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Can complexity decrease in congestive heart failure?

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HIGHLIGHTS

- We study the complexity in cardiac signals for healthy and heart patients.
- The cardiac dynamics of a healthy person is more complex and stochastic.
- We construct a threshold to distinguish the two dynamics.

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ABSTRACT

The complexity of a signal can be measured by the Recurrence period density entropy (RPDE) from the reconstructed phase space. We have chosen a window based RPDE method for the classification of signals, as RPDE is an average entropic measure of the whole phase space. We have observed the changes in the complexity in cardiac signals of normal healthy person (NHP) and congestive heart failure patients (CHFP). The results show that the cardiac dynamics of a healthy subject is more complex and random compare to the same for a heart failure patient, whose dynamics is more deterministic. We have constructed a general threshold to distinguish the border line between a healthy and a congestive heart failure dynamics. The results may be useful for wide range for physiological and biomedical analysis.

1. Introduction

Human heart reveals electrical discharges from specific localized nodes within the myocardium. These discharges propagate through the cardiac muscles and stimulate contractions in a coordinated manner in order to pump deoxygenated blood via the lungs (for oxygenation) and back into the vascular system. The physical action of human heart is therefore induced by a local periodic electrical stimulation. As a result of that, a change in potential can be measured during the cardiac cycle by electrodes which are attached to the upper torso of heart (usually both side of the heart). This recorded signal is known as electrocardiogram (ECG) [1]. A typical ECG waveform, consists of P, Q, R, S, T, U & V as major components,

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reveals definite pattern in the oscillation. However, different pattern can be observed due to changes of heart condition. The increasing and decreasing mechanical activities are the major causes for this complex phenomena in heart dynamics [2]. This paper studies the complexity of ECG signal of NHP and CHFP by using the method of phase space analysis.

Phase space analysis is one of the most useful methods for explanation of long term dynamics. It is an abstract Euclidean space that reflects asymptotic nature of the interconnected variables which are responsible for the original dynamics [3–5]. The number of such variables is known as Embedding dimension [4] in which trajectory of the phase space can be flourished properly. For a continuous signal, reconstruction of phase space can be done by suitable time-delay and proper embedding dimension [6]. Suitable time-delay is generally obtained by the method of Average Mutual Information [7,8] and proper embedding dimension is obtained by method of False nearest neighbor [9–11]. However, different types of trajectory's movements have been observed in the phase space, viz; periodic, quasi-periodic, chaotic, etc., which can be described from Recurrence plot (RP) [12–16].

Recurrence plot is a diagrammatic representation of a 2D matrix, whose elements are considered 1 if it is recurrent; otherwise it is considered 0. 1 and 0 are represented by black and white dots respectively in RP. RP quantifies the structure of the phase space; it does not have anything to do directly with the signals. The diagonal lines in RP are used to measure the complexity [13]. But those lines reflects the parallel movements of the trajectories, which explain the deterministic nature of the system [13]. So measuring complexity using diagonal lines in RP characterizes the degree of chaos present in the phase space dynamics. Recently, another measure of complexity with a different form of recurrence have been proposed in Ref. [17], which quantifies the presence of non-deterministic term in stochastic dynamics. So far, there is no particularly effective tool to quantify the complexity of a stochastic signal. Therefore, to investigate this type of complexity, we have implemented recurrence period density (RPD) method of Ref. [18].

RPD is a probability measure which calculates density of the recurrent times. In RP, recurrent times are considered as length of white horizontal/vertical lines between each pair of recurrent points. It can be observed that, a system possesses more complex dynamics if length of the white lines varies frequently in RP. Consequently, variation of recurrent times becomes very high. Thus, probability of recurrent times reveals a proper justification to identify the complex dynamics. The quantification parameters recurrence period density entropy (RPDE) measures complexity of such dynamics. In this concern, Shanon entropy is utilized by probability density of recurrent times. So far, the analysis of complexity was done with respect to the corresponding time series only [19–21], which does not predict the long-term behavior of the dynamics. So, to investigate the long-term behavior, it is important to study complexity of the phase space for more accurate prediction.

It is well known that a deterministic system is a model, which always produces the same output for a particular initial state. Any ODE system (autonomous/non-autonomous) $\frac{dX}{dt} = F(X, t)$ is deterministic by nature and can produce chaotic scenario with proper conditions. The most important point is, there are non-deterministic (random/stochastic) systems, generated by differential equations, produce chaos. For example, the additive noise term (ξ) with a deterministic model $\frac{dX}{dt} = F(X, t) + \xi(t)$ can make the whole system non-deterministic [22], as the same initial condition does not give same output. In fact, this is an example of a non-deterministic system produces stochastic chaos. This kind of chaos can be observed in Ecological models, Lasers [23–25] and other semiconductor devices. In many cases noise can increase the nature of the complexity of the system, sometimes it may be useful to decrease chaos [26] to revert back the system to a regular state. Although, a noisy signal or a purely stochastic signal does not have any determinism and can be investigated properly by using the corresponding time series, sometimes the non-deterministic outputs can also be generated by the governing equations. Noise induced (also added) chaos are very interesting to investigate, due to its rich complexity and non-deterministic nature. Recently there are research on noise induced synchronization and also chaos synchronization between stochastic models. Even the Chua system can be stochastic [27] with induced noise, studied both theoretically and experimental observations. In this article, we have proposed the dynamical complexity of some known nonlinear deterministic and stochastic systems as well as power noise by RPDE analysis. Further, by defining window Normalized Recurrence period density entropy (NRPDE), we have categorized ECG of NHP and CHFP into two classes. In fact, mean window NRPDE successfully distinguishes both types of ECG in term of complexity. Further, a proper threshold can be found in the mean window NRPDE by which we can conclude that whether a NHP becomes CHFP or not.

2. Recurrence plot and recurrence period density

For a n-dimensional phase space $X = \{(x_i) : x_i \in \Re^n,\ i = 1, 2, \ldots, N\}$, recurrence means closeness of any two points. Two points are considered close if their state vectors certainly lie in a ϵ-neighborhood. Formally, two points $x_i, x_j \in X$, $i = 1, 2, \ldots, N$ are recurrent if $\|x_i - x_j\| < \epsilon$. The recurrent matrix is thus defined as

$$R_{i,j} = \Theta(\epsilon - \|x_i - x_j\|), \quad i = 1, 2, \ldots, N, \tag{1}$$

where Θ is the Heaviside function, $\|.\|$ is Euclidean norm of the reconstructed phase space, and ϵ is radius of the neighborhood. RP corresponds recurrent and non-recurrent point by '1' (black dots) and '0' (white dots) respectively. Phase space is reconstructed by suitable time-delay (τ) and proper embedding dimension (m). An m-dimensional reconstructed phase space is given by

$$\{(u_i, u_{i+\tau}, u_{i+2\tau}, \ldots., u_{i+(m-1)\tau})\}. \tag{2}$$