Vestibulo-Cardiorespiratory Responses at the Onset of Chair Rotation in Endurance Runners

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Abstract: Stimulation of the vestibular system has been reported to elicit ventilatory and circulatory changes in humans. The purpose of this study was to clarify the characteristics of vestibular-mediated ventilatory and circulatory responses in male endurance runners at the onset of passive chair rotation, which selectively stimulates the semicircular canals. Fourteen runners and 14 male untrained subjects participated. The vestibular stimulus test, which consists of 180° chair rotations (left or right half-turns on an earth-vertical axis) for a duration of 2 s, was carried out on each subject. Inspiratory minute ventilation, tidal volume, respiratory frequency, heart rate, and blood pressure were measured by breath-by-breath and beat-to-beat techniques before, during, and after the chair rotation for a total of

60 s. It was found in this study that (i) the relative change of minute ventilation response in the endurance runners was significantly ($P < 0.05$) greater than in the untrained subjects during and after the rotation, and that (ii) no significant group differences were observed in heart rate and mean blood pressure responses during and after the rotation. In conclusion, vestibular-mediated ventilatory response, but not circulatory response, at the onset of the chair rotation in the endurance runners was significantly greater than that in the untrained subjects. The results from the present study suggest that an increase in vestibulo-ventilatory response would be attributed to an adaptation to long-term endurance training. [The Japanese Journal of Physiology 55: 11–18, 2005]

Key words: vestibular system, passive chair rotation, endurance training, ventilatory response, circulatory response.

The activation of the vestibular system has been reported to contribute to ventilatory and circulatory changes [1, 2]. Selective stimulation of the vestibular system through a rotation of the head elicits changes in the nervous activity of the respiratory and upper airway muscles in animals [3] and in the ventilation in humans [4, 5]. A series of human studies by Ray and his colleagues demonstrated that a stimulation of the semicircular canals but not the otolith organ mediates increases in respiratory frequency and ventilation [5–7]. More recently we have assessed the potential contribution of the semicircular canals to ventilatory

control in humans, with particular reference to a short-term influence, by the use of 180° chair rotation for a duration of 1.5 s [8]. On the contrary, the otolith organ but not the semicircular canals mediates sympathetic and cardiovascular responses [5, 6, 9].

In general, it is well known that endurance runners train mainly by prolonged running for several hours for fairly long distances. In the previous study, Lepers *et al.* [10] observed an increase in body-sways after prolonged running, and they suggested that the running motion induced acute functional changes in a runner's vestibular system. Since endurance runners are con-

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stantly and extensively stimulating the vestibular system during running, it is possible to presume that their vestibular organs undergo functional changes, which might have an influence on the vestibular-mediated ventilatory and circulatory responses [11]. However, to our knowledge, there were no available data as to whether functional and morphological changes in the vestibular organs occur as a result of endurance training, and we hypothesized that vestibular-mediated cardiorespiratory responses in the endurance runners would differ from those in the untrained subjects.

The purpose of this study was, therefore, to clarify the characteristics of vestibular-mediated ventilatory and circulatory responses in the endurance runners at the onset of passive chair rotation by comparing those responses observed in the untrained subjects.

METHODS

Subjects. Fourteen male endurance-trained runners (peak oxygen uptake [$\dot{V}O_{2\text{ peak}}$] > ~65 ml/kg/min) who belong to the athletic club at Nagoya University, and 14 male untrained subjects ($\dot{V}O_{2\text{ peak}}$ < ~55 ml/kg/min) from the university participated as subjects in this study. The endurance runners had trained mainly by running for about 2–3 h, 5–6 times a week all year for approximately 2–10 years. The untrained subjects were not engaged in any sort of athletic training in daily life. The physical characteristics of the subjects are summarized in Table 1. The subjects were informed of the experimental protocol and the possible risks involved in this study before their written consents were obtained. The approval for this study was given by the ethics committee of the Research Center of Health, Physical Fitness and Sports, Nagoya University.

Preliminary test. All subjects came to the laboratory three times on separate days. On the first day, each subject was familiarized only with the apparatus and testing procedures involved in the study. The subjects performed a preliminary test to become sufficiently accustomed to a vestibular stimulus test by chair rotation and a maximal exercise test on a treadmill. The

testing sessions were typically conducted in either the mid-morning or the mid-afternoon, and were separated from meals by at least 2 h.

Maximal exercise test. To estimate the aerobic capacity of each subject, a maximal exercise test was performed according to a treadmill incremental exercise protocol [12]. The subjects first ran on the treadmill at speeds of 15 km/h (endurance runners) and 10 km/h (untrained subjects) at a 0% gradient for 4 min; the gradient was then increased by 2% every minute until exhaustion occurred in both groups. The Douglas bag method was utilized to measure the oxygen uptake ($\dot{V}O_2$) during the treadmill exercise; expired gases were collected into a Douglas bag during the last 30 s at each grade and at volitional fatigue. The expired gas volume was measured with a wet-gas meter (Shinagawa, model WE), and a gas analysis was performed by means of a mass spectrometer (Arco System, ARCO-1000). The heart rate (HR) was continuously recorded by a three-lead electrocardiogram (Nihon Koden, OEC-6401) throughout the maximal exercise test. The highest value obtained for $\dot{V}O_2$ during the exercise protocols were defined as $\dot{V}O_{2\text{ peak}}$. The subjects exercised to volitional fatigue, which was determined by having fulfilled two of the following three criteria: identification of a plateau in $\dot{V}O_2$ with an increase in work rate (<150 ml $\dot{V}O_2$ increase), HR $\pm$ 10% of the age-predicted maximum (220 – age), and/or a respiratory exchange ratio (RER) $\geq$ 1.1 [12].

Vestibular stimulus test. The vestibular stimulus test was designed by referring to methods from our previous study [8]. It was carried out on each subject by the use of chair rotations; i.e., the subjects sat with their backs against experimental chairs. They were seated on motorized rotating chairs (Nagashima medical instruments, TYPE-S2) with their heads upright and fixed to the chairs with velcro bands. They were rested comfortably in a sitting position for 10–15 min and then asked to relax during the experimental period. All testing was performed with the subject's eyes closed. The vestibular stimulus was a 180° chair rotation (a left or right half-turn on an earth-vertical axis) for a duration of 2 s that reached a peak velocity of 180°/s. From the starting position, the chair moved either to the right or the left, with the direction being randomly chosen. The consequence of this was the stimulation of the semicircular canals, which are sensitive to an angular acceleration of the head. The time of the onset of chair motion was randomly varied so the subjects could not predict when the chair would begin moving. Typically, each direction of chair rota-

Table 1. Physical characteristics of the subjects.

	Endurance runners	Untrained subjects
Age (year)	21.5 $\pm$ 2.3	21.5 $\pm$ 0.6
Height (cm)	173.1 $\pm$ 1.2	173.5 $\pm$ 1.1
Body mass (kg)	57.4 $\pm$ 0.9	62.1 $\pm$ 1.8
$\dot{V}O_{2\text{ peak}}$ (l/min)	3.93 $\pm$ 0.10*	3.03 $\pm$ 0.09
$\dot{V}O_{2\text{ peak}}$ (ml/kg/min)	69.1 $\pm$ 0.8*	49.2 $\pm$ 1.3

Values are means $\pm$ SE. $\dot{V}O_{2\text{ peak}}$, peak oxygen uptake. * P < 0.05 Endurance runners differ from untrained subjects.

tion (left or right) was repeated eight times at approximately two to three minute intervals with the eyes closed. These chair rotations were initiated just before the start of the inspiratory phase; the experimenter checked this on an oscilloscope that was connected to the hot wire flow meter.

Measurement. Inspiratory minute ventilation ($\dot{V}_I$), tidal volume (V_T), and inspiratory and expiratory periods were determined by the breath-by-breath method. The subject breathed through a respiratory facemask to which a hot wire flow meter (Minato Ika-gaku, RF-H) was attached. The dead space in the respiratory facemask was about 100 ml. V_T was determined by digitally integrating the airflow signals. Respiratory frequency (f) was calculated from the total respiratory time, and $\dot{V}_I$ was obtained as the product of V_T and f . HR was measured beat-to-beat from the R spike by the use of an electrocardiogram through a bioamplifier (Nihon Kohden, AB 621G). Blood pressure (BP) was also measured beat-to-beat with the finger photoplethysmographic method (Ohmeda, Finapres 2300) and the subject's hand kept at heart level. Systolic and diastolic blood pressures (SBP, DBP) were obtained by instantaneous pressure outputs, and mean blood pressure (MBP) was calculated from the formula: $MBP = 1/3 (SBP - DBP) + DBP$. All ventilatory and circulatory signals were continuously displayed on the screen of an oscilloscope, and all measurements were determined by breath-by-breath and beat-to-beat techniques before, during, and after rotation for a total of 60 s. They were converted from analog to digital data with an A/D converter (Canopus, ADX 98H) at a sampling frequency of 100 Hz. These data were stored on a hard disk unit, and analyzed later on a personal computer (NEC, PC 9821Xa).

Data analysis and statistics. Breath-by-breath and beat-to-beat data were aligned with the onset of chair rotation, then linearly interpolated between each breath and between each beat to yield data points at 1 s intervals [13, 14]. Ensemble averaging was done across all repetitions. To confirm whether the parameters had actually changed as a result of chair rotation compared with at rest (absolute change), we used a one-way analysis of variance (ANOVA) with repeated measurements and a Dunnett's t -test. The resting value (Rest) was the average of 30 s before chair rotation. In comparing the endurance runners with the untrained subjects (relative change), we conducted a Kolmogorov-Smirnov test to examine data normality. When the data were normally distributed, a two-sample t -test was done. When the data were not normally

distributed, a nonparametric test (Mann-Whitney's U-test) was performed. These statistical analyses were computed by software (SPSS 10.0, SPSS), and the level of significance was set at 5%.

RESULTS

Physical characteristics

The physical characteristics of the subjects are summarized in Table 1. There were no significant differences in age, height, and body mass between the two groups. $\dot{V}O_{2\text{peak}}$ (l/min and ml/kg/min) was significantly ($P < 0.05$) higher in the endurance runners than in the untrained subjects.

Absolute change

In the present study, none of the subjects reported malaise or discomfort during the vestibular stimulus test. Figure 1 illustrates prominent changes in respiration (flow curve), HR (R-R interval), and BP in one endurance runner and an untrained subject before, during, and after chair rotation. In this example, respiration, but not HR, increased shortly after the onset of chair rotation. Furthermore, BP increased slightly after chair rotation. This was the typical response pattern in all subjects.

During and after chair rotation, no significant differences in ventilatory or circulatory responses were found between the left and right half-turns; thus each direction (left and right) of chair rotation was combined for the remainder of the analysis. Figure 2 shows the ventilatory responses before, during, and after chair rotation in the two groups. It was found that $\dot{V}_I$ increased significantly ($P < 0.05$) at 1 s after the onset of chair rotation in both groups. Significant ($P < 0.05$) absolute changes in $\dot{V}_I$ were observed at 1–17 s for endurance runners and at 1–6 s for untrained subjects during and after the onset of chair rotation as compared with Rest (Fig. 2A). Significant ($P < 0.05$) absolute changes in V_T were detected at 1–9 s for endurance runners and at 2–6 s for untrained subjects during and after the onset of chair rotation as compared with Rest (Fig. 2B). On the other hand, respiratory frequency did not change significantly in either group during or after chair rotation (Fig. 2C).

Figure 3 represents the circulatory responses in the endurance runners and the untrained subjects. Resting HR in the endurance runners was significantly ($P < 0.05$) lower than that in the untrained subjects. No significant absolute changes in HR were observed in the two groups (Fig. 3A). By contrast, MBP significantly ($P < 0.05$) increased after chair rotation at 4–7 s in

Fig. 1. Change in respiratory and circulatory responses during chair rotations in one endurance runner (left) and an untrained subject (right). Chair velocity (A); flow curve (B); R-R interval (C); blood pressure (D).

both groups (Fig. 3B).

Relative change

Figure 4 indicates the relative changes of $\dot{V}_I$, HR, and MBP normalized by Rest (100%). The relative change of $\dot{V}_I$ in the endurance runners was significantly ($P < 0.05$) greater than those in the untrained subjects during and after chair rotation (Fig. 4A). The trend of the relative change of V_T was the same as those of $\dot{V}_I$. No significant group differences were observed in HR or MBP during or after chair rotation (Fig. 4, B and C).

DISCUSSION

In this study, we attempted to elucidate the ventilatory and circulatory responses at the onset of chair rotation in endurance runners. The main results are as follows:

(i) chair rotation elicits a significant increase in $\dot{V}_I$ with a significant change in V_T but not in respiratory frequency; (ii) no significant increase in HR and only a small increase in MBP were observed during and after chair rotation; (iii) the relative change in $\dot{V}_I$, but not in HR or MBP, at the onset of chair rotation was significantly greater in the endurance runners as compared with untrained subjects. These findings indicate that long-term endurance training would enhance the vestibular-mediated ventilatory response at the onset of passive chair rotation, which selectively stimulates the semicircular canals.

Methodology. Several methods will stimulate the vestibular system; we used chair rotation mainly for the stimulation of semicircular canals. Similar to chair rotation, caloric stimulation selectively stimulates the semicircular canals. However, unlike caloric stimulation, chair rotation does not elicit symptoms of

Fig. 2. Ventilatory responses before, during, and after chair rotations in endurance runners and untrained subjects. $\dot{V}_I$, minute inspiratory ventilation (A); V_T , tidal volume (B); f , respiratory frequency (C). The values are absolute values, which were converted by interpolation into values for each second. The time 0 indicates the onset of chair rotation. The rotation period is indicated by the shaded area. The values are expressed as means and standard errors (SE). †Significantly different ($P < 0.05$) from Rest.

dizziness and nausea, factors that would have an influence on cardiorespiratory responses [6]. Moreover, stimulation to the runners vestibular system originating in running motion was natural and physiological. Therefore, we chose chair rotation to compare the vestibulo-cardiorespiratory responses between endurance runners and untrained subjects in this study.

Vestibulo-ventilatory response. Activation of the vestibular system can cause an increase in ventilation. Studies recently carried out on humans demonstrated that a stimulation of the semicircular canals mediated the increase in ventilatory response [4, 5, 8].

Fig. 3. Circulatory responses before, during, and after chair rotations in endurance runners and untrained subjects. HR, heart rate (A); MBP, mean blood pressure (B). The values are absolute values, which were converted by interpolation into values for each second. The time 0 indicates the onset of chair rotation. The rotation period is indicated by the shaded area. Values are expressed as means and standard errors (SE). †Significantly different ($P < 0.05$) from Rest.

These studies suggested the presence of a vestibulo-ventilatory response in humans.

The mechanism behind the greater vestibulo-ventilatory response in the endurance runners as compared with the untrained subjects induced by chair rotation should be considered from functional changes in the vestibular organs as a result of long-term endurance training. During running, Pozzo *et al.* [15] demonstrated that head frequencies of rotation ranged from 2.5–3.5 Hz with maximal head velocities reaching 60°/s and 81°/s for the horizontal and vertical planes, respectively. In other words, long-distance running exercises can be considered a natural model of repeated and constant activation of the vestibular system [10, 16]. For endurance runners, the head stabilization in space during running exercise is crucial for gaze stabilization and optimizing sensitivity to visual stimuli [16]. Therefore it is conceivable that endurance training over a long period may allow endurance runners to

Fig. 4. Relative changes of $\dot{V}_I$, HR, and MBP during and after chair rotations in endurance runners and untrained subjects. The relative changes were obtained by normalizing the resting values (100%). The rotation period is indicated by the shaded area. The values are expressed as means and standard errors (SE). *Significant differences ($P < 0.05$) between endurance runners and untrained subjects at each time point.

develop adaptive mechanisms to compensate for excessive and over vestibular stimulation during running exercises. Moreover, the regular practice of physical activity, including jogging exercise, improves dynamic postural control with a sizable advantage for vestibular sensitivity, leading to the generation of more appropriate vestibulo-ocular and vestibulo-spinal reflexes [17, 18]. It may be assumed that for long-distance runners, the performance of a long-distance running exercise could induce adaptations that increase the excitability and sensitivity of the vestibular system because of the

augmentation of primary vestibular neurons.

Previous animal studies demonstrated that skeletal muscle afferents have inputs to the vestibular nuclei during muscle contractions, suggesting that neural integration and interaction exist between vestibular nuclei and muscle contraction [11, 19–22]. An understanding of this neural interaction may be important because running exercise engages the muscle afferents and also the vestibular afferents [23]. It is possible to assume that the vestibular system in endurance runners undergoes functional changes induced by repetitive muscle contractions as a result of daily running exercise. However, because there is no information concerning long-term endurance training and its inducing of adaptations on the vestibular system, further research is required.

The vestibulo-ventilatory response would be important for ventilatory responses at the onset of non-stationary exercise such as running [5, 8]. It is possible that the vestibular system will be stimulated in various forms of running exercise in which the head is accelerated and displaced in respect to gravity, and this may contribute to an increase in ventilation [5]. Concerning endurance runners, the vestibulo-ventilatory response could assist in meeting the oxygen cost elicited at the onset of running, and lead to a more precise and coordinated ventilatory response during movement and exercise. Kuipers *et al.* [7] reported that the vestibular-mediated ventilatory response to chair rotation for one minute was attenuated with aging. They also speculated that the rapid increase in ventilation at the onset of non-stationary exercise such as walking and running might be blunted in the elderly. When the results from the elderly subjects of Kuipers *et al.* [7] and from the endurance runners in the present study are considered together, it is quite likely that the vestibular-mediated ventilatory response in humans might be affected by aging and training status.

Vestibulo-circulatory response. A great deal of evidence has demonstrated that the vestibular system influences circulatory control in humans [1, 9, 24–26]. Yates *et al.* [1] reported that an increase in circulatory response, which stimulates the otolith organ, appears by exposing subjects to linear acceleration while they are seated on chairs. Furthermore, a selective stimulation of the otolith organ by head down neck flexion in prone subjects has been shown to increase muscle sympathetic nerve activity [9]. On the basis of previous studies, it has been demonstrated that circulatory response to natural vestibular stimulation resulted from otolith organ activation, but not

from the semicircular canals [5–7].

In the present study, no significant increase in HR was observed during or after chair rotation. These results support the idea that a stimulation of the semicircular canals is not enough to change the HR in humans [6]. In contrast with HR response, we observed a small increase in MBP response after chair rotation. This result did not agree with the findings of previous human studies [5, 7]. The possible discrepancy between our study and previous studies might be explained by a difference in methodology; we used only 2 s chair rotation periods, whereas other researchers had used 1 min periods. In our subjects, a stimulation of the semicircular canals at the onset of chair rotation may have increased sympathetic nerve activity to the peripheral vessel with a subsequent increase in BP response. Furthermore, a previous animal study that observed an increase in BP response induced by gravitational stress was inhibited by the baroreceptors reflex (baroreflex) [27], indicating that the BP response during gravitational stress is a combination of the vestibular feed forward system and the baroreflex feedback system. Although we did not specifically examine these issues, it is assumed that the small change in MBP response at the onset of chair rotation resulted from an increase of muscle sympathetic nerve activity and the baroreflex.

Ray and Carter [11] speculated the possibility that endurance training induced a decrease in the vestibulo-sympathetic reflex, which might be mediated by the otolith organ, would be related in part to an orthostatic intolerance in endurance-trained athletes. However, our findings are limited to the activation on the semicircular canals, but not on the otolith organ. It may be that a selective stimulation of the otolith organ would produce different results. Further investigations are necessary to confirm this point.

Studies of vestibulo-cardiorespiratory responses in humans are still at an early stage in comparison with vestibular-ocular responses, i.e., nystagmus and saccade. Further investigations are required to elucidate the functional and physiological significance of vestibular-cardiorespiratory responses in humans. Moreover, the interrelation between vestibulo-cardiorespiratory responses and vestibular-ocular responses has not been investigated. Future studies, such as including recording of electrooculograms (EOG), will be needed to establish how vestibulo-cardiorespiratory responses interact with vestibular-ocular responses.

Limitation. We must acknowledge that our study suffers from several limitations. First, our study design was a cross sectional study, but not a longitudinal

study. Second, non-vestibular mechanisms are also activated during chair rotation, e.g., startle by the onset of movement (non-specific response). With respect to the latter, the failure of HR responses to change during chair rotation in the present study might argue against this possibility. And, it may be expected that a non-specific response would habituate over time, becoming smaller with subsequent stimulus presentation [1]. However, the order of stimulus presentations had no effect on response magnitude in this study. This observation indicated that non-specific responses were not responsible for eliciting ventilatory or circulatory response at the onset of chair rotation [1].

Conclusion. In conclusion, vestibular-mediated ventilatory response at the onset of passive chair rotation in the endurance runners was significantly greater than in the untrained subjects. We suggest that the increase in vestibulo-ventilatory response could be attributed to an adaptation to long-term endurance training.

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