Medical Engineering & Physics 36 (2014) 1693–1698

Contents lists available at ScienceDirect

Medical Engineering & Physics

journal homepage: www.elsevier.com/locate/medengphy

Technical note

A multi-scale feedback ratio analysis of heartbeat interval series in healthy vs. cardiac patients

Chengyu Huo [a,b], Xiaolin Huang [a,*], Huangjing Ni [a], Hongxing Liu [a], Chunhua Bian [a], Xinbao Ning [a,*]

[a] Institute of Biomedical Electronic Engineering, School of Electronic Science and Engineering, Nanjing University, Nanjing 210093, China
[b] School of Physics and Electronic Engineering, Changshu Institute of Technology, Changshu 215500, China

ARTICLE INFO

Article history:
Received 27 July 2013
Received in revised form 22 August 2014
Accepted 25 September 2014

Keywords:
Second-order difference plot
Heart rate variability
Multi-scale
Feedback ratio

ABSTRACT

The second-order difference plot, as a modified Poincaré plot, is one of the important approaches for assessing the dynamics of heart rate variability. However, corresponding quantitative analysis methods are relatively limited. Based on the second-order difference plot, we propose a novel method, called the multi-scale feedback ratio analysis, which can measure the feedback properties of heart rate fluctuations on different temporal scales. The index $\bar{R}_{TF}^{[\tau_1,\tau_2]}$ is then defined to quantify the average feedback ratio through a definite scale range. Analysis of Gaussian white, 1/*f* and Brownian noises show that the feedback ratios are indeed on different levels. The method is then applied to heartbeat interval series derived from healthy subjects, subjects with congestive heart failure and subjects with atrial fibrillation. Results show that, for all groups, the feedback ratios vary with increasing time scales, and gradually reach relatively stable states. The $\bar{R}_{TF}^{[10,20]}$ values of the three groups are significantly different. Thus, $\bar{R}_{TF}^{[10,20]}$ becomes an effective parameter for distinguishing healthy and pathologic states. In addition, $\bar{R}_{TF}^{[10,20]}$ for healthy, congestive failure and atrial fibrillation subjects are close to those of the 1/*f*, Brownian and white noises respectively, indicating different intrinsic dynamics.

1. Introduction

The Poincaré plot is the classic method for qualitative and quantitative study of chaotic phenomena. A standard Poincaré plot of the heart rate is a scatter plot of the current RR interval (successive R peaks interval in the electrocardiogram) against the RR interval immediately following [1]. It has been reported to have the ability to reveal patterns of heart rate dynamics resulting from nonlinear processes that are not readily available from a conventional time-domain or frequency-domain analysis [2–4], and thus has been extensively used for the assessment of the dynamics of heart rate variability (HRV) [2,5–9]. However, because the instantaneous heart rate is mainly concerned, the standard Poincaré plot of the heart rate contains much redundant information specifically of linear correlation, which complicates the extraction of nonlinear features. As an improvement, a modified Poincaré plot, named the second-order difference plot [10–12], is also used. It is a scatter plot of the current ΔRR interval (difference of successive RR intervals) against the ΔRR interval immediately following. It has four quadrants (shown in Fig. 1), and accordingly, four patterns can be identified: +/+ (quadrant I; a lengthening-sequence, cardiac deceleration), −/+ or +/− (quadrant II or IV, respectively; balanced sequences), and finally −/− (quadrant III; a shortening-sequence, cardiac acceleration) [13]. This plot removes the dominant characteristics apparent in the Poincaré plot, namely the high correlation between consecutive intervals, and highlights the correlation of variability between consecutive rate values [13,14], i.e., it measures the change of heart rates of three successive heart beats rather than an instantaneous heart rate. In addition, as a result of the differential process involved in the plot construction, the interference caused by the nonstationarity of the original physiologic series will be significantly reduced. Consequently, it may be more conducive to find the intrinsic mechanism of the cardiac dynamic system. Besides, the second-order difference plot is easy to construct and understand. For some indices in the standard Poincaré plot, the definitions can be greatly simplified if the second-order difference plot is taken, e.g. the clouds I, D, and N in [7].

Some indices have been proposed as quantitative analysis of the second-order difference plot, such as the central tendency measure (CTM) [10,12] and the distribution entropy (DE) [15]. Overall, related reports are limited. And the current methods require either

* Corresponding authors. Tel.: +86 15951802029.
E-mail addresses: xlhuang@nju.edu.cn, huang_xiaolin@163.com (X. Huang), xbning@nju.edu.cn (X. Ning).

http://dx.doi.org/10.1016/j.medengphy.2014.09.015
1350-4533/

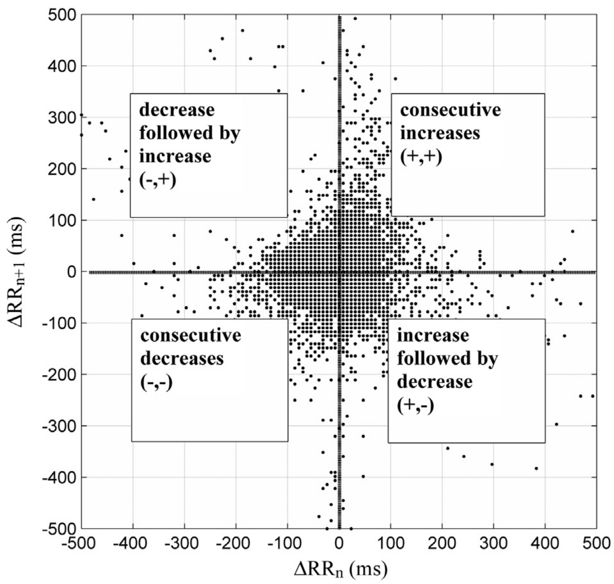

Fig. 1. An illustration of the second-order difference plot. In this example, the original RR series is from a healthy subject in MIT-BIH Normal Sinus Rhythm Database (record no. 16539, female, 35 years old). The differential sequence of the RR series is defined as ΔRR_n, and the scatter points are plotted with coordinates (ΔRR_n, ΔRR_{n+1}) in the two-dimensional plane. Thus, the plot is divided into four quadrants, marked as I, II, III and IV, respectively. The notations in each of the quadrants explain the changes in sign sequences represented by each quadrant.

a very long data length, or relatively complex calculation, which is not very suitable for real time monitoring application.

In this study, motivated by the descriptions of quadrant II and IV patterns and quadrant I and III patterns as previously reported [13,14], we propose a new method, named the feedback ratio analysis. In addition, it has been realized that heart rates are regulated by various mechanisms, ranging from subcellular to systemic levels, and multiple feedback loops incorporating different delays. Consequently, the heartbeat interval time series (RR interval series) should exhibit various dynamic characteristics over multiple time scales [16,17]. For these reasons, we further propose a multi-scale analysis of the feedback ratio. This method is then applied to simulated noises and heartbeat interval series from healthy and pathologic subjects.

2. Methods

2.1. Feedback ratio analysis

In the second-order difference plot shown in Fig. 1, the heart rate variation mode represented by quadrants I and III can be summarized as follows: the changes will be followed by changes in the same direction (continuous acceleration or deceleration of the heart rate), which is similar to a certain positive feedback effect. Under this effect, the RR interval (or heart rate) will tend to deviate from the original state. For quadrants II and IV, the heart rate variation mode can be summarized as follows: the changes will be followed by changes in the opposite direction, so that accelerations and decelerations alternate in time, which is similar to a certain negative feedback effect. Under this effect, the RR interval will be dragged back and tend to oscillate.

In a dynamic system, if the positive feedback mechanism is absolutely dominant, the system will be divergent and there will be no attractors; on the contrary, if the negative feedback mechanism is absolutely dominant, the system will tend to be constant or periodic. The cardiac dynamic system, as a typical dissipative system far from equilibrium, contains both positive feedback and negative feedback effects. Therefore, to summarize the general feedback characteristics and to show the overall tendency, we defined a general parameter, named total feedback ratio, R_{TF}:

$$R_{TF} = \frac{N_{I} + N_{III}}{N_{II} + N_{IV}} \quad (1)$$

where N_I, N_{II}, N_{III} and N_{IV} represent the number of points in quadrants I, II, III and IV, respectively.

2.2. Multi-scale feedback ratio analysis

Further, we used a multi-scale analysis based on coarse-graining the original time series on multiple temporal scales. Given the original heartbeat interval time series of length N as $\{r_i\}$ ($i = 1, 2, 3, \ldots, N$), the consecutive coarse-grained time series $\{x_j\}$ is constructed as:

$$x_j^{(\tau)} = \frac{1}{\tau} \sum_{i=(j-1)\tau+1}^{j\tau} r_i, \quad 1 \le j \le \frac{N}{\tau} \quad (2)$$

where the integer τ represents the coarse-graining scale factor. The length of $\{x_j^{(\tau)}\}$ is equal to the length of the original time series divided by the scale factor τ [18]. Then, the corresponding differential series of $\{x_j^{(\tau)}\}$ can be calculated as:

$$y_k^{(\tau)} = x_{k+1}^{(\tau)} - x_k^{(\tau)}, \quad 1 \le k \le \frac{N}{\tau} - 1 \quad (3)$$

Finally, the second-order difference plots for each coarse-grained time series are plotted based on $\{y_k^{(\tau)}\}$ and the R_{TF} values are calculated as functions of the scale factor τ.

For the selection of τ, we just followed Costa et al. [18] and set the scale factor in the range of 1–20. In fact, this range comprises both "large" and "small" time scales compared to a typical respiratory cycle length, which is approximately five cardiac beats [18]. A larger τ (greater than 20) is theoretically feasible; however, to guarantee the statistical effectiveness, it will raise the demand for a longer data length, which is hard to acquire, especially for a cardiac rhythm series.

Furthermore, for an integrated quantitative description, the mean R_{TF} over a defined scale range [τ_1, τ_2] is considered and designated as $\bar{R}_{TF}^{[\tau_1,\tau_2]}$:

$$\bar{R}_{TF}^{[\tau_1,\tau_2]} = \frac{1}{\tau_2 - \tau_1 + 1} \sum_{\tau=\tau_1}^{\tau_2} R_{TF}^{(\tau)} \quad (4)$$

where $R_{TF}^{(\tau)}$ represents the R_{TF} value corresponding to a specific scale τ.

2.3. Demands for the data length N

For stationary ergodic processes, it is suggested that the sample size should be far greater than the number of available states for statistic validity. Although the cardiac rhythm is not usually stationary, the differential process can largely remove the non-stationary trend, so that the above principle can still be applicable. For this method, there are only two states of adjacent heartbeat interval variability: monotonic variation and alternative variation. Thus, theoretically, dozens of scatter points (e.g., 50 points) in the second-order difference plot will be sufficient. That is, when the largest τ is set to 20, N should be at least set to $20 \times 50 = 1000$. Additionally, a better statistical effectiveness may be achieved when a larger N is selected.