International Journal of Current Engineering and Technology
E-ISSN 2277 – 4106, P-ISSN 2347 – 5161
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Available at http://inpressco.com/category/ijcet

Research Article

Analyzing Electrocardiography (ECG) Signal using Fractal Method

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Accepted 26 March 2017, Available online 02 April 2017, **Vol.7, No.2 (April 2017)**

Abstract

Background: *Today, the process of ECG signal analysis is one of the most important issues in processing biosignals, which has gained attention of lots of scholars. Increasing enhancement of heart care activities across the world and vast advancements of technology that play key role in diagnosis of diseases by biological signals could be the main cause gained attention of majority of scholars. These signals can have different types. As ECG signals have same morphological features, they are more important than other biological signals. Through processing these morphological changes, lots of heart diseases could be diagnosed visually. Therefore, this study has been conducted with the aim of analyzing ECG signal using fractal method.*
Materials and Methods: *In this study, to analyze ECG signals, fractal features are used. Using fractal features, ECG signals are analyzed and different scale behavior are observed for people with healthy and unhealthy heart. Moreover, fractal features are proved for ECG series. As the method provides a proper diagnosis method for heart diseases, the method is used by specialists to diagnose types of different heart diseases with the accuracy coefficient of 89.33%.*
Results: *The results obtained from the study showed that the proposed method has higher accuracy and speed to diagnose heart diseases compared to old methods including analysis of ECG signals based on morphological features. With the increase in normal rhythms, the correlation dimension is increased. This shows more complex nature of normal rhythms. Hence, it could be used as a criterion to separate normal and abnormal ECG signals.*
Conclusion: *according to obtained results for arrhythmia, in addition to significant correlations, Hurst index, correlation dimension and fractal dimension (FD) could be used as diagnosis instruments for arrhythmia.*

Keywords: *Electrocardiography (ECG) signal, fractal method, heart rate time series*

Introduction

Nowadays, electrocardiography (ECG) process is one of the most important research topics in field of processing biosignals, which has gained attention of many scholars. Growth of heart healthcare activities across the world and increasing advancements of technology that play key role in diagnosing disease by biosignals could be the main causes gaining attention of scholars to this filed. This is because; the analysis process of biosignals is just relied on quality, accuracy and speed. These signals can have different types. As ECG signals have same morphological features, they are more important than other biosignals. Through processing and analyzing these morphological changes, most heart diseases could be diagnosed visually.

The importance of analysis of biological time series that show usually a complicated dynamic has been investigated for many years by nonlinear analysis. Various features are proposed to identify the dynamic features hided from signals. The nonlinear dynamic technique has been used in different fields, especially medicine and biology (M. Raghav, 2010).

In 2004, nonlinear techniques have been used for purpose of analysis of physiological signals: Heart rate, nervous system activity, renal blood flow, blood pressure, EEG and respiratory signals (FH. Netter, 1971).

In order to investigate time-varying features, time-varying analysis is used by common statistical information (A.Vishwa and A. Sharma, 2011). Although such method has not been successful for nonlinear analysis of these signals; fractal analysis used in this study to analyze ECG signals allows processing these signals more effectively and gain regular results and data.

ECG is the process of recording the electrical activity of the heart over a period of time using electrodes placed on the skin. The biological signal is not basically fixed and shows a fractal in self-similar form. Moreover, the signal may be indicator of disease or even warning about impending disease. Such indices may happen most of the times or randomly in time scale. However, analysis of irregular dataset is difficult and time consuming (M. Al-Alfi, 2014).

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As hear is one of the most important body organs and is responsible for pumping blood in cardiovascular system, if heart has gone out of its natural rhythm, blood circulation faces insufficiency and this can result in serious risks for the individuals. Hence, proper and on-time diagnosis of cardiac arrhythmias is very important. One way for on-time diagnosis of these cardiac arrhythmias is analyzing electrical activities of heart using electrocardiography (ECG) signals. Significant changes could be diagnosed from the structure of heart of patients and their heart rates using the ECG signals. The main insufficiencies that are diagnosable by the SCG signals include Tachycardia, Bradycardia, hypertrophy and myocardial infarctions (I. Sedjelmacif, B. Reguig, 2014; H. Namazi and V. Kulish, 2016).

ECG signals refer to recording cardiac electric activity in each contraction and a graphical display of heart rate and a series of initial measurements to diagnose different heart diseases and abnormalities. As ECG signals have same morphological features, they are more important than other biological signals. Through processing and analyzing these morphological features, lots of heart diseases could be diagnosed visually (M. Ashori Rad and R. Baghbani Khezerlu, 2015).

ECG signals play vital role in cardiovascular system and these signals can also be considered as a simple, effective, expanded and economical method to diagnose heart disorders and could be appropriate to affect life of patients. One of the pathologic changes diagnosable by ECG signals is a heart rhythm disorder (arrhythmia). As arrhythmia is a factor threating the life, diagnosis of disorders in patients in ICU is vital. Hence, analysis of ECG signals and diagnosis of abnormalities could be useful and can also help clinical staffs in absence of doctors and can also help doctors in way of diagnosis, decision making and act quickly in an emergency (S. Don, D. Chung, M. Dugki, E. Choi, 2013).

In order to design an intelligent system for diagnosis of cardiac arrhythmias from ECG signals, it is necessary to extract appropriate features of these signals at the first. In different references, various methods have been proposed to extract appropriate features.

Fractal was introduced by Mandelbrot (BB. Mandelbrot, 1982) and provides a novel approach to model the homogenous structures and they could be used widely in different fields like astronomy, medical imaging and signal processing (BB. Mandelbrot, 19829; S. Don, K. Revathy, 2007). Several features of fractal could be derived and one of these features is fractal dimension (FD).

Fractal dimension (FD) could be measured through different methods. The most common and simplest method is box-counting method. In general, a fractal object is self-similar and shows limited change in features with change in scale. West *et al* claimed that heart rate is a time-based fractal (BJ. West *et al*, 1999). Amit *et al* have proposed the nearest classification to local neighbor based on FD to classify arrhythmia. The nearest neighbor is estimated based on –RR distance data, Euclidean distance. The potential of using fractal in analysis of biosignals is still under examination. A few studies have been conducted in this field so far (A. Goldberger *et al*, 1990)

Therefore, this study has been conducted with the purpose of ECG signal processing using fractal method.

Methodology

In this study, fractal features are used to analyze electrocardiography (ECG) signals. Using fractal features, ECG signals are analyzed and processed and different scale behavior is observed for people with healthy heart and the patients with heart disorders. Moreover, fractal features arte proved for ECG series. As the method could provide proper diagnosis model for heart diseases, this method is used by different experts to diagnose types of diseases with accuracy coefficient of 89.33%.

In this study, the proposed methods are used and ECG of 63 people with introduced arrhythmia types (atrial fibrillation (AF); premature ventricular contraction (PVC) and ventricular fibrillation (VF)) and 21 healthy people are analyzed. ECG signals of these people have been mainly selected from the BIH-MIT Arrhythmia Database.

First, these individuals were divided to the age groups of 25-32, 32-39 and 39-46 years old. Using Fractan and MATLAB software for each age group, the values of correlation dimension and Hurst index were estimated. Moreover, Hausdorff dimension values and correlation dimension values were obtained for all participants.

Studied cardiac arrhythmias

In this study, 3 types of arrhythmia are studied. Any kind of disorder in regular heart rate is called arrhythmia. Cardiac arrhythmias can be caused by irregular heartbeat of SA node with additional and abnormal heartbeat of other parts of heart. Arrhythmia types studied in this study include atrial fibrillation (AF), Premature Ventricular Contraction (PVC) and ventricular fibrillation (VF) explained in short as follows:

1. In atrial fibrillation (AF), is heartbeat about 120-170 times per minute. The main features of AF is that P wave is not observed in ECG (figure 1). Different factors such as high blood pressure, heart valve disease or other heart diseases may cause the complication. First, through conducting different examinations, the risk of heart attack is examined. If the problem is rejected, doctors prescribe appropriate drugs.

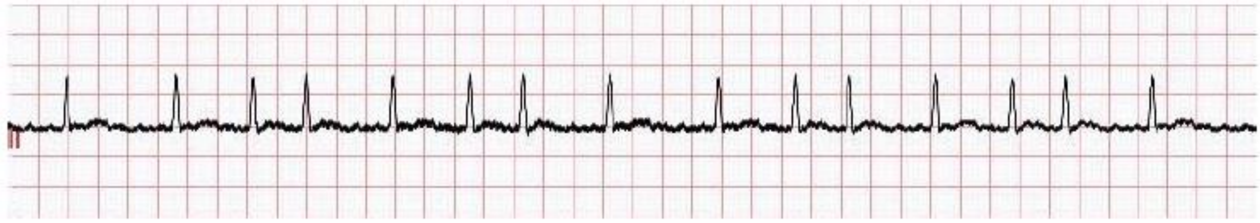

Figure 1: Atrial fibrillation (AF)

Figure 2: Premature ventricular contraction (PVC)

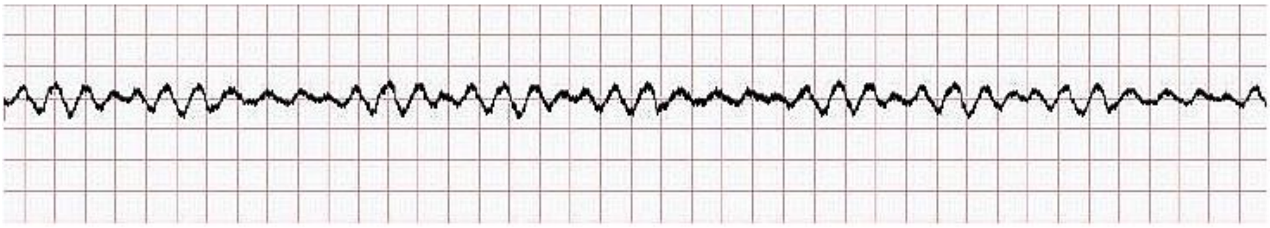

Figure 3: Ventricular fibrillation (VF)

2. Premature ventricular contraction (PVC) is created as a result if depolarization automatically. Under this situation, QRS status lasts more than 0.12s. Moreover, different waves with normalized mode are observed. T and ST waves are in contradiction with QRS wave (figure 2). If the arrhythmia happens once in young people, it would not be significant; although if it happens in the elderly people and the changes are observed several times in ECG signal, further examinations are required to specify the cause.
3. In ventricular fibrillation (VF), heartbeat is intensified and make ST, P and Q waves not be identifiable properly (figure 3). It may happen for different reasons like heart attack, VF and shocks for CPR. However, the arrhythmia is one of the most emergencies and if it is not handled on time, it may cause death.

Fractal

Fractals are used in medicine directly. Because of existence of fractal behavior in the nature of biological systems, cases with no appropriate explanation in Euclidean geometry could be described easily in fractal geometry; such as tissue disease characterized by changes in cell morphology and duration of diabetes. These changes could be observed in microscopic or tiny microscopic scale. Using histological images, effective diagnosis and treatment could be helped. Analysis of these asymmetric images by conventional instruments for histologists is difficult because of their complexity. Fractal can solve this problem through proposing novel measurement methods and appropriate understanding of complexity of form. Moreover, it could be used in many physical and natural problems, which have apparently irregular behavior.

Fractal features

The most important features of fractal include self-similarity and false dimension. The self-similarity features could be observed in a fern leaf (figure 3) (B.B Mandelbrot, 1982). Clearly, each small leaf – a section of larger leaf – has similar features of fern leaf. It could be mentioned that fern leaf is self-similar. Same process is true for fractal. They could be magnified several times and after each step, they would be same and this is one main feature of fractal.

Figure 3: Fern leaf

Explanation of false dimension is difficult. Classic geometry is measures using an instrument and with true dimensions. Next zero points, 1-d curve and lines, 2-D flat images like square and circle and 3-D solids like cube and sphere are shown in the figure (Yu and Guyon, 1997).

Therefore, lots of natural phenomena should be explained in better manner using a dimension between two total values. Hence, a straight line has one dimension (figure 4).

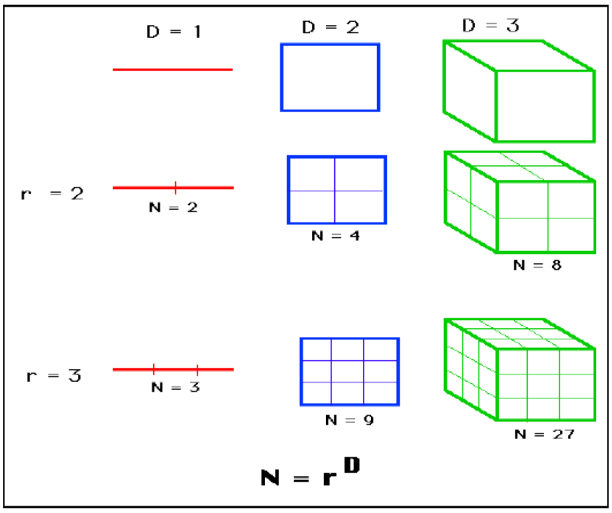

Figure 4: Classic geometric objects

Fractal dimension could be shown with the initial fractal set as follows:

$Nn=C/mD$

Where; Nn refers to number of sections defined with linear dimensions as m; where, C is constant and D defines fractal dimension. If the equation is rewritten using simple algebra, the new form would be as follows:

$$D = \frac{[\ln(N_n + {}^{1}/_{N_n})]}{[\ln(m/m+1)]}$$

According to line length unit, it could be segmented through different methods and different work could be done on each section. For figure 5.a, if the section is divided to two segments, r_1=2.1, where r1 is division length.

One segment is maintained and the other one is excluded, so that N_1= 1. If the remained segment is divided to two segments and again one segment is maintained, then, N_2= 1 and r_2= 1.4. If the process is repeated, D becomes 0 that is an equivalent for Euclidean point. Regardless of number of repetitions, in n step, Nn =1. Hence, D is always equal to 0. The method is acceptable, since if a line is divided to two segments continuously and only one segment is maintained, the segment length reaches to 0 and becomes close to infinity.

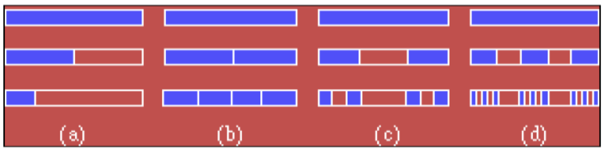

Figure 5: Fractal dimension with Euclidean segment

Euclidean line is at the first dimension shown as a simplest dimension. The example is illustrated in figure 5.b. In this model, the line is again divided to two segments; although all segments are maintained. Hence, r1=1.2 and N1=1. If same process if repeated, r2=1.4 and N2=4. Hence, In(2)/In(2)=1 is also acceptable, since never a segment of line is omitted and the line would always remain with unit length.

In two first examples, the results of two Euclidean images with 0 and 1 dimension are illustrated. However, it is simple to create a line with fractal dimension in range (0, 1). In figure 5.c, the line is divided to 3 different segments and only two segments are maintained. After first iteration, N1=2 and r1=1.3. With repeating the process, N2=4 and r2=1.9. Hence,

$$D = \frac{\ln(2)}{\ln(3)} = 0.6309$$

To show the process of creation of line segments with different fractal dimensions, a segment of length unit is begun and is divided to 5 segments. As it is illustrated in figure 5.d, only two end segments and central segment are maintained: r1=1.5 and N1=3 and repeating the process, r2=1.25 and N2=9 and in this example, D=In(3)/In(5)=0.6826; if the process is repeated, infinite set of points is created called dust.

Extraction of Fractal features from ECG signal

Fractal dimension (FD) is a descriptive scale that is useful in measurement of complexity or self-similarity of biosignals. Analysis of complexity of biosignals helps assessment of physiological processes. Fractal dimension (FD) could be used to analyze dynamicity of exchange of various states of different organs such as heart and under different physiological and pathological conditions (A. Accardo *et al*, 1997). ECG signal of human heart if self-similar and hence, it should have a fractal dimension, so that special states of cardiac pathological conditions could be diagnosed using some mathematical methods. Various methods are provided in the literature to estimate fractal dimension (FD) of signal or time series data in scope of time or frequency.

For purpose of analysis in time scope in the process, signal data are processed directly; although analysis in scope of frequency needs Fourier transform or wavelet signal (HE. Schepers *et al*, 1992).

In this section, time series data are analyzed to estimate FD values of time series signals of ECG based on fractal to extract its main features.

Fractal dimension measurement

The main idea here is time series analysis of heartbeat intervals obtained from ECG with different statues and comparing 3 fractal dimensions for them. First, adjustment of these methods is investigated. At the first, correlation dimension, Hausdorff and counting-box are estimated for sinus wave. Sinus wave has less roughness hence, it is expected that the dimension possess values close to 1 (sinus wave is illustrated in figure 6). In table 4.1, the results obtained from correlation diagrams, Hausdorff dimension and counting-box are presented. According to these results, sinus wave is obtained close to 1 in all methods and this shows suitable adjustment of the proposed methods.

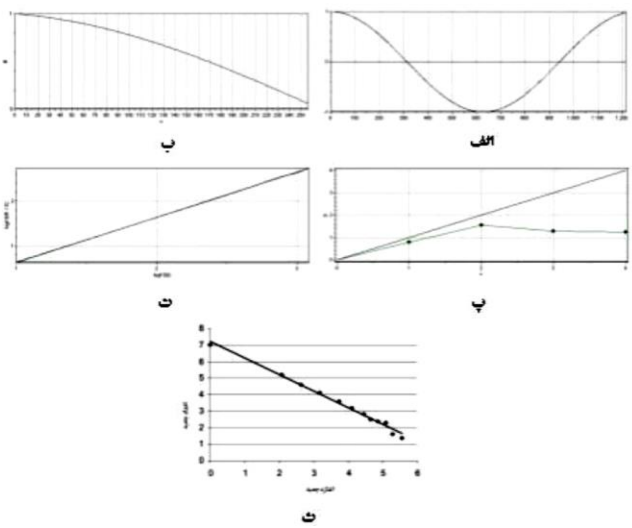

Figure 6: a) sinus wave, b) self-correlation function c) correlation dimension d) Hurst and Hausdorff dimension e) regression line

Heart rate time series

Heart is an organ that is responsible for pumping blood to whole body. This organ contains 4 parts including two atria at the top of the heart and two ventricles the lower part. Heart pumps blood in whole body with the help of periodic contractions. Recording electric potential of heart is called electrocardiography (ECG). Heartbeat identity is depended on the waves appeared in recorded signals including P, Q, R, S and T waves, which could be used to diagnose diseases or categorize heart patients. These waves could be described in this way: P wave refers to depolarization (contraction) of ventricles, QRS wave shows depolarization of atria and T wave shows repolarization (expansion) of atria (N.M Elaine, 1989). Over the years, lots of efforts are taken to determine turbulent nature and irregularity of heart activity using nonlinear system methods. Figure 7 illustrates number of healthy and unhealthy heartbeat.

As it is clear, they have apparently same conditions; although they transfer different data in time series. The statistical data can lead to wrong outputs. However, nonlinear dynamic methods can provide better approaches to analyze signals.

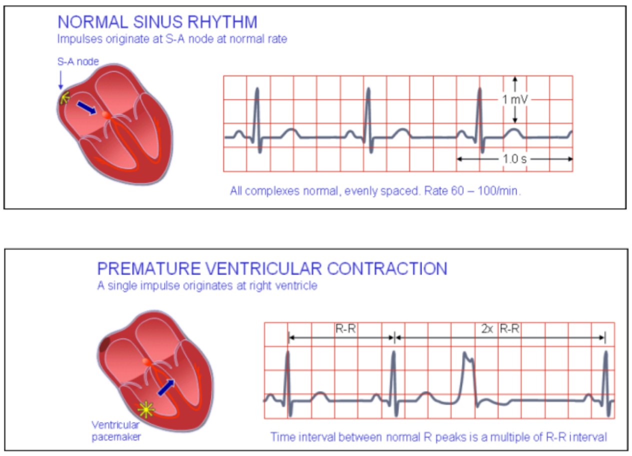

Figure 7: a) time series related to healthy heart rate b) time series of heart with insufficiency

Figure 7 has illustrated number of heartbeats in healthy and unhealthy heart. Clearly, they have almost same appearance, but they transfer different data in time series. The statistical data could lead to wrong outputs. However, nonlinear dynamic methods provide better approaches for analysis of signals. Here, some proposed methods to determine FD for heartbeat are investigated. In statistical analyses, the ECG signal is not used, but also time series of the intervals between heartbeats RR or heart rate HR series is used.

The time intervals between successive pulses measures from electrocardiogram are called RR intervals. The interval is usually measured from the beginning of QRS to the beginning of next QRS. The intervals are called RR contractually regardless of their measurement point. Assume that heartbeat of a person is recorded in times t_1 t 2000 t_{N+1}, RR_i time series is obtained from differentiation of successive times $RR_i = t_{i+1} - t_i$ (figure 8). The time series is analyzed here.

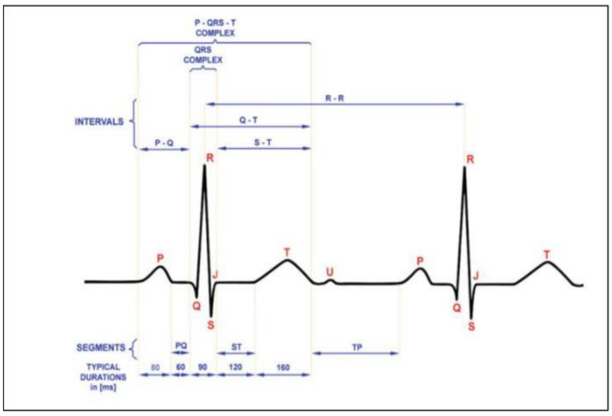

Figure 8: time intervals between pulses

Table 1: Different dimensions for sine wave

counting-box dimension	correlation dimension	Hausdorff dimension
1.009	1.15	0.9887

Calculation and comparison of fractal dimension in different individuals

At the present study, using the proposed methods, ECG of 63 separated individuals with introduced types of arrhythmia (atrial fibrillation (AF); premature ventricular contraction (PVC) and ventricular fibrillation (VF)) and 21 healthy people are analyzed. ECG signals of these people have been mainly selected from the BIH-MIT Arrhythmia Database.

First, these individuals were divided to the age groups of 25-32, 32-39 and 39-46 years old. Using Fractan and MATLAB software for each age group, the values of correlation dimension and Hurst index were estimated and their weighted average is presented in tale 4.2. Moreover, Hausdorff dimension values and correlation dimension values for all participants are respectively presented in tables 20.4 and 21.4. As it is clear, correlation dimension is reduced in case of arrhythmia. The reduction shows reduction of active functional processes in heart while arrhythmia. Moreover, arrhythmia can reduce Hurst index and as a result, due to the equation D= 2-H, it can result in rise of Hausdorff dimension. It is known that if $H < 0.5$, series has long-term memory; meaning that series fluctuations in present time are positively correlated to all fluctuations in future. Stationary processes face less dysfunction compared to non-stationary processes and hence, they are predictable. On the other hand, Hurst value for VF arrhythmia is less than 0.5. This could show risk of the arrhythmia in terms of medicine, since as it was mentioned before, the arrhythmia in most emergency arrhythmia that should be handled urgently.

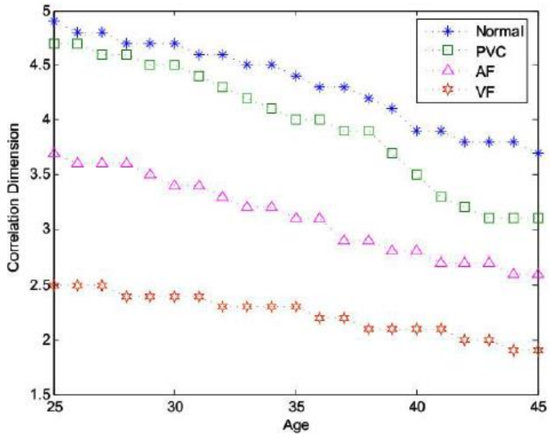

Figure 9: Correlations dimension of various arrhythmias

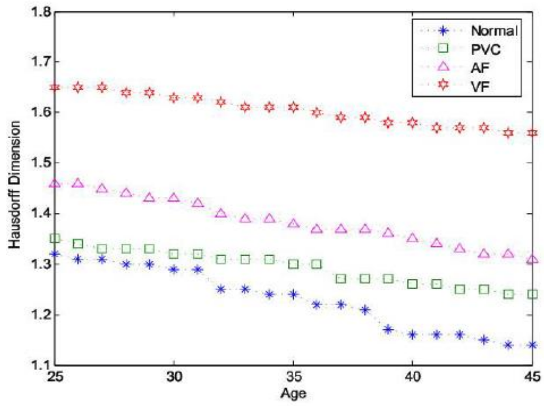

Figure 10: Hausdorff dimension of various arrhythmias

Table 2: Results for the three types of arrhythmia

	Age group	correlation dimension	Hausdorff dimension	Hurest dimension
Normal	32-25	4.74	1.3	0.69
	39-32	4.4	1.23	0.76
	39-46	3.86	1.15	0.84
Premature ventricular contraction (pvc)	32-25	4.57	1.33	0.66
	39-32	4.05	1.29	0.7
	39-46	3.28	1.25	0.74
Atrial fibrillation (af)	32-25	3.54	1.44	0.55
	39-32	3.1	1.38	0.61
	39-46	2.7	1.33	0.68
Ventricular fibrillation (vf))	32-25	2.4	1.64	0.36
	39-32	2.24	1.6	0.39
	39-46	2.01	1.57	0.43

Discussion

In this study, fractal dimension (FD) is estimated for ECG of 63 individuals with 3 types of arrhythmia and 21 healthy individuals in time scope. Then, the FD sequence was specified for healthy individuals and separated individuals with 3 types of arrhythmia. ECG of these individuals was mainly derived from BIH-MIT Arrhythmia Database. The database contains both types of natural and unnatural ECG signals. Unnatural ECG signals are related to people with AF arrhythmia, PVC arrhythmia and VF arrhythmia. Figure 7 has illustrated time series related to electric signals of healthy heart (a) and time series related to electric signals of heart with arrhythmia (b).

Correlation dimension is an index of complexity and number of state variables required to describe a dynamic system. For a turbulent series, correlation dimension should not vary with deformation of time series. With the increased number of normal rhythms, the correlation dimension is also increased. This shows more complicated nature of normal rhythms. Hence, it could be used as an index to separate normal and abnormal ECG signals. According to obtained results, it could be mentioned:

1. With ageing, Hausdorff and correlation dimension is increased; meaning that function of heart of young people is more complicated than old people.
2. During the mentioned arrhythmia types, Hurst index is reduced and hence, Hausdorff dimension is increased and correlation dimension is also declined.
3. If someone is suspected of PVC, due to the age and based on results of measurement of dimensions, the theory could be rejected or confirmed. Correlation and Hausdorff dimension are not normal for young people in case of PVC arrhythmia is not significantly different from normal state.
4. As Hurst index is obtained less than 0.5 with no exception in all age groups in VF arrhythmia, if the ECG of a person has Hurst Index with this feature, the person should be examined urgently regardless of age.

Conclusion

In this study, an exact and rapid method is proposed to analyze ECG signals of healthy people and those with heart disease (patients with 3 types of arrhythmia) using fractal dimension (FD). In the proposed method, first the features of ECG signals of arrhythmia are extracted based on fractal theory and time series methods are used to estimate fractal values for different pathological and normal conditions and finally, different sequence of FD was created for each type of arrhythmia. Such time intervals are used to diagnose healthy people and patients through placement of each of them in sequence of FD.

One advantage of the proposed method is achievement to high accuracy compared to methods used in previous works. The reason for such high accuracy is using special type of features adjusted with analysis instruments.

According to results obtained from arrhythmia, in addition to significant correlations, Hurst index, correlation dimension and Hausdorff dimension could be used as instruments to diagnose arrhythmia. Moreover, using the obtained results, the process of fluctuating series of heartbeat could be predicted due to fractal instrument. The hypothesis could be emphasized as a further research.

Today, the process of ECG signal analysis is one of the most important issues in processing biosignals, which has gained attention of lots of scholars. Increasing enhancement of heart care activities across the world and vast advancements of technology that play key role in diagnosis of diseases by biological signals could be the main cause gained attention of majority of scholars. These signals can have different types. As ECG signals have same morphological features, they are more important than other biological signals. Through processing these morphological changes, lots of heart diseases could be diagnosed visually. Therefore, this study has been conducted with the aim of analyzing ECG signal using fractal method.

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The results obtained from the study showed that the proposed method has higher accuracy and speed to diagnose heart diseases compared to old methods including analysis of ECG signals based on morphological features. With the increase in normal rhythms, the correlation dimension is increased. This shows more complex nature of normal rhythms. Hence, it could be used as a criterion to separate normal and abnormal ECG signals.

According to obtained results for arrhythmia, in addition to significant correlations, Hurst index, correlation dimension and fractal dimension (FD) could be used as diagnosis instruments for arrhythmia.

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