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The Continuous Time Dynamical Analysis of Heart Rate Asymmetry

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Abstract. Heart rate asymmetry (HRA) can investigate the asymmetric characteristics that cannot be analyzed by traditional heart rate variability (HRV). The asymmetric pattern of heart rate acceleration and deceleration can be described by the projection of RR interval (RRI) series on the Poincaré plot. In this study, two new asymmetric variables of HRA are proposed. By using the moving window method, the dynamical analysis of HRA can be illustrated on the time series diagram. Two kinds of physiological experiments and an artificial chaotic RRI system are evaluated. The binomial experimental results (p-value: 0.004) verify that the proposed method can quickly and effectively respond to the HRA.

Keywords. Heart rate asymmetry, HRV, artificial chaos system, Poincaré plot

1. Introduction

Heart rate variability (HRV) is used to measure the variation of RR interval (RRI) of ECG. Previous studies proved that HRV can investigate the sympathetic-parasympathetic system and autonomic activity [1]. Recently, some new methods of HRV have been proposed to extract the asymmetrical information of heart rate acceleration and deceleration. By using Poincaré plot geometry, Heart rate asymmetry (HRA) can evaluate the asymmetrical energy distribution of heart rate acceleration and deceleration [2].

In [3], the authors consider the geometric distribution of the Poincaré plot of HRA. Two characteristic variables $\mathrm{SD1}_{up}$ and $\mathrm{SD1}_{down}$ are defined. The variables of HRA can correspond to the deceleration and acceleration variance of short-term HRV, respectively. The results of ECG experiments validated that the healthy adults existed a statistically significant asymmetry in heart rate. Furthermore, the authors introduced two long-term characteristic variables: $\mathrm{SD2}_{up}$ and $\mathrm{SD2}_{down}$. The experimental results showed that 76% of the subjects had long-term HRA [4].

The long-term correlation of bio-signals can be evaluated by Detrended Fluctuation Analysis (DFA). J. Piskorski proposed the Asymmetric Detrended fluctuation Analysis (ADFA) method and found that RRI had the global and local asymmetry scaling exponents. In addition, when the artificial synthetic signal is added with asymmetric noise, the asymmetric phenomenon can be observed by using ADFA [5].

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The bio-signal data analysis is a critical and useful method, especially for epidemic prevention and control [6, 7]. The previous studies validated that HRA can be used to evaluate the activities of the cardiovascular system [8, 9]. However, the previous study only discussed HRA on a fixed time scale. More exploratory and practical studies are needed to investigate the dynamic variation of HRA.

The motivation of this study includes three parts:

1. Design the binomial hypotheses experiment and evaluate HRA asymmetrical characteristics on the Poincaré plot.
2. By using the moving window method, observe and validate that the proposed asymmetric variables can reflect the dynamic variation of HRA.
3. Design an artificial chaotic RRI system and investigate whether the artificial RRI series has the same asymmetric characteristics as the real RRI series.

2. Experimental Method

When the RRI series is in a stable condition, the projection of RRI series on the Poincaré plot must be around a fixed attractor. The two energy variables (i.e. $\mathrm{SD1}_{up}^2$ and $\mathrm{SD1}_{down}^2$) can correspond to the variances of HR deceleration and acceleration, respectively. Furthermore, the asymmetry of HRA can be expressed that the variance of RRI series is not a normal distribution.

Poincaré plot is a nonlinear dynamic method to describe the variation of RRI series. Each RRI pair (i.e. RR n, RR n+1) can be marked on a two-dimensional phase space coordinate. On the plot, the standard deviation of the distance between each RRI pair to the straight line (L1): y = x and (L2): y = -x is defined as $SD1^2$, $SD2^2$, respectively (Fig. 1). $SD1^2$ corresponds to rapid variability and $SD2^2$ corresponds to long-term variability. The detailed quantitative method of HRA can be referred to [3].

In Fig. 1, with line L1 as the boundary, the RRI points falling above L1 are classified as $\mathrm{SD1}_{up}^2$ area, representing the time of the next RRI becoming longer (i.e. the heart rate becomes slower). On the other hand, the points falling below L1 are classified as $\mathrm{SD1}_{down}^2$ area, representing that the heart rate becomes faster. For healthy physiology, the heart rate always maintains at a stable interval. When RRI series are projected to the phase space plane, the statistics distributed in the up area seem should be consistent with that of the down area. In this study, the Binomial test is used to evaluate the asymmetric probability distribution on the Poincaré plot.

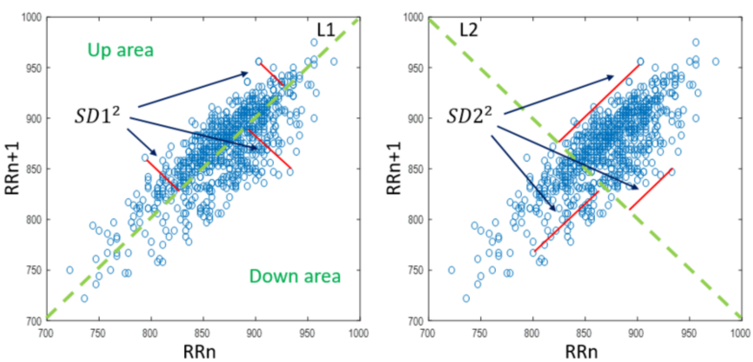


Figure 1. The projection of RRI series on the Poincaré plot.

2.1. Binomial Hypothesis of Heart Rate Asymmetry

Twenty-two healthy adults (21 males and 1 female, aged from 21 to 45 years) were measured by electrocardiography (ECG) in sitting posture for 5 minutes. After the automatic R wave detection process, the 300 RRI pairs were extracted from each subject's ECG. The RRI series were drawn on the Poincaré plot. The energy index ($\mathrm{SD1}_{up}^2$ and $\mathrm{SD1}_{down}^2$) were calculated, respectively.

Under the assumption of normal distribution and no interpersonal difference, half of the subjects should have $\mathrm{SD1}_{up}^2 < \mathrm{SD1}_{down}^2$ and vice versa. Therefore, the sample proportion P (i.e. the subjects with $\mathrm{SD1}_{up}^2 < \mathrm{SD1}_{down}^2$) should be 0.5. The binomial test of HRA is as follows (the significance level α is 0.05):
H_0: The sample proportion P = 0.5; H_1: The sample proportion P $\neq$ 0.5.

2.2. The Continuous Time Dynamical Analysis of HRA

The previous studies only considered the asymmetrical characteristics of HRA at a specific time scale. To clarify the dynamic properties of HRA, the moving window method was used to explore the dynamic variation of HRA.

The asymmetry of HRA means that there will be more RRI points falling on the up area but less $\mathrm{SD1}_{up}^2$ energy, and vice versa. To conveniently evaluate the results of dynamic analysis, two new asymmetric indexes of HRA are proposed:

$$\mathrm{SD1}_{u-d}^2 = \mathrm{SD1}_{up}^2 - \mathrm{SD1}_{down}^2, \tag{1}$$

$$\mathrm{HRA\_P}_{u-d}=\mathrm{HRA\_P}_{up} - \mathrm{HRA}_{\mathrm{P}_{down}}, \tag{2}$$

where $\mathrm{HRA\_P}_{up}$, $\mathrm{HRA\_P}_{up}$ means the RRI points are located in the up area and down area, respectively. $\mathrm{HRA\_P}_{u-d}$ is the difference of RRI point number between up and down area.

By using the moving window and recursive method, move one RRI series at a time. The new asymmetric index can reflect the dynamical variation of HRA. The flowchart of the dynamical analysis of HRA and comparison diagram are in Fig. 2.

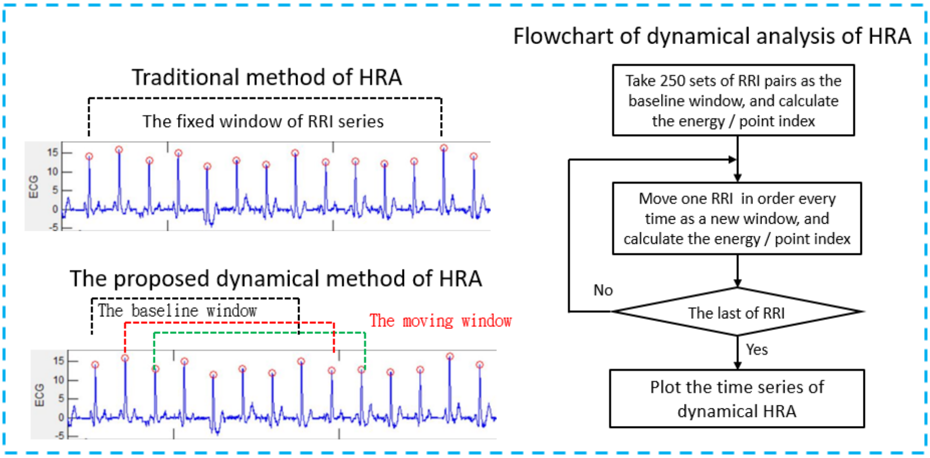


Figure 2. The flowchart of dynamical analysis of HRA and comparison diagram.

Two scenarios of physiological activities were designed to evaluate the dynamic analysis of HRA.

Scenario 1: Measure a 12-minute ECG of a healthy adult in a sober and sitting posture.

Scenario 2: Measure the ECG of a healthy adult taking a siesta. At the same time, record the start and end times of the siesta.

2.3. The Dynamical Analysis of HRA for artificial RRI series

Artificial bio-signals have great potential for application. Artificial bio-signals must have the same dynamic characteristics as real physiological signals.

In this study, the chaotic RRI system is designed. By adjusting the coefficients of Duffing equation, the artificial RRI series has the dynamic characteristics of self-similar. When the chaotic RRI series are projected on the Poincaré plot, the chaotic RRI signal appears the strange attractors similar to the real RRI series. The proposed dynamic analysis method is used to verify whether the chaotic RRI series has an asymmetric phenomenon similar to the real RRI series.

3. Experimental Results

3.1. The Experimental Result of Binomial test

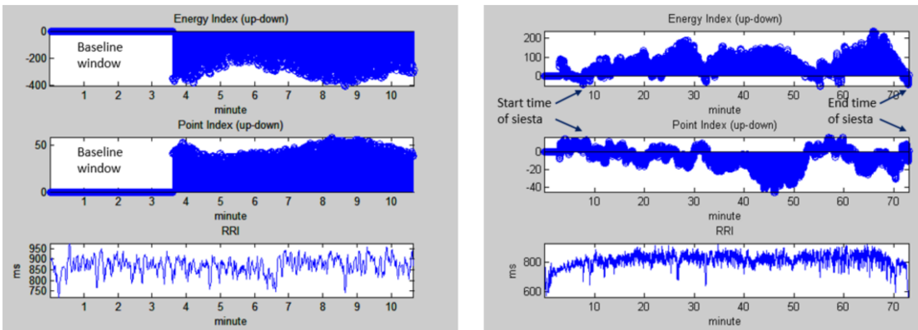
All variables of HRA in 22 subjects are listed in Table 1. Only three subjects (No. 10, 16, and 17) have higher $\mathrm{SD1}_{up}^2$. Therefore, the sample proportion P= $\frac{19}{22}$ =0.86. Due to the n=22, binomial distribution $\mu = 11$ and $\sigma = \sqrt{nPQ} = 2.345$, the p-value is 0.004. The hypothesis of H_0 must be rejected. The p-value validates the asymmetry of HRA.

Table 1. HRA Characteristic Variables of 22 Subjects

No.	Mean of RRI (ms)	$SD1^2$	$\mathbf{SD1}_{up}^2$	$\mathbf{SD1}_{down}^2$	Points in the up area	Points in the down area
1	924.75	378.36	164.85	213.5	154	130
2	736.62	902.93	424.66	478.26	146	138
3	685.48	29.24	10.17	19.06	109	105
4	672.23	209.4	98	111.39	136	121
5	731.35	208.26	67.74	140.51	160	113
6	936.6	3474.6	1695.8	1778.7	156	139
7	907.77	591.12	240.72	350.39	168	122
8	824.64	417.83	186.63	231.19	154	136
9	685.29	20.19	9.61	10.57	110	104
10	772.16	809.3	**437.47**	**371.82**	137	140
11	861.77	850.06	424.27	425.79	152	143
12	897.26	761.18	365.58	395.59	150	140
13	973.62	762.97	362.75	400.22	154	138
14	860.08	368.33	128.6	239.72	181	101
15	818.4	692.78	266.35	426.42	174	119
16	866.6	317.69	**159.05**	**158.63**	143	139
17	968.32	2901.9	**1463.2**	**1438.7**	153	137
18	828.04	399.83	149.93	249.9	170	111
19	792.94	637.32	235.31	402	174	113
20	863.74	1271	601.9	669	161	128
21	943.54	683.33	295.08	388.24	164	129
22	996.14	430.23	210.28	219.94	142	143

3.2. The Experimental Result of Continuous Time Dynamical Analysis

The experimental results of the two scenarios are in Fig. 3. In Fig. 3 (a), the asymmetry variables of HRA appear stably in the time series diagram. In the sober condition, the energy of $\mathrm{SD1}_{up}^2$ is steadily lower than $\mathrm{SD1}_{down}^2$. The new index $\mathrm{SD1}_{u-d}^2$ remains at a negative value, indicating that the asymmetric energy distribution is a persistent asymmetry. On the other hand, the Point index $\mathrm{HRA\_P}_{u-d}$ is always at a positive value, indicating that the RRI points falling in the up area are steadily higher than that of the down area.



(a) Scenario 1 experimental result (sober state). (b) Scenario 2 experimental result (siesta state).

Figure 3. Continuous time dynamical analysis of HRA.

In Fig. 3 (b), the proposed index shows another characteristic of HRA. When physiological activity transfers from a sober state to a sleeping state, the asymmetry changes in the opposite direction immediately. When siesta starting, the energy of $\mathrm{SD1}_{up}^2$ is steadily higher than $\mathrm{SD1}_{down}^2$. $\mathrm{SD1}_{u-d}^2$ is a positive value in most moving windows.

Although the $\mathrm{HRA\_P}_{u-d}$ is not as stable as that of scenario 1, we can still observe that the RRI points fallen on the up area are fewer in the most moving windows. Scenario 2 experiment illustrated that the direction reverses of asymmetric took place immediately with physiological state transform. The proposed new asymmetric index can describe the different physiological states in real-time.

3.3. The Experimental Result of artificial RRI series

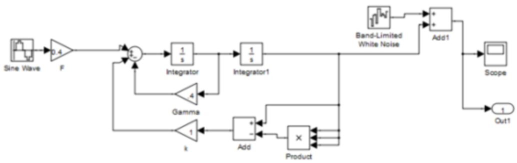
Duffing equation was used in the RRI chaotic system to generate an artificial RRI series. The Duffing equation is defined as follows:

$$\ddot{x}(t) + \gamma\dot{x}(t) - kx(t) + \zeta x^3(t) = \mathrm{F}\cos\omega t, \tag{3}$$

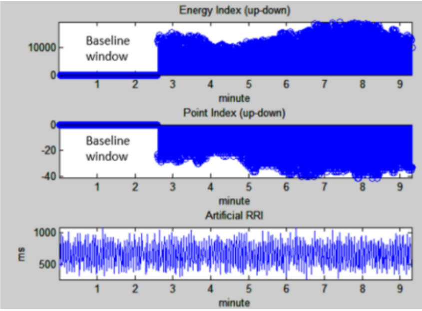
where γ is the friction coefficient, F is the strength of the driving force with oscillate frequency ω, and k, ζ are constants.

Set $\gamma = 0.4$, $k = \zeta = 1$, $\mathrm{F} = 1$, and $\omega = 1$, the Simulink model of the chaotic RRI system and the experimental result are illustrated in Fig. 4.

First, ten minutes of artificial RRI series are generated by the chaotic system (Fig. 4 (a)). By using the moving window method, the asymmetry of HRA appears stably in Fig. 4 (b). Just like the experimental result of scenario 2, the energy of $\mathrm{SD1}_{up}^2$ is steadily higher than $\mathrm{SD1}_{down}^2$. On the other hand, the Point index $\mathrm{HRA\_P}_{u-d}$ explains the artificial RRI points fallen on up area is steadily fewer than that of down area.



(a) Scenario 1 experimental result (sober state).



(b) Scenario 2 experimental result (siesta state).

Figure 4. HRA dynamical analysis of Artificial RRI.

4. Conclusion

In this study, the algorithm of continuous time dynamical analysis of HRA is proposed. By using the moving window method, two new HRA asymmetric variables ($SD1_{u-d}^2$, HRA_P$_{u-d}$) can effectively reflect the asymmetric characteristic of HRA on the Poincaré plot. Two real RRI series and an artificial RRI series are evaluated in the dynamical analysis of HRA. The proposed quantification method of HRA is also convenient for researchers to apply in different clinical environments.

Acknowledgment

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