Ventilatory and Heart Rate Responses at the Onset of Chair Rotation in Man

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Abstract: In the present study, we attempted to confirm whether pulmonary ventilation and heart rate increased immediately after passive chair rotation in man. Inspiratory minute volume ($\dot{V}_I$), tidal volume (V_T), respiratory frequency (f), and heart rate (HR) were determined by breath-by-breath and beat-by-beat techniques before, during, and after rotation for a total of 45 s. It was found that $\dot{V}_I$ significantly increased immediately

ly after chair rotation, but HR remained almost constant. These results suggest that the activation of horizontal semicircular canals is one causal factor of ventilatory response at the onset of exercise with rotational movement in healthy subjects, but heart rate response is not. [The Japanese Journal of Physiology 54: 499–503, 2004]

Key words: phase I, semicircular canal, human.

It is well known that pulmonary ventilation and heart rate both increase immediately after light or moderate exercise. This abrupt increase in ventilation has been shown to occur usually from the first breath [1] and is termed phase I [2]. This phase I response, lasting about 15 s, is observed not only during voluntary exercise, but also during passive movement following electrically induced muscle contractions or flexion extensions of the lower legs with ropes [3, 4].

Nevertheless, many investigators have pursued mechanisms that are responsible for the phase I response, and their opinions about its nature are still a matter of dispute. At present, it is considered that two neural mechanisms, central command and peripheral reflex, mainly trigger the increase in ventilation that appears at the onset of exercise [5–7]. Central command arises from the activation of the cerebral cortex and hypothalamus [8, 9], and peripheral reflex originates in the stimulation of groups III and IV muscle afferents [10, 11]. Recently, a stimulation of the vestibular system has been reported to elicit cardiovascular and respiratory changes [12, 13]. In support of this concept, Jauregui-Renaud *et al.* [14] observed

that a stimulation of the vertical semicircular canal increased breathing frequency in normal subjects, but not in vestibular-deficient patients. Monahan *et al.* [15] also reported significant changes in respiratory frequency and minute ventilation from the baseline during dynamic chair rotation for one minute. From these results, it is possible to hypothesize that an abrupt increase in minute ventilation and heart rate immediately after exercise may be related not only to central command and afferent impulses from working muscles through groups III and IV, but also to semicircular canals that would be stimulated in various sports situations, such as rotation in ice skating or artistic gymnastics. To our knowledge, however, no data are available concerning this hypothesis in healthy subjects. The purpose of this study, therefore, was to clarify whether the horizontal semicircular canal afferents mediate the ventilatory and heart rate responses at the onset of passive chair rotation in man.

METHODS

The present study was approved by the Human Research Committee of the Research Center of

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Health, Physical Fitness and Sports of Nagoya University. Eight healthy men volunteered to participate, and they were informed of the experimental protocol and possible risks involved in the study before giving written consent. None had a history of cardiorespiratory disease, of medications that seriously affected cardiorespiratory response, or of tobacco. The mean and standard errors of age, height, and weight of the subjects were 27.0 (1.92) years, 171.6 (1.20) cm, and 63.1 (2.40) kg.

The vestibular stimulus tests were carried out on each subject by using chair rotations; i.e., during the experiment, the subject sat with his back against an experimental swivel chair. Each subject's torso and head were securely fastened to the chair with belts. The chair could be swiveled 360° about a central axis by an experimenter, and a rotation would be denoted as either "right turn" or "left turn." After resting comfortably in a sitting position for 20 min, the subject was asked to relax during experiment. The rotation chair was turned 180° manually by an experimenter for 1.5 (1.4–1.6) s in mean from right to left or the reverse.

The right-turn and the left-turn were repeated randomly three times at intervals of approximately a few minutes; the subject's eyes were closed to exclude the effects of the field of vision. These rotating tests were initiated just before the start of the inspiratory phase, and the experimenter observed the activity on an oscilloscope connected to a hot-wire flow meter (RF-H, Minato Ikagaku, Japan). The goniometer was attached to the axis of the turn chair to detect the start of turning. Inspiratory minute volume ($\dot{V}_I$), tidal volume (V_T), and inspiratory and expiratory periods were determined by the breath-by-breath technique before, during, and after turning for a total of 45 s. That is, $\dot{V}_I$ and V_T were measured continuously for 30 s before, 1.5 s during, and 13.5 s after chair rotation. The subject breathed through a respiratory face mask attached to a hot-wire flow meter. The respiratory frequency (f) was calculated from the total respiratory time, and $\dot{V}_I$ was obtained as the product of V_T and f . Furthermore, heart rate (HR) was also monitored beat-to-beat by using electrocardiography before, during and after rotation for a total of 45 s. All ventilatory and circulatory signals were converted from analog to digital data with an A/D converter (Canopus, ADX 98H, Japan) at a sampling frequency of 100 Hz. These data were stored on a hard disk unit, and analyzed afterward on a personal computer (NEC, PC-9821Xa, Japan). Breath-by-breath and beat-by-beat data were aligned with the onset of each turn, linearly interpolated between each breath

or beat to yield a data point at each 1 s interval, and the ensemble average was done across all three repetitions [16, 17]. The peak attained times of $\dot{V}_I$, V_T , and f for each subject were calculated in both right- and left-turn conditions. The changes in absolute values of the parameters during and after a turn, compared with the rest levels, were analyzed in regard to variance with repeated measurements. If a significant F ratio ($p < 0.05$) was obtained, Dunnett's test was used to determine when the differences during the turn occurred. In comparing a left-turn with a right-turn, the Wilcoxon test was used. The level of significance was set at 0.05.

RESULTS

Figure 1 shows the results of ventilatory response before, during, and after chair rotation in both the left-turn and the right-turn. $\dot{V}_I$ increased significantly ($p < 0.05$) immediately after rotation. V_T also increased at the onset of rotation, except at 1 s in the left-turn. In contrast, f unchanged immediately after rotation in both the left-turns and the right-turns, except at 2 s in the left turn. Mean values ($\pm$ SE) of peak attained time of $\dot{V}_I$, V_T , and f were 3.7 (1.1), 2.6 (0.6), and 5.1 (2.0) s for the right-turn and 2.6 (0.2), 2.4 (0.3), and 3.7 (1.4) s for the left-turn. There are no significant differences in the peak attained times of $\dot{V}_I$, V_T , and f between the right-turn and the left-turn. And as indicated in Fig. 2, HR did not increase significantly by chair rotation in either condition, except for the value obtained at 2 s after the beginning of left rotation. Since the values at rest of $\dot{V}_I$, V_T , f , and HR were different in the two turns, we compared the differences in ventilatory and circulatory responses at the onset of the right-turn and the left-turn by the Δ value estimated from a mean value of rest for 30 s of 100%. The $\Delta\dot{V}_I$ and ΔV_T increased immediately after rotation in both conditions. The $\Delta\dot{V}_I$ was significantly ($p < 0.05$) greater in the left-turn than in the right-turn at 2–5 s, but no significant difference was found in ΔV_T . Compared with the right turn, the Δf was significantly ($p < 0.05$) greater in the left-turn at 1–3. On the other hand, no significant difference was observed in ΔHR between the right-turn and the left-turn, except at 10 s in ΔHR .

DISCUSSION

In the present study, we attempted to confirm whether pulmonary ventilation increases at the onset of passive chair rotation in healthy subjects. It was found that $\dot{V}_I$ significantly increased immediately after chair

Fig. 1. Absolute changes (left panel) and relative changes (right panel) in inspiratory minute volume ($\dot{V}_I$), tidal volume (V_T) and respiratory frequency (f) before, during and after chair rotation in left-turns (opened circles) and right-turns (closed circles). Values in the right panel are absolute values that were converted by interpolation into values for each second. The percentage changes in inspiratory minute volume ($\Delta \dot{V}_I$), tidal volume (ΔV_T) and respiratory frequency (Δf) in the right-turn and left-turn when the average of the values at rest was 100%. The turn period is shown with shade area. Time 0 indicates the onset of rotation. Values are expressed as mean ($\pm$ SE). The symbol * indicates a significant difference ($p < 0.05$) from rest, and the symbol # indicates a significant difference ($p < 0.05$) between the right-turn and the left-turn.

Fig. 2. Absolute changes (left panel) and relative changes (right panel) in heart rate (HR) before, during and after chair rotation in the left-turn (opened circles) and the right-turn (closed circles). The values in the right panel are absolute values, which were converted by interpolation into values for each second. The percentage changes in heart rate (ΔHR) in the right-turn and left-turn when the average of the values at rest is 100%. The turn period is shown as a shaded area. Time 0 indicates the onset of rotation. The values are expressed as mean ($\pm$ SE). The symbol † indicates a significant difference ($p < 0.05$) from rest, and the symbol # indicates a significant difference ($p < 0.05$) between the right and the left-turns.

rotation in both the right- and left-turns, but not f or HR, as shown in Figs. 1 and 2. We believe this is the first study to show a contribution of the horizontal semicircular canal to ventilatory responses at the onset of passive rotation in humans.

In the previous study, Monahan *et al.* [15] observed that breathing frequency and minute ventilation were increased, whereas tidal volume is unchanged during chair rotation. In contrast, it was found in the present study that minute ventilation and tidal volume increased immediately after chair rotation, but respiratory frequency did not. The difference in the results obtained by Monahan *et al.* and those in the present study may be due to the differences in the time, velocity, and maneuver of chair rotation. On the other hand, $\Delta\dot{V}_I$ and Δf were significantly ($p < 0.05$) greater in the left-turn compared with the right-turn, as shown in Fig. 1. We cannot now explain why these results were obtained. It may be possible to assume that the right and left differences in the sensitivity of semicircular canals exist even if the subjects are healthy men. However, this assumption requires further investigation.

Since the changes in ventilation are so rapid during the transition from rest to exercise, phase I response cannot be explained by humoral agents because of the delay in transport. At present, the causal factors of phase I are classified largely into central and peripheral neurogenic stimuli, or both [6, 9]. Jauregui-Renaud *et al.* [14] recently measured respiratory frequency during rotational stimuli by using a motorized rotating chair with acceleration in <1 s to a constant rotational velocity of $60^\circ/\text{s}$ on vertical axis, sustained for 1 min. They observed that in normal subjects, rotation in the pitch plane elicited an increase in respiratory frequency because of a shortening of the time for expiration. From these results, they conclude that vertical semicircular activity exerts a regulatory drive on respiration in human subjects. Furthermore, Monahan *et al.* [15] have determined cardiorespiratory parameters such as inspiratory time, expiratory time, ventilation, heart rate, and mean blood pressure during seven various conditions (dynamic upright pitch, dynamic lateral pitch, dynamic head roll, dynamic yaw, dynamic chair rotation, static head down rotation, and static head rotation in the lateral decubitus position) in order to confirm the hypothesis that the activation of the semicircular canals would increase respiration in humans. Since significant changes in inspiratory time, expiratory time, and minute ventilation from the baseline during dynamic chair rotation of 15 cycle/min for one

minute were observed, they suggested that the semicircular canal, but not the otolith organs or neck muscle afferents, mediates increased ventilation in humans and supports the concept that vestibular activation alters respiration in humans. Because they did not indicate the results of respiratory parameters obtained by the breath-by-breath technique for 15 s from the start of chair rotation, however, it is unclear whether this horizontal vestibular activation produced functional alterations in phase I. In other words, it is important to emphasize that ventilatory and heart rate responses should be determined continuously with breath-by-breath and beat-by-beat techniques within 15 s rather than one minute total in order to clarify whether a horizontal semicircular canal stimulus is related to ventilatory response (phase I) at the onset of exercise.

As described previously, it is very possible that semicircular canals would be stimulated in various situations of actual physical exercise and sports, such as rotations in ice skating or in artistic gymnastics. In the present study, $\dot{V}_I$ increased significantly immediately after passive chair rotation, but HR was unchanged at the onset of chair rotation in both left- and right-turns, as shown in Figs. 1 and 2. We could not compare the ventilatory kinetics with respect to time constant and amplitude between chair rotation and exercise stimuli, since rotation time of the present study was very short (1.5 s). So, we calculated peak attained time of $\dot{V}_I$ for each subject in both left- and right-turn conditions. The mean values of peak attained time of $\dot{V}_I$ were 3.6 s for the right-turn and 2.6 s for the left-turn. These results suggest that the activation of the horizontal semicircular canal is one causal factor of ventilatory response in human subjects at the onset of exercise with rotational movement, but not of heart rate response. Although afferent signals from the body trunk and/or neck through groups III and IV could have also made some contribution to the abrupt increase in $\dot{V}_I$ and V_T immediately after rotation, it is unlikely that the contributions of group III and IV afferents was mainly caused by the increase of $\dot{V}_I$ and V_T in the present study because the subject's torso and head were securely fastened with belts in a rotation chair. However, we cannot explain based on physiological grounds why respiratory frequency and heart rate are unchanged at the onset of chair rotation in both conditions. It will be necessary to conduct further investigation why f and HR remained constant, though $\dot{V}_I$ and V_T significantly increased immediately after passive rotation.

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