (EEG) signals [3], [4]. This paper presents the application of fractal theory and Poincare plot method to the analysis of ECG data. The PVC cardiac abnormalities are discussed in this paper. The ECG's are taken for 30 minutes and sampled at 360Hz. At first FD of healthy persons are determined by the three methods. These three methods are then applied for patients with PVC diseases to determine its range of variation from healthy patients. So by determining the FD of an ECG signal, an estimation of heart condition can be made.

The aim of this study was to determine how and which of the variability and complexity parameters of the HRV derived from the FD and Poincare plots are different in patients with PVC compared with subjects with normal rhythm.

2 METHODS

The ECG signal will be processed through a series of steps to calculate fractal dimension (FD). Different methods of calculating FD such as relative dispersion (RD) analysis, power spectral density (PSD) analysis, and rescaled range (RS) analysis [11], [12] will be applied. An algorithm based on indexes of Poincaré plots developed to distinguish between ECG of normal and PVC subjects. The data sets of ECG are taken from MIT-BIH arrhythmia database.

2.1 Relative Dispersion (RD) Analysis

The basic principle of RD analysis making estimates of the variance of the signal at each of several different levels of resolution form the basis of the technique; for fractal signals a plot of the log of the standard deviation versus the log of the measuring element size (the measure of resolution) gives a straight line with a slope of 1 - D, where D is the fractal dimension. Studies were done known signals with a specified value for H, the characterizing Hurst coefficient. H is a measure of roughness; the roughness in the signal is maximal at H near zero. White noise with zero correlation has H = 0.5. Smoother correlated signals have H near 1.0. For one-dimensional series, H = 2 - D, where D is the fractal dimension, 1<D<2.

Standard deviation (SD) = $$\frac{\sum_{i=1}^{n}\left(x_i - \bar{x}\right)^2}{N}$$

Where, x_i = Random variable, $\bar{x}$ = Mean of the variables
N= Number of Samples.

By calculating the RD for different bin sizes, n and fitting the square law function:

$$RD = RD_0\left(\frac{n^{H-1}}{n_0}\right)$$

Where, RD_0 is the RD for some reference bin size n_0.

The whole data set is used for each calculation of RD (n) at each level of resolution or number of pieces, n. The exponent can be best estimated by a log-log transformation.

$$\log(RD) = \log(RD_0) + (H-1)\log\left(\frac{n}{n_0}\right)$$

Here, H-1 = slope, for fractal dimension, D=2-H

$$D = 2 - (1 + Slope)$$

So, $D = 1 - Slope$

2.2 Power Spectral density

The power spectrum (the square of the amplitude from the Fourier transform) of a pure fractional Brownian motion is known to be described by a power law function:

$$|A|^2 = \frac{1}{f^{\beta}}$$

Where |A| is the magnitude of the spectral density at frequency f, with an exponent equal to $\beta = 2H + 1$.. Here again, a straight line is fitted from a log-log plot, and H is calculated from the slope β. In the frequency domain, fractal time series exhibit power law properties:

$$P(f) = f^{-\alpha}$$

Where P (f) is the power spectral density f and the exponent α is the so called power-spectral index. For the values region between FD = 1 and FD = 2 the following relationship between FD and α is valid,

$$FD = \frac{(5-\alpha)}{2}, \text{ for } 1 < FD < 2$$

Fractal dimension, $D = \frac{(5 - Slope)}{2}$

2.3 Rescaled Range analysis

The basis of the rescaled range analysis was laid by Hurst [2]. Mandelbrot and Wallis examined and further elaborated the method. Feder [9] gives an overview of theory and applications, and adds some more statistical experiments. There are two factors used in this analysis: firstly the range R, this is the difference between the minimum and maximum 'accumulated' values or cumulative sum of $X(t,\tau)$ of the natural phenomenon at discrete integer-valued time t over a time span τ and secondly the standard deviation S, estimated from the observed values $X_i(t)$. Hurst found that the ratio R/S is very well described for a large number of natural phenomena by the following empirical relation

$$\frac{R(\tau)}{S(\tau)} \propto \tau^{H}$$

Where τ is the time span, and H the Hurst exponent? The coefficient c was taken equal to 0.5 by Hurst. R and S are defined as

$$R(\tau) = \max_{1\le t\le \tau} X(t,\tau) - \min_{1\le t\le \tau} X(t,\tau)$$

And, $$S(\tau) = \left(\frac{1}{\tau}\sum_{t=1}^{\tau}\left[\xi(t) - \langle\xi\rangle_{\tau}\right]^2\right)^{\frac{1}{2}}$$

Where: $$\langle\xi\rangle_{\tau} = \frac{1}{\tau}\sum_{1}^{\tau}\xi(t)$$

And, $$X(t,\tau) = \sum_{N=1}^{t}\left[\xi(u) - \langle\xi\rangle_{\tau}\right]$$

We calculate the individual calculations for each interval length. A straight line is fitted in the log-log plot:

$$\log\left[\frac{R(\tau)}{S(\tau)}\right] = c + H \log(\tau)$$

Where H = slope. So, Fractal dimension, $D = 2 - H$ or $D = 2 - Slope$.

Variation of FD Range = Max^m Value - Min^m Value

2.4 Poincaré plot analysis

The Poincaré plot is a two-dimensional visualization display of the dynamic properties of a system from a time series [8]. The Poincaré plot was generated as a scatter plot of current instantaneous heart rate (IHR) against the IHR immediately preceding it [10].

In this paper we define the Poincaré plot for a data vector $RR_i = (RR_1, RR_2 \ldots RR_N)$ of length N. First, we define two auxiliary vectors:

$$RR_i^+ = (RR_1, RR_2, \ldots\ldots\ldots, RR_{N-1})$$
$$RR_i^- = (RR_2, RR_3, \ldots\ldots\ldots, RR_N)$$

The Poincaré plot consists of all the ordered pairs:

$$(RR_i^+, RR_i^-), \qquad i = 1 \ldots\ldots N-1.$$

SD1 and SD2 are two standard Poincaré plot descriptors. SD1 is defined as the standard deviation of projection of the Poincaré plot on the line perpendicular to the line of identity (y = –x) while SD2 as that on the line of identity (y = x). We can define SD1 and SD2 as:

$$SD1 = \sqrt{Var(X_1)}$$
$$SD2 = \sqrt{Var(X_2)}$$

Where,

$$X_1 = \frac{(RR_i^+ - RR_i^-)}{\sqrt{2}}$$
$$X_2 = \frac{(RR_i^+ + RR_i^-)}{\sqrt{2}}$$

We define a parameter S which reflects the total variability of the Poincaré plot which is the area of the ellipse S:

$$S = \pi \times SD1 \times SD2$$

3 Result and Discussion

Figures 1, 2 and 3 depict the RD, PSD and RS analysis for data 115 with data length N=4096. RD, PSD and RS parameter were measured for each data set and the range was calculated. Table 1 summarizes the result from RD, PSD and RS for HP and PVC. Here the values of seven data sets (MIT-BIH data set # 115,117,122,100,105,111 and 116) of normal ECG are computed. Same is done for seven data sets (MIT-BIH data set # 119, 208, 221,106,201,210 and 233) of PVC patients. The FD descriptors are analyzed to see if any significant difference is found between HP and PVC data series. Figures 4 and 5 show the Poincaré plot and IHR time series of normal and PVC data sets. Here, the average values of 8 data sets (MIT-BIH data set # 100, 105, 111, 112, 116, 118, 121 and 122) of normal ECG are computed. Same is done for rest 8 data sets (106, 119, 201, 208, 210, 221, 223 and 233) of PVC patients. The SD descriptors are analyzed to see if any significant difference is found between normal and PVC data series. Figure 7, 8, 9, 10, 11 and 12 show the Fractal Dimension with RD, PSD, and RS method for HP and PVC.

From Table 1, it is obvious that there is a clear reduction of FD for RD, PSD and RS in PVC data series. We found a significant difference between the two groups exists. From Table 2, we found different range of RD, PSD and RS for HP and PVC. For RD the range of PVC (1.38-1.51) falls in HP (1.34-1.54). For PSD the range of PVC (1.69-1.74) is lower than HP (1.69-1.90). For RS the range of HP (1.63-1.71) is higher than the ranges of PVC (1.48-1.53). Table 3, signify the FD range variation for different beat type and its difference with different methods. From Table 4, it is obvious that there is a clear reduction of SD1, SD2, Ratio and S in the HP and PVC.

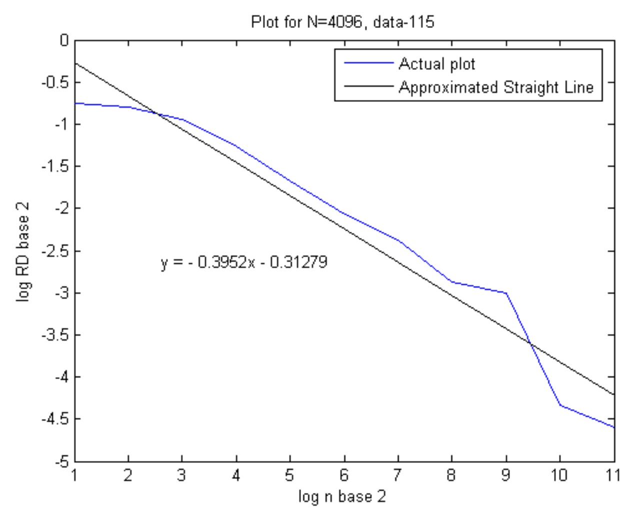

Figure 1: Actual and approximated straight line for RD analysis using N=4096, for data set-115.

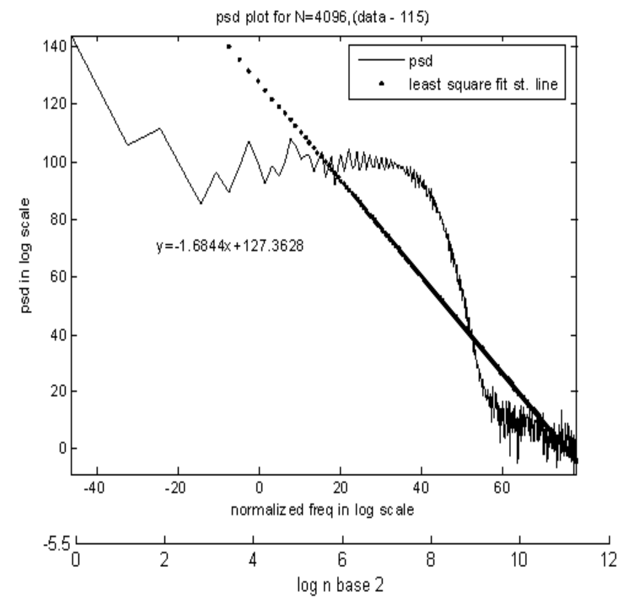

Figure 2: Actual and approximated straight line for PSD analysis using N=4096, for data set-115.

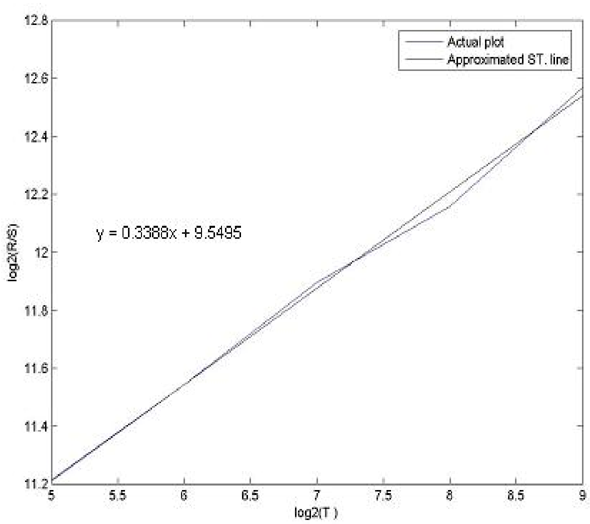

Figure 3: Actual and approximated straight line for RS analysis using 4096, for data set-115

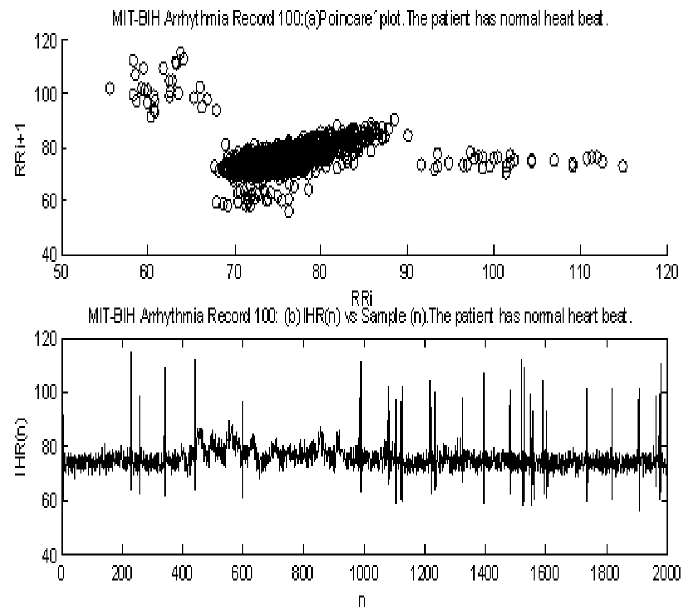

Figure 4: (a) Poincaré plot and (b) IHR of MIT-BIH Record_100: The patient has HP heart beat

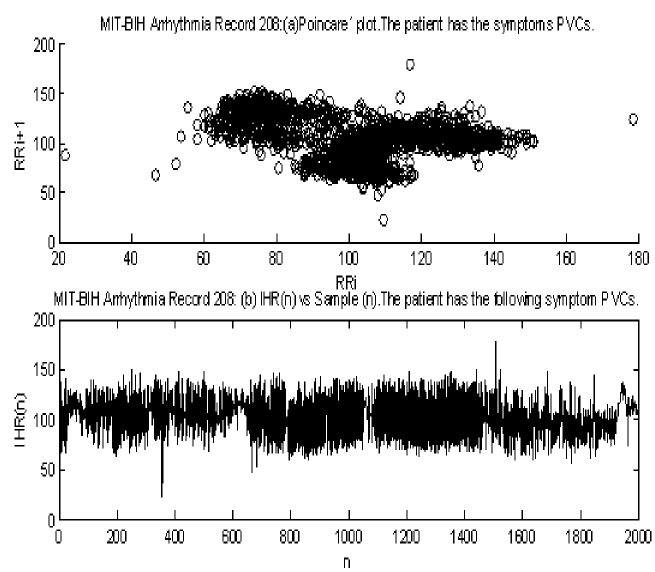

Figure 5: (a) Poincaré plot and (b) IHR of MIT-BIH Record_208. The patient has PVC beats

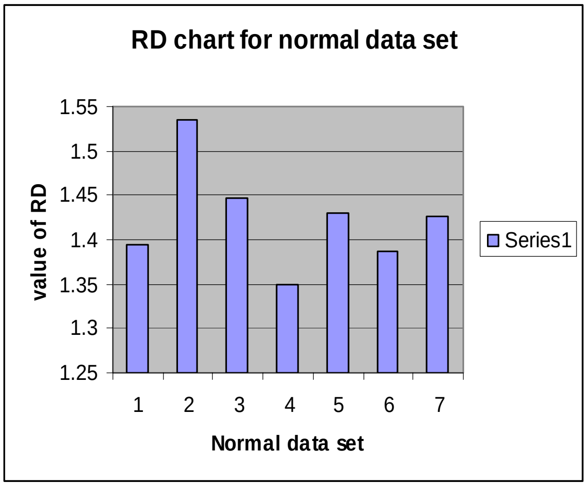

Figure 6: FD with RD method for Healthy Person

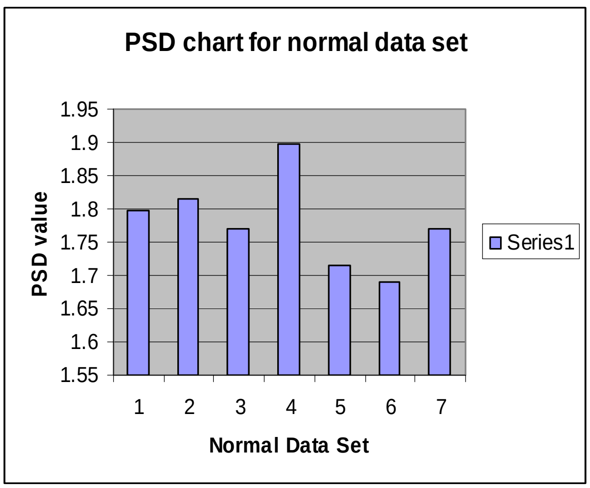

Figure 7: FD with PSD method for Healthy Person.

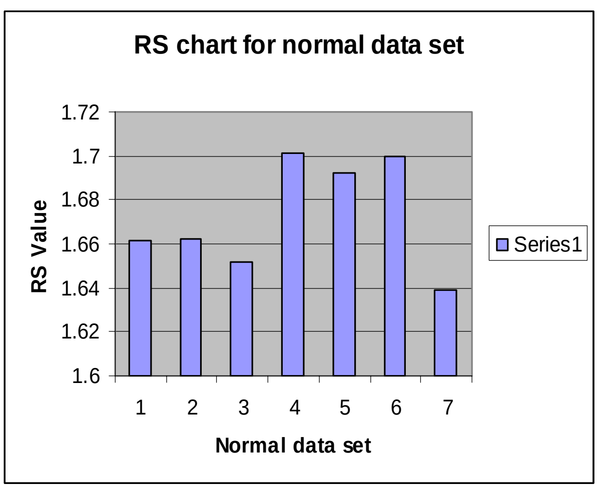

Figure 8: FD with RS method for Healthy Person.

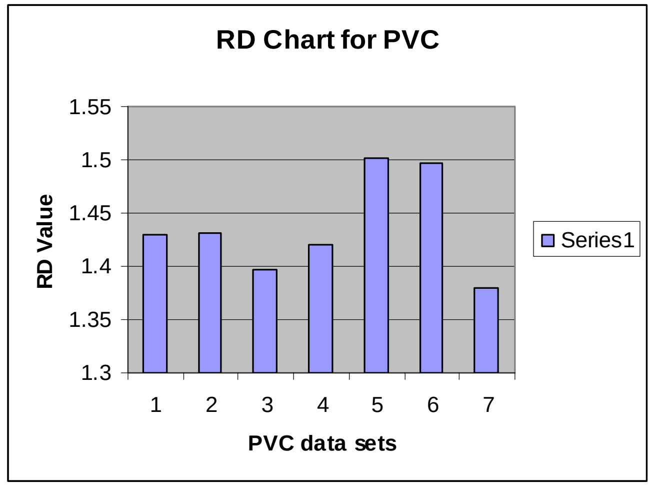

Figure 9: FD with RD method for PVC.

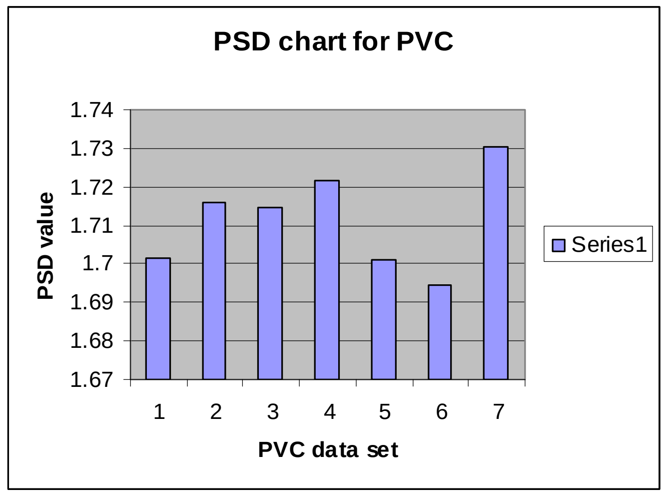

Figure 10: FD with PSD method for PVC

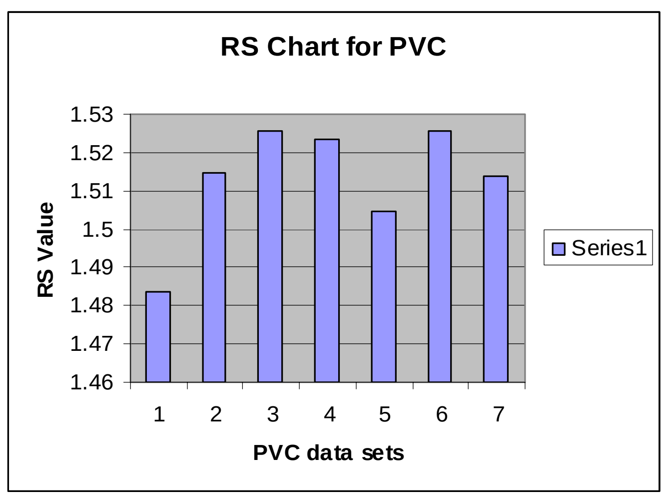

Figure 11: FD with RS method for PVC.

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Table 1: Fractal Dimension of different beat type for different methods when data length N=4096.

Beat Type	Record No	FD for RD	FD for PSD	FD for RS
HP	115	1.3952	1.7965	1.6612
	117	1.5349	1.8148	1.6626
	122	1.4460	1.7704	1.6521
	100	1.3492	1.8975	1.7012
	105	1.4309	1.7142	1.6925
	111	1.3861	1.6905	1.7001
	116	1.4258	1.7709	1.6392
PVC	119	1.4302	1.7015	1.4836
	208	1.4312	1.7159	1.5146
	221	1.3975	1.7147	1.5256
	106	1.4202	1.7215	1.5236
	201	1.5012	1.7009	1.5046
	210	1.4975	1.6947	1.5256
	233	1.3802	1.7305	1.5136

Table 2: Range of FD for different beat type for different method when data length N=4096

Beat Type	FD range for RD	FD range or PSD	FD range for RS
HP	1.34-1.54	1.69-1.90	1.63-1.71
PVC	1.38-1.51	1.69-1.74	1.48-1.53

Table 3: FD range variation for different beat type and its difference with different methods.

Beat Type	FD range Variation for RD	FD range Variation for PSD	FD range Variation for RS
HP	0.186	0.207	0.040
PVC	0.121	0.234	0.042
Difference	0.065	0.027	0.002

Table 4: Average values of Poincaré plot parameters

Parameter	Normal rhythm	PVC
SD1	5.61	24.91
SD2	7.14	20.44
Ratio	0.74	1.31
Area of ellipse(S)	150.48	1607

4 Conclusions

This work describes the application of fractal theory to heart rate dynamics. The fractal dimension for normal hearts as well as hearts with PVC is calculated here. We compared three numerical methods to estimate the fractal dimension. RD analysis provides good result for longer data length, for PSD analysis the range of FD is close to the range of healthy person. Best result is obtained for Weierstrass function using PSD analysis because the range of FD is clearly different from each other but in RD and RS analysis the range of FD has merged for few data series. The Poincare plot analysis to differentiate the normal rhythm from the PVC. Poincare plot can provide supplementary information about beat to beat HRV structure which cannot be obtained by conventional time and frequency domain analysis [13]. Poincaré plot images represent short and long-term variability. The results show that there is a significant difference between the Poincaré plot parameters of normal rhythm data sets and that of PVC data sets. The nonlinear measures can be investigated further in future studies of heart rate variability in different cardiac diseases.

The same methods can be used for analysis of two or three dimensional signals, the methods can be extended to account for anisotropy, making the analysis more complicated but adhering to the same basic theory. A technique of nonlinear analysis, the fractal analysis is most suitable. The fractal analysis can also be applied further in image analysis, fluid dynamics, investing natural phenomenon etc.

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Md. Meganur Rhaman.
Assistant professor in the Department of Electrical and Electronic Engineering (EEE), Ahsanullah University of Science and Technology (AUST). He joined at AUST in October 2005 after completion his BSc. Engg. in (EEE). He has completed his MEngg. From Bangladesh University of Engineering and Technology (BUET). Right now he teaches the courses on Biomedical Engineering, Measurement and Instrumentation, Digital Electronic, Digital Signal Processing, Electrical & Electronic Circuits and Control System.

Md. Rezwan Islam has completed his Bachelor's Degree in Electrical &Electronics Engineering from Ahsanullah University of Science & Technology Dhaka, Bangladesh in 2012. He is currently trying to go abroad for higher study. He has two international journal & one conference paper. His field of interest includes free-space optical communication, different types of turbulence in communication medium, Signal Processing & Biomedical Instrumentation.

Tanzia Afrin Haque received the Bachelor's Degree in Electrical & Electronics Engineering from Ahsanullah University of Science & Technology, Dhaka, Bangladesh in 2012. She is currently trying to go abroad for higher study. She has several publications. Her areas of interest include free-space optical communication, Signal processing and Biomedical Instrumentation.