A Chaotic Model for Generating Heart Rate Variability Signal Using Integral Pulse Frequency Modulation

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Abstract

Heart rate variability (HRV) is a very useful signal to investigate the activity of the autonomic nervous system (ANS), which affects and the heart function. Constructing a mathematical model for producing artificial HRV signal is needed to get a conceptual understanding of how ANS controls the heart rate (HR). The integral pulse frequency modulation (IPFM) structure is employed in this paper to model the sino-atrial node (SAN). Considering the complexity and nonlinear dynamics in the real HRV signal, a chaotic input is used in the proposed model. Instead of using a fixed threshold in IPFM model as in most previous works, we applied an appropriate variable signal, which has nonlinear chaotic dynamics. After running the model, the power spectrum of the output signal is extracted, which was then followed by calculating the nonlinear characteristics. The results were closely correlated with the real data, which confirm the effectiveness of the proposed model.

1. Introduction

Heart rate variability (HRV) analysis is a very useful tool for investigation of autonomic nervous system (ANS) activities. Several known and unknown items effect on HRV, such as: respiratory sinus arrhythmia (RSA), blood pressure (Mayer waves), mental and physical activities, drugs, gender, age, sleep, etc [1].

Therefore, the HRV is more complicated than we think and should be taken into account as a chaotic phenomenon. ANS as a part of central nervous system (CNS) is composed of two subsystems, sympathetic and parasympathetic (vagal) components.

Sympathetic stimulation, which occurs in response to stress, causes an increase in heart rate (HR) by increasing the firing rate of pacemaker cells in the heart's sino-atrial (SA) node [1]. Parasympathetic control, occurring in relaxation, decreases the firing rate of pacemaker cells and consequently the HR.

The integral pulse frequency modulation (IPFM) model that firstly developed by Hyndman and Mohn [2], is a simple and considerably efficient representation of SA node. In other words, it is an artificial pacemaker that can be used for generating HRV signal.

Constructing a mathematical model for producing artificial HRV signal is needed to get a conceptual understanding of how ANS controls the heart rate. In addition, an accurate HRV model can be used to drive an Electrocardiogram (ECG) model for producing artificial ECG signal. Moreover, this model could be the base of new generation of artificial heart pacemakers for cardiac patients.

2. Materials and methods

The IPFM model gets a continuous input and converts it to a time series as a discrete output. This model integrates the input signal while it reaches to a certain threshold. Later it generates a pulse as a heartbeat. The integrator resets to zero, afterwards, and this sequence continues to produce a pulse train [3].

The IPFM model has three separate inputs that consist of sympathetic and parasympathetic input $m(t)$, intrinsic input m_0 and threshold Th, and also one output that is $s(t)$, all are shown in Figure 1.

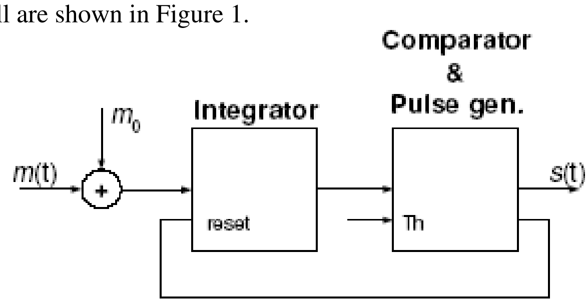

Figure 1. IPFM model block diagram

The model's mathematical representation could be written as follows:

$$s(t) = \sum_k \delta(t - t_k)$$

$$Th = \int_{t_k}^{t_{k+1}} (m_0 + m(t))dt.$$

Where t_k is the instance of k^{th} heartbeat and $m_0+m(t)$ should have positive value.

In proposed model, the $m(t)$ as sympathovagal effects, is set to a sinusoidal wave with variable parameters. The intrinsic input m_0, which comes from inherent properties of SA node cells and causes fixed rate heartbeats, is set to a constant value.

For setting the threshold in proposed model, three states were considered. The first state is the fixed threshold, which *Th* is set to a constant value. This state is the simplest model. The second state is the stochastic threshold, which *Th* is set to a random function. In this state the Gaussian noise was used. Eventually, the third state is the chaotic threshold, which *Th* is set to some nonlinear functions. These functions are: Feigenbaum function, Logistic Map function and Lorenz Equations, which all imply to different chaotic systems with nonlinear dynamics.

3. Results

The proposed model implemented in three threshold states separately. After running the model, the output signal and its power spectrum is extracted for each state, which was then followed by calculating the nonlinear characteristics. The nonlinear parameters of output signal, such as Lyapunov exponent, correlation dimension and information dimension, were calculated.

In order to comparing the three proposed states results with reality and validation of the proposed model, a real HRV signal database belonged to a normal individual was analyzed, its power spectrum and nonlinear parameter determined.

4. Discussion and conclusion

Considering the model's simulation results for the three distinct states of threshold function, walking from constant threshold to stochastic one and then getting to chaotic space, observed that the model goes into more compliance with reality. This means that the third state is in accordance with the real HRV, more than the two other states.

It showed that the calculated power spectrum and the nonlinear parameters of the output artificial HRV signal are closely correlated with the real ones, when the threshold function has chaotic properties, which confirms the effectiveness of the third state proposed model.

Of course, the ultimate result was predictable, because the complexity and nonlinear dynamics of heart rate variability is just depicting well by such chaotic model.

The future work will be concerned with manipulation of sympathovagal effects input functions and take the model toward more nonlinearity to get the better image of reality.

References

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