

Analysis of Heart Rate Asymmetry During Sleep Stages

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Abstract. It is one of the hot spots in recent years to explore changes in the sleep stage by assessing autonomic nervous activity. In recent years, heart rate asymmetry (HRA) is often used to measure the activity of autonomic nerves. However, the relationship between HRA and sleep stage is not clear. We performed Porta's index (PI), Guzik's index (GI), slope index (SI) and area index (AI) analyses on RR intervals per 30-s for understanding the HRA during sleep. Two measurement protocols were set: 1) the HRA values were calculated; 2) the degrees of heart rate deviation from symmetry were estimated. Results showed that PI significantly decreased from N1 and N2 to N3 ($p < 0.01$), and it is increased the highest in REM than other stages ($p < 0.05$). The asymmetry of HRA were significantly lower in N3 (PI and AI p 's < 0.05 ; GI and SI p 's < 0.01), and it increased in REM (PI $p < 0.05$; GI, SI and AI p 's < 0.0001). The results suggested that HRA has the potential to be used in sleep stage monitoring.

Keywords. sleep, heart rate asymmetry, autonomic nervous system

1. Introduction

About one-third of a person's life is asleep, so quantifying the quality of sleep plays a vital role in human health. Sleep can be divided into 5 stages with 30s as the step size which named wake (W), N1, N2, N3 and rapid eye movement (REM) according to American Academy of Sleep Medicine.

A number of studies indicated that during the onset of sleep and transitions to different sleep states, the autonomic nervous system (ANS) has specific performance in different stages of sleep [1], [2]. During non-REM (NREM) sleep, that is combined with N1, N2 and N3, parasympathetic activity causes a decrease in heart rate, while sympathetic nerve activity results in heart rate acceleration in REM sleep [3]. Therefore, understanding the changes of ANS in different stages of sleep is helpful for accurately assess individual sleep quality. Heart rate variability (HRV), a non-invasive method, has been widely applied to detect the ANS modulation [4], [5], which describes the fluctuation of RR intervals from an electrocardiogram (ECG), including to understand ANS changes during different sleep stages.

Poincaré plot was used as a visualized tool for evaluating the increase and decrease of HRV based on the scatter diagram drawn from the current RR interval as abscissa

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against the preceding one as ordinate in Cartesian coordinate [6]. Several metrics had been proposed to estimate the asymmetry of points besides the line of identity of Ponicare plot which were also named as heart rate asymmetry (HRA), such as Porta's index (PI) [7] assesses the asymmetry by points number, Guzik's index (GI) [8] estimates the asymmetry through points distance, slope index (SI) [9] quantify the asymmetry via phase angle and area index (AI) [10] calculated the asymmetry by the way of area of sector. It was reported that the severity of obstructive sleep apnea has a certain correlation with the oscillation pattern of heart rate acceleration and deceleration [11]. However, there is no relevant research on the relationship between HRA and sleep stage.

The purpose of the present study is to show the performance of heart rate asymmetry to analyze differences of HRV or ANS in different sleep stages. Besides, the values of HRA further deviates from 50 indicates the RR intervals are more asymmetry. Hence, the asymmetry of HRA in different sleep stages were also explored.

2. Data and methods

2.1. Data

The MIT-BIH Polysomnographic Database [12], [13] was used in this study, which consists of 18 recordings of polysomnographic signals during sleep collected from 16 male subjects (age:32-56, weight: 89-152 kg). The sampling frequency of all recordings including an ECG channel were 250 Hz. The R waves are annotated and the sleep stages were scored already. Each recording comes from a separate participant except that the files "slp01a" and "slp01b", "slp02a" and "slp02b" were collected from the same person, respectively.

2.2. Algorithm of heart rate asymmetry

For a RR interval series $(RR_1, RR_2, \dots, RR_i, RR_{i+1}, \dots, RR_{n-1}, RR_n)$, figure 1 summarized the algorithm of the four HRA measures which can be achieved by the following formulas:

- Porta's index

PI measures the proportional to the number of points below LI [7]. The formula to calculate PI is

$$PI = \frac{b}{m} \times 100 \quad (1)$$

wherein, b and m present the number of points below LI and not located on LI, respectively. Similarly hereinafter.

- Guzik's index (GI)

GI was the ratio of the cumulative distance corresponding the points [8], which can be calculated by

$$GI = \frac{\sum_{i=1}^l D_i}{\sum_{i=1}^m D_i} \times 100 \quad (2)$$

wherein, D_i can be calculated as

$$D_i = \frac{|RR_{i+1} - RR_i|}{\sqrt{2}} \quad (3)$$

- Slope index (SI)

SI assesses the percentage of cumulative phase angle above LI [9]. The way to

calculate SI is

$$SI = \frac{\sum_{i=1}^l |R\theta_i|}{\sum_{i=1}^m |R\theta_i|} \times 100 \tag{4}$$

wherein, $R\theta_i = \theta_{LI} - \theta_i$, where θ_{LI} is the angle between LI and abscissa, and $\theta_i = \text{atan}(RR_{i+1}/RR_i)$.

- Area index (AI)

The area of the i th sector is denoted by

$$S_i = \frac{1}{2} \times R\theta_i \times r^2 \tag{5}$$

Then AI was defined as the ratio of S_i above LI [10]. The formula of AI is,

$$AI = \frac{\sum_{i=1}^l |S_i|}{\sum_{i=1}^m |S_i|} \times 100 \tag{6}$$

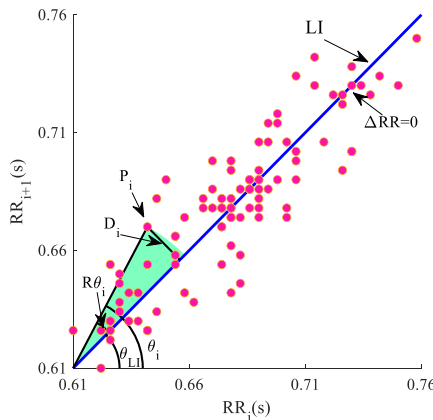


Figure 1. Schematic diagram of HRA algorithm in a Poincaré plot. Red dots show points in the Poincaré plot. LI is the line of identify. P_i is the i th point which can be denoted by (RR_i, RR_{i+1}) , $\Delta RR = RR_{i+1} - RR_i$. D_i represents the distance of P_i respect to LI; The angle between the line between P_i and the origin of the coordinate and the abscissa (and LI) is denoted by θ_i (and $R\theta_i$); θ_{LI} is the phase angle between the abscissa and LI.

2.3. Asymmetry of HRA metrics

HRA greater than or less than 50 indicates asymmetry. The farther away from the specific value, the higher the asymmetry. Therefore, the results of subtracting 50 from the HRA index value and then taking the absolute value were named HRA asymmetry, i.e.,

$$\text{Asymmetry of PI} = |PI - 50| \tag{7}$$

$$\text{Asymmetry of GI} = |GI - 50| \tag{8}$$

$$\text{Asymmetry of SI} = |SI - 50| \tag{9}$$

$$\text{Asymmetry of AI} = |AI - 50| \tag{10}$$

2.4. HRA analysis of RR intervals

The RR intervals with a duration of 30s were constructed with the annotated R waves according to the sleep stage label in the database. A RR interval was excluded if it was

less than 0.7 times the mean of the RR intervals or larger than 1.5 times mean of the RR intervals. In addition, SI and AI were impacted by the reference lines and reference points [14]. The minimum of every RR interval series was applied as the reference point. Two procedures were performed on the preprocessed RR intervals.

- 1) the HRA values were estimated from the RR intervals in different sleep stage;
- 2) the degrees of heart rate deviation from symmetry during sleep stage changes were assessed.

2.5. Statistical analysis

The values of different HRA belonging to the same sleep stage were averaged within each participant. Linear mixed-effect models were performed to examine the differences in the eight HRA measures across different sleep stages. When the alpha level is 0.05, statistical significance is accepted. Matlab software (Ver. R2021a, The MathWorks Inc., Natick, MA, USA) were used for all statistical analyses.

3. Results

The HRA results of RR intervals corresponding to different sleep stage were summarized as mean + 95% confidence interval in Figure 2. It was found that the asymmetry of heart rate variability was significantly decreased in N3 stage than the other two NREM sleep stages (Fig 2(a), $p < 0.01$). Then PI in REM sleep was significantly difference with other sleep stage ($p < 0.05$). GI, SI and AI showed no significant difference among the different sleep state ($p > 0.05$).

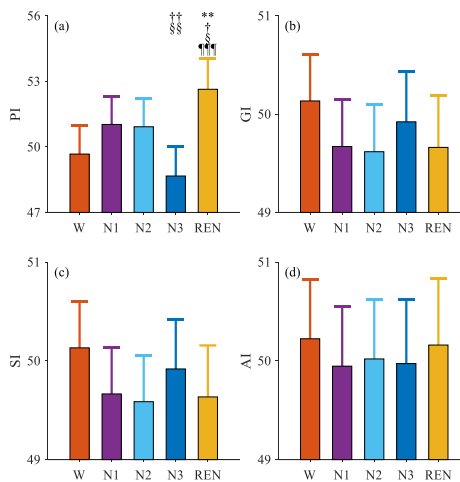


Figure 2. HRA results of RR intervals corresponding to different sleep stage. (a) PI; (b) GI; (c) SI; (d) AI. The error bar indicates the 95% confidence interval in each stage. *: W vs. the four sleep stages; †: N1 vs. N2, N3 and REM; §: N2 vs. N3 and REM; ¶: N3 vs. REM. The number of symbols means the degree of significant difference, e.g., †, §: $p < 0.05$, **: ††, §§: $p < 0.01$; ¶¶¶¶: $p < 0.0001$.

The results of asymmetry of HRA assessed by PI, GI, SI, and AI calculated were summarized as mean + 95% confidence interval in Figure 3. There was a significant tendency of decreased in the asymmetry of RR intervals in the N3 sleep stage compared

with W, N1 and N2 (asymmetry of GI, SI and AI, p 's<0.05, figure 3 b, c, d). Asymmetry of PI showed N3 stage showed no significant difference with N2 stage. All of the four measures suggested that the asymmetry of REM was higher than N3 sleep (PI, p <0.05; GI, SI and AI, p <0.0001).

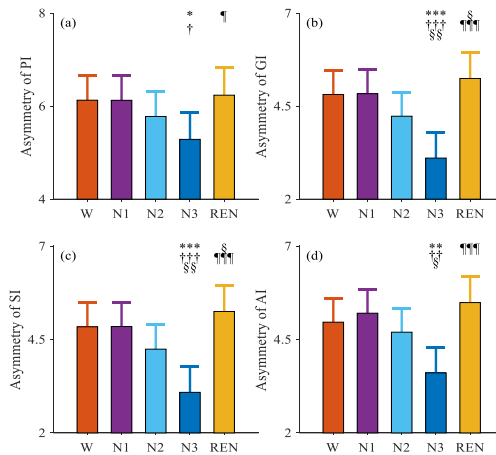


Figure 3. Asymmetry of HRA results of RR intervals corresponding to different sleep stage. (a)-(d) Asymmetry of PI, GI, SI and AI, respectively. The error bar indicates the 95% confidence interval in each stage. *: W vs. the other four stages; †: N1 vs. N2, N3 and REM; §: N2 vs. N3 and REM; ¶: N3 vs. REM. The number of symbols means the degree of significant difference, e.g., *, †, §, ¶: p <0.05, **, ††, §§: p <0.01; ***, †††, ¶¶¶: p <0.0001.

4. Discussion

Due to the regulation of autonomic nervous system (ANS), the speed of heart beats accelerates or decelerates during sleep. The activation of sympathetic or parasympathetic speeds up or slows down the heartbeat, respectively [15]. The pattern of heart rate increases or decreases, or the activity state of the ANS in different sleep stages were analyzed by four heart rate asymmetry measures that is PI, GI, SI and AI.

It is found that the lowest HRA and asymmetry of HRA were detected in N3 stage, and then they increased significantly in REM sleep by PI. This result is consistent with previous findings that heart rate decreases during sleep stage N1, N2 and N3, and increases in REM sleep [16]. PI is a method to estimate the asymmetry of number of points aside the LI which is most intuitive way to express heart rate changes. The number of points below LI decreased in N3 stage, and it increased in REM sleep, so PI could distinguish N3 and REM from other sleep state. However, GI, SI and AI, estimated the heart rate asymmetry by distance, angle and area, respectively, cannot found the difference. It is speculated that the accumulation of the product of the distance, angle or area and quantity buffers the difference among different sleep states.

All of the four asymmetries of HRA indices showed N3 was much lower than other stages. It may be that the heart rate in the N3 stage becomes slower and more stable, and the asymmetry of the heart rate does not deviate from 50 much. Whereas, compared with N3, the heart rate accelerates very fast in the REM sleep. Our study suggests that the HRA indices and asymmetry of HRA metrics could be promising indicators for the clinical N3 and REM sleep monitoring.

Study limitations. The 30s RR intervals were analyzed by HRA measures in this

paper. However, the statistical stability and consistency were not systematically investigated. The physiological significance of asymmetry of HRA during sleep was not entirely understood. It remains to be further studied. Only 16 people's ECG data were used in this study. We will use more data to study the HRA during sleep in future.

5. Conclusion

In this study, PI, GI, SI and AI were used to describe the heart rate asymmetry features during sleep. Both two different analyzing protocols suggested that the asymmetry of N3 stage was the lowest and it increased in REM sleep. Besides, the results obtained by 30s RR series. Our study suggests that the HRA analysis may be applicable in recognizing different sleep stages, especially in differentiating N3 and REM.

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