Factors Affecting Coordination between Heart Rate Variability and Physical Acceleration in Daily Lives of Free-moving Adults

Kentaro Taniguchi,* ** Akito Shimouchi,* # Junji Seki,** Naoya Jinno,* Mikiyasu Shirai,* Akitoshi Seiyama**

Abstract  The aim of this study was to identify factors affecting the relationship between heart rate variability (HRV) and physical acceleration (PA) in daily lives of free-moving adults. In 65 subjects comprising 18 young (20 to 39 years), 26 middle-aged (40 to 59 years), and 21 elderly (≥ 60 years) subjects, ECG R-R intervals and PA data were simultaneously obtained every minute for 24 hours as the subjects went about their normal daily lives. The R-R intervals were subjected to linear frequency domain analysis, and the low frequency (LF)/high frequency (HF) and HF/(LF+HF) ratios were used as HRV indices. Lag was defined as the time difference that gave maximum cross-correlation between the HRV parameters and PA. The proportion of subjects who exhibited no lag was significantly higher in young subjects, and was significantly lower in elderly subjects. After waking, the proportion of subjects who exhibited no lag tended to decrease in all groups. The lag between HRV and PA correlated significantly with psychological conditions and/or mental stress.

Keywords: heart rate variability, physical acceleration, aging, cross-correlation.


1. Introduction

Heart rate variability (HRV) represents the degree of fluctuation from the mean heart rate and provides valuable information in various clinical settings [1]. Most human studies on the HRV spectrum examined the power of the high frequency (HF) and low frequency (LF) ranges [2, 3]. Especially, the power of the HF range is considered to represent parasympathetic nervous system activity, and the LF/HF ratio has been suggested to represent sympathovagal balance [4, 5].

Many factors affect the neurohormonal mechanisms that control the cardiovascular system [6]. Based on laboratory and animal studies of the interactions between the autonomic nervous system and muscular activity, it is generally accepted that neuromuscular interactions occur within a half min, for example, in the head-up tilt tests [7–9] and that several neuromuscular diseases including diabetic neuropathy can alter the power of HRV response [10, 11]. It is speculated that the coordination between HRV and physical acceleration (PA) is impaired not only by autonomic insufficiency caused by peripheral neuropathies, aging, or neuromuscular diseases, but also by psychological or metabolism-related disorders. However, little is known about the response time under physiological or pathological conditions.

The use of three-dimensional accelerators to evaluate physical activity is well established, and numerous types of accelerators are widely used in health-oriented studies. Several portable devices that allow simultaneous recording of PA and electrocardiogram (ECG) R-R intervals are commercially available. In the present study, one of these portable devices was used to examine whether coordination between HRV and PA, as indicators of autonomic nervous system and physical activity, respectively, can be detected by cross-correlation analysis. Although several studies on athletic interval training have analyzed the lag between HRV and PA [12, 13], very few reports have attempted to use cross-correlation analysis to detect impaired coordination between the autonomic nervous system and PA in free-moving adults. The present study is the first attempt to study the coordination between HRV and PA in free-moving adult volunteers with a wide range of ages.

2. Methods

2.1 Subjects

Eighty-seven subjects volunteered for this study. Among them, current smokers, drinkers, persons with arrhythmia, and those who were taking medications that could affect the autonomic nervous system were excluded, based on their responses to medical interviews about their past and present illnesses, physical findings, screening blood test results, and ECG. Eventually, 65 subjects (16 males and 49 females; aged 20 years and over) were analyzed for this study. We divided the subjects into three age groups: young (20 to 39 years; 18 females), middle-aged (40 to 59; 6 males and 20 females), and elderly groups (60 years or above; 10 males and 11 females). Among the 65 subjects, 4 (0 [young]/1 [middle-aged]/3 [elderly]) had type II diabetes, 26 (1/11/14) had hyperlipidemia, 7 (0/2/5) had hepatic dysfunction, 6 (0/2/4) had hyperuricemia, 12 (0/5/7) had essential hypertension, 3 (0/2/1) had renal dysfunction, 16 (7/8/1) had allergic diseases, and 5 (4/0/1) had atopic dermatitis. However, all the diseases were mild and none of the subjects were restricted in...
2.2 Protocols
All of the subjects gave informed consent before participating in this study. On the day of assessment, each subject completed the questionnaires at home and brought them to the laboratory. They arrived at the laboratory around 13:00 and underwent a physical examination, venous blood sampling, an ECG, and body composition analysis. Thereafter, they wore a portable monitor (Active Tracer AC301, GMS Inc., Tokyo, Japan) to record physical acceleration and R-R intervals over a period of 24 hours. R-R intervals were obtained from the CMS-lead ECG. During monitoring, the subjects were instructed to continue with their normal lives, but to avoid bathing. After completion of the 24-hour monitoring, each subject returned to the laboratory and underwent the above mentioned assessments again.

2.3 Questionnaires
We used the General Health Questionnaire 28 (GHQ28) to evaluate mental stress [14], the Cornell Medical Index (CMI) to assess physical and psychological symptoms [15], and the Self Depression Scale (SDS) to evaluate depression levels [16].

2.4 Physical Activity
For measurements of physical acceleration (PA), the body of the Active Tracer equipped with a triaxial accelerometer [17, 18] (52 mm in length, 80 mm in width, 17 mm in thickness, 72 g in weight) was positioned on the frontal midline of the waist above the navel to avoid disturbing sleep. The resolution of acceleration was 2 mG and the sensitivity ranged from 0 to 4.0 G. The triaxial accelerations were recorded at 10 Hz for 24 hours. The absolute values of the resultant vector, which were calculated from the signals of triaxial accelerations, were averaged for every one min.

2.5 Analysis
The time domain analysis and spectral analysis of HRV were performed at 1-min intervals using the maximal entropy combined with the least square method (MEM Calc System, Suwa Trust Co., Ltd., Tokyo), and separated into the HF range (0.15–0.4 Hz) and the LF range (0.04–0.15 Hz) for power analysis [2]. In this study, frequencies below 0.04 Hz were not analyzed because these required longer data series for accurate power estimation. The power of the HF components was evaluated as the ratio to TF (LF+HF), according to the method of Dingli et al. [19]. We divided the observation period into evening (from the start of the monitoring period until the subject went to sleep at night), night sleep (night time sleep including periods of nocturnal waking), and morning (after waking to the end of the monitoring period). The times at which the subjects fell asleep and woke up were estimated based on records kept by the subjects and changes in body position evaluated from the acceleration vector recorded by the monitor. Arrhythmia was determined based on the assessment of 12-lead ECG, electrocardiographic complexes derived from active tracing, and Lorenz plots. Subjects with arrhythmia were excluded from the study.

2.6 Lag
The lag was determined as the time difference that yielded the minimum p value for the correlation coefficient obtained from an analysis of the cross-correlation between the HRV components examined (LF/HF or HF/TF) and PA. Cross-correlation coefficients were calculated for 10-min time windows over consecutive 60 or 180 min periods. The absolute time difference was employed to simplify the interpretation of results. If lag ≠ 0, we considered that coordination was impaired.

2.7 Statistics and Ethics
Data are expressed as mean ± standard deviation. Statistical analyses were performed with two-way analysis of variance followed by Tukey’s test using Excel or SPSS. Multiple regression analysis was also performed to determine the correlations among the questionnaire scores, lags, age, sex and body mass index. Statistical significance was accepted if p < 0.05. This study was approved by the ethical committee at the National Cerebral and Cardiovascular

Table 1 Comparison of physical acceleration (PA) and heart rate variability expressed in low frequency (LF)/high frequency (HF) ratio and HF/LF+HF (TF) ratio between the age groups.

<table>
<thead>
<tr>
<th>Age</th>
<th>Young (n = 18)</th>
<th>Middle-aged (n = 26)</th>
<th>Elderly (n = 21)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>[Evening]</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PA (mG)</td>
<td>23 ± 14</td>
<td>31 ± 18</td>
<td>21 ± 11</td>
</tr>
<tr>
<td>HF/TF</td>
<td>0.30 ± 0.095</td>
<td>0.27 ± 0.098</td>
<td>0.29 ± 0.082</td>
</tr>
<tr>
<td>LF/HF</td>
<td>5.1 ± 3.3</td>
<td>6.8 ± 5.1</td>
<td>5.1 ± 2.1</td>
</tr>
<tr>
<td><strong>[Night sleep]</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PA (mG)</td>
<td>1.6 ± 1.4</td>
<td>2.3 ± 2.4</td>
<td>1.7 ± 0.82</td>
</tr>
<tr>
<td>HF/TF</td>
<td>0.28 ± 0.12</td>
<td>0.24 ± 0.097</td>
<td>0.20 ± 0.065*</td>
</tr>
<tr>
<td>LF/HF</td>
<td>2.6 ± 2.0</td>
<td>3.2 ± 1.8</td>
<td>3.5 ± 1.8*</td>
</tr>
<tr>
<td><strong>[Morning]</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PA (mG)</td>
<td>47 ± 28</td>
<td>49 ± 24</td>
<td>39 ± 15</td>
</tr>
<tr>
<td>HF/TF</td>
<td>0.23 ± 0.058</td>
<td>0.22 ± 0.073</td>
<td>0.26 ± 0.089</td>
</tr>
<tr>
<td>LF/HF</td>
<td>6.0 ± 2.8</td>
<td>7.6 ± 4.0</td>
<td>5.9 ± 3.9</td>
</tr>
</tbody>
</table>

Evening: 3 hours before night sleep, Morning: 3 hours after waking up, *: p < 0.05, young vs. elderly.
Four examples PA precedent to HF/TF in a 56-years-old woman (1-a), PA antecedent to HF/TF in a 23-years-old woman (1-b), PA precedent to HF/TF in a 22-years-old woman (1-c), and PA antecedent to HF/TF in a 32-years-old woman (1-d). Arrows are the time-points of physical activities recorded by the subjects. All the peak correlation coefficients are statistically significant ($p < 0.05$).
Research Center, and all of the volunteers gave informed consent.

3. Results

The PA and HRV (LF/HF and HF/TF) data for each period (evening, night sleep, and morning) are summarized in Table 1. During the night sleep, the young group displayed significantly higher HF/TF and lower LF/HF than the elderly group. However, in the evening and morning, there were no significant differences in PA, LF/HF, and HF/TF among the three groups. Furthermore, the elderly group did not display lower PA levels than the younger group.

As examples, four cases with PA precedent and antecedent to HF/TF, and PA precedent and antecedent to LF/HF are shown in Fig. 1-a, 1-b, 1-c and 1-d, respectively. Each lag depended on the consecutive changes in daily physical activities such as walking, housework, PC work and driving.

Figure 2 illustrates the lag (min) between HRV and PA experienced by the subjects during 3 hours before sleep and 3 hours after waking up. In both evening and morning periods, the young group tended to contain a higher proportion of subjects who did not exhibit any lag. On the other hand, the elderly group tended to contain a larger proportion of subjects who displayed a lag of ≥4 min.

As shown in Fig. 3, in the evening after waking up, the percentage of subjects who exhibited no lag between HF/TF and PA was significantly lower in the elderly group than in the young group (p < 0.05). As for the lag between LF/HF and PA observed in the evening, the proportion of subjects who displayed no lag was significantly lower in the elderly group than in the young group (p < 0.05).

The psychological conditions that correlate significantly with the lag between HRV and PA are listed in Table 2. The subjects with lags between HF/TF and PA had significantly higher scores of social impairment and depression. Subjects with lags in the morning had significantly higher score of frequency of illness. The subjects who experienced evening lags between LF/HF and PA also had significantly higher depression scores. However, there was no significant correlation between the lag and other variables such as sex and diseases in the present study (date not shown).

4. Discussion

4.1 Analytical issues

The times at which the subjects went to bed and woke up varied widely depending on the subjects’ daily habits, the ambient conditions, and other circumstances. Therefore, to prevent external factors interfering with HRV and PA, we focused on 3 hours before sleep and 3 hours after waking up. In our preliminary cross-correlation analysis, we confirmed that similar results were obtained regardless of whether we used a time window of 10 or 20 min for evaluating the lag between HRV and PA. Thus, we considered that a time window of 10 min was appropriate.

On the other hand, we noticed that the calculated lag between PA and HRV varied depending upon the time range of interest. Because we considered that the lag between PA and HRV was affected not only by direct interaction between autonomic nervous system and physical activity, but also by higher central nervous system including mental or psychological conditions [20]. In order to explore detailed information of the coordination between HRV and PA, we employed two analytical methods; macroscopic en bloc calculation of the lag for one hour as shown in Fig. 1, and microscopic consecutive one-min analysis for a given range of time and then evaluating the frequency of lag+ and lag− for every one hour as shown in Fig. 3 and Table 2. The latter analytical method appears to provide more detailed information of the items associated with the lag as discussed in 4.2 and 4.3.

In previous cross-correlation studies, HRV components were extracted every 5 min [12, 13]. However, the coordination between physical activity and the autonomic nervous system is
generally considered to involve a short time frame under normal physiological conditions. Thus, we employed one-min data collection intervals to obtain more precise information. However, as far as the HRV components are concerned, the extraction interval could be shortened to 30 seconds. The optimal extraction time should be determined in a future study.

4.2 Aging

In our preliminary analysis, we found that the numbers of positive and negative signs in all four lag patterns, i.e., HRV precedence or antecedence with respect to PA, were nearly even (data not shown). Therefore, we evaluated the lags as the absolute value. The compiled frequencies of the absolute lag indicated that the lag in the elderly subjects was widely distributed compared with those in younger generations. Furthermore, when comparing the lag between HRV and PA during 3 hours before sleep and that during 3 hours after waking up among the age groups, we found that a greater proportion of the elderly subjects tended to display lags of ≥4 min in the evening and morning as shown in Fig. 2. These results suggest that the coordination between HRV and PA is impaired by aging.

4.3 Mental stress

The cardiovascular response pattern elicited during conditioned emotional response is known to be mediated by sympathetic and parasympathetic pathways to the cardiovascular system. Autonomic responses occur in anticipation of the somatomotor responses demonstrating that the cortical signals have direct access to the autonomic centers independent of the afferent feedback but in conjunction with it [20, 21]. In addition, mental stress is reported to be closely associated with impairment of the autonomic nervous system [22]. In this study, the subjects’ CMI and GHQ28 scores were correlated significantly with the coordination between HRV and PA. Psychological conditions and/or mental stress might affect not only the autonomic nervous system itself but also its coordination with physical activity.

4.4 Limitations

The analytical method employed in the present study to evaluate the coordination between the activity of the autonomic nervous system and physical activity has several limitations. First, it is difficult to calculate the lag between these parameters for successive periods involving small physical movements such as during night sleep. Second, even in the absence of movement, changes in HRV occur throughout daily life. For example, HRV is affected differently by PC work, housework, driving, and walking, as shown in Fig. 1. For this reason, the present method is limited by its inability to evaluate the effects of psychological alterations in the absence of physical activity and of physical activity accompanied by psychological alterations on HRV. However, we consider

<table>
<thead>
<tr>
<th>Item</th>
<th>Lag</th>
<th>N</th>
<th>Score ±</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>[evening] GHQ C: Lag−</td>
<td>33</td>
<td>0.6 ± 1.2</td>
<td>0.032</td>
<td></td>
</tr>
<tr>
<td>social impairment</td>
<td>Lag+</td>
<td>32</td>
<td>1.3 ± 1.8</td>
<td></td>
</tr>
<tr>
<td>GHQ D: Lag−</td>
<td>33</td>
<td>0.4 ± 1.2</td>
<td>0.019</td>
<td></td>
</tr>
<tr>
<td>depression</td>
<td>Lag+</td>
<td>32</td>
<td>0.8 ± 1.6</td>
<td></td>
</tr>
<tr>
<td>[evening] GHQ D: Lag−</td>
<td>26</td>
<td>0.1 ± 0.3</td>
<td>0.010</td>
<td></td>
</tr>
<tr>
<td>LF/HF frequency of illness</td>
<td>Lag−</td>
<td>24</td>
<td>0.4 ± 0.7</td>
<td>0.001</td>
</tr>
<tr>
<td>Lag+</td>
<td>41</td>
<td>0.9 ± 0.8</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Lag−: subjects who exhibited no lag between HRV and PA for ≥50% of an hour; Lag+: subjects who exhibited a lag between HRV and PA for ≥50% of an hour; CMI J: frequency of illness score on the CMI; GHQ C: social impairment score on the GHQ28; GHQ D: depression score on the GHQ28.
that evaluations of the lag between HRV and PA are, to some extent, useful for assessing the coordination between the autonomic nervous system and physical activity in free-moving persons.

5. Conclusion

In the present study, the lag between HRV and PA was determined based on the minimum p-value for the cross-correlation between the two variables. The proportion of subjects without lag was higher in young subjects, but lower in elderly subjects. After waking, the proportion of subjects who experienced no lag tended to decrease in all groups. The lag between HRV and PA was significantly related to psychological conditions and/or mental stress.

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References


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