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Effects of Different Breathing Patterns on Oxygen Consumption of Respiratory Muscles

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呼吸筋酸素消費量に対する異なる呼吸パターンの効果

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Key words : abdominal muscles, dead space breathing, diaphragm muscle, energy efficiency, rib cage muscles

We measured oxygen consumption of respiratory muscles under abdominal or rib-cage restrictive breathing in 7 normal male subjects. Restriction of rib cage movement (Restrict-rib, i.e., diaphragm- and abdominal-muscle dominant breathing) or abdominal movement (Restrict-abd, i.e., rib-cage-muscle dominant breathing) was achieved by using an inelastic corset and was compared with no restriction of breathing (control). The oxygen consumption of respiratory muscles ($\Delta\log \dot{V}_{O_2}/\Delta\dot{V}_E$) was assessed in the three breathing modes as a parameter of energy efficiency. The mean $\Delta\log \dot{V}_{O_2}/\Delta\dot{V}_E$ in Restrict-rib was significantly smaller than those of the other two breathing modes ($p<0.05$). The mean $\dot{V}_{O_2}$met ($\dot{V}_{O_2}$ at $\dot{V}_E=0$ l/min by extrapolation) did not differ significantly between the three modes. At the end point of measurement in Restrict-rib, total $\dot{V}_{O_2}$ was significantly decreased and endurance time was significantly elongated compared with those of Restrict-abd, respectively ($p<0.05$). The results indicate that Restrict-rib breathing consumes less energy than Restrict-abd breathing in normal subjects. Therefore, it is speculated that diaphragm- and abdominal-muscle dominant breathing is an important breathing mode which reduces oxygen consumption of respiratory muscles and is thus beneficial in patients with COPD.

Introduction

It is well known that the diaphragm is a major inspiratory muscle[1)] and abdominal breathing has been thought to be effective in the rehabilitation of patients with chronic respiratory failure[2)～4)]. Recently, we have developed an apparatus for measuring oxygen consumption of respiratory muscles with loading of an expandable dead space[5)]. By using this system, we can measure the ratio of oxygen consumption of respiratory muscles ($\dot{V}_{O_2}$) per minute ventilation ($\dot{V}_E$) which corresponds with the energy efficiency of respiratory muscles, and have reported that the oxygen consumption of patients with chronic obstructive pulmonary disease (COPD) is 2.8 times higher than that of normal subjects of the same age[6].

Although previous study has examined the partitioning of respiratory muscles with restriction of the rib cage or abdomen using electrical activity of the diaphragm (Edi)[7], the oxygen consumption of respiratory muscles ($\dot{V}_{O_2}$) as a parameter of energy efficiency in such breathing modes has not been well characterized. Therefore, we used the above-mentioned apparatus[5] to measure the oxygen consumption of respiratory muscles in three modes of breathing in normal subjects. We found that breathing in the restriction of rib cage mode (i.e., diaphragm- and abdominal-muscles dominant breathing) was characterized by the smallest the oxygen consumption per minute-ventilation among these three breathing modes.

Methods

Subjects

We examined seven normal male subjects (mean age 30 ± 0.9 yr.) who were free from cardiac, pulmonary or neuromuscular complaints and whose physical examination findings were normal. None of the subjects was informed of the purpose of this study. Each subject gave informed consent to the protocol which had received prior approval of the Human Research Committee of Tohoku University School of Medicine.

Experimental apparatus

Figure 1 shows the experimental apparatus for measurement of oxygen consumption of respiratory muscles. The principle of the apparatus is basically the same as that described in a previous paper[5]. The apparatus consists of a fixed section, an expandable dead-space section, and a section for measuring oxygen consumption. The fixed section consists of rigid tubing, a three-way valve, and a Fleisch no. 4 pneumotachometer heated to 37°C. The expandable dead space section is made of a long piece of corrugated plastic tubing functioning as an expandable bellows. The external and internal diameters of the corrugated tubing are 4.0 and 3.3 cm, respectively. One end of the corrugated tubing is connected to the fixed section described above, and the other end, free to move, is pulled along the groove at

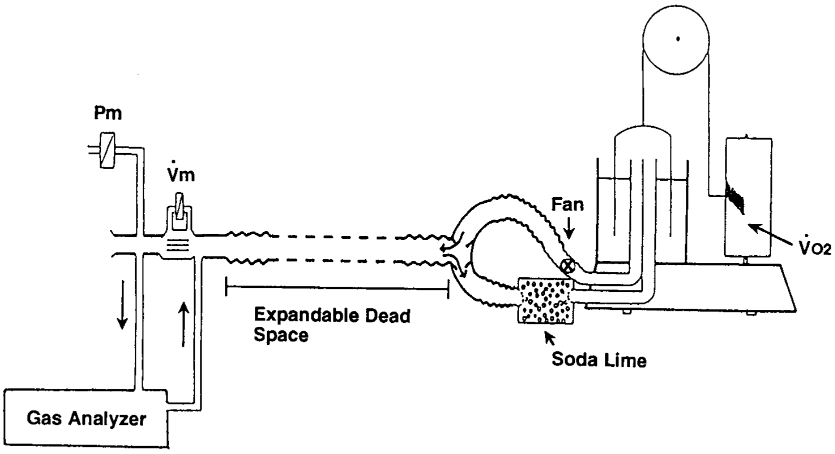


Fig. 1. A block diagram of the apparatus to measure oxygen consumption of respiratory muscles.

a constant rate of 100 ml/min, and is connected to the section which measures oxygen consumption. The minimal volume of this dead space (corrugations fully compressed) is 1.0 liter, and the maximal volume (fully extended) is 3.0 liters. The resistance of the combined system varies from 0.83 $cmH_2O/l/s$ in the minimal configuration to 0.99 $cmH_2O/l/s$ in the maximal one.

Oxygen consumption ($\dot{V}_{O_2}$, STPD) is measured by a decrease in volume of a 9-liter water shield Collins spirometer, which is filled with 100% oxygen and connected to the movable end of the expanding dead space through a pair of flexible tubes. Circulating airflow from the spirometer to the termination of the dead space through the pair of tubes is generated by a 40 l/min fan in one tube ; a container of soda lime is placed in the other tube to absorb carbon dioxide. This arrangement effectively provides a constant gas composition of 100% oxygen at the termination of the dead space. The absence of gas leakage from the whole apparatus is confirmed before every measurement.

Mouth flow ($\dot{V}_m$) is measured by the pressure drop across the heated (37°C) Fleisch pneumotachometer with a differential pressure transducer (MP 45±5 cm ; Validyne Corp., Northridge, CA) and is electrically integrated to obtain minute ventilation ($\dot{V}_E$, BTPS). The fractional concentration of oxygen (F_{O_2}) and that of carbon dioxide (F_{CO_2}) in the expired gases are measured at the mouthpiece with a polarographic and infrared gas analyzer (1H26, San-Ei, Japan). Gas at the mouthpiece is sampled at 20 ml/min for measurement of F_{O_2} and F_{CO_2}, and is then returned to the circuit. Lung volume is monitored with an inductance plethysmograph (Respitrace, Ardsley, NY) using abdominal and rib cage belts, following the method of Konno and Mead[8]. It is performed with isovolume maneuvers at functional residual capacity (FRC) to adjust the summation of rib-cage and abdominal movement to 0 liters, and then performed with inspiration of a 2-liter balloon for calibration of the summation volume of rib-cage and abdominal signals to 2 liters. Abdominal and rib-cage displacements are displayed on an oscilloscope (TEKTRONIX R5103N, USA) that is visible to the subjects along an approximately 45 degree line. Each subject was instructed to adjust FRC position as a target for end expiration during the subsequent testing. The $\dot{V}_m$, $\dot{V}_E$, F_{CO_2}, F_{CO_2} signals and the displacements of the rib cage and abdomen and their summation are recorded on an eight-channel hot-pen recorder (Recti-Horiz 8 K, San-Ei, Japan).

Experimental protocol

The measurements were performed in the morning, in subjects who had not eaten breakfast, after the subjects had sat in a comfortable chair for more than 30 min. Before the experiments, vital capacity (VC) and forced expiratory volume per second (FEV_1) were measured with a computerized spirometer (Chest, Japan). The predicted normal values of VC and FEV_1 were in reference to those of Cotes[9]. An inelastic corset for separate chest wall and abdominal restriction, the configurations of which were obtained by gauge and plaster in each subject, were made by a professional. Before applying each corset, the rib cage and abdomen were fitted with Respitrace belts. The corset was applied to restrict the rib cage (Restrict-rib) or the abdominal wall (Restrict-abd) at FRC (functional residual capacity). For Restrict-abd, the corset was applied circumferentially around the abdomen between the iliac bone and the lowest one or two ribs to restrict posteriorly in an attempt to maximally restrict the abdominal expansions while minimally interfering with rib-cage movement. For Restrict-rib, the corset was applied circumferentially around chest wall between the axilla and lowest ribs.

The subjects were then asked to take a supine position. A control trial, corresponding to thoraco-abdominal breathing, was done without the inelastic corset. Before each trial, VC and FEV_1 were measured in each condition in the supine position. These three trials were performed in random order with a rest of more than 30 min after each trial.

In all three breathing modes, the subjects were under air breathing conditions for a few minutes, with the three-way valve between the pneumotachometer and dead-space tube open to the atmosphere (i.e., baseline). As described above, the subjects were instructed to maintain their control FRC level by matching their rib-cage and abdominal-displacement signals at end expiration of the isovolume FRC line on the oscilloscope. In other words, the subjects had to maintain their FRC level constant on the oscilloscope. The three-way valve was then turned on to connect the subject to the expandable dead space and oxygen measurement parts. The expandable dead space was held at minimal volume for 3 min and then increased at a rate of 100 ml/min. This initial 3-minute period allowed the subjects to reach a quasi-steady state. Each subject breathed continuously through this increasing dead space until he could not tolerate this maneuver any longer. When the subject signaled this point (i.e., end point) by raising a hand, the procedure was immediately halted.

Data analysis

$\dot{V}_{O_2}$ (ml/min, STPD) was calculated as the 1-min increase in end expiratory volume recorded spirometrically minus the increase in the volume of dead space[5]. The logarithm of $\dot{V}_{O_2}$ was therefore regressed by least squares against $\dot{V}_E$ for each subject. We characterized $\dot{V}_{O_2}$ by the slope of the semilog regression ($\Delta\log \dot{V}_{O_2}/\Delta\dot{V}_E$) and the intercept ($\dot{V}_{O_2}$met) at $\dot{V}_E = 0$ l/min. Paired data were tested by paired *t*-test. Significance was accepted for $p < 0.05$. Results were expressed as means ± SE.

Results

Anthropometric and spirometric data of seven normal male subjects are listed in Table 1. Spirometric data were as follows: VC (4.9 ± 0.2 l), %VC (110 ± 3.2%), and FEV_1/VC

Table 1. Characteristics of seven normal male subjects

Subject	Age (yr)	Height (cm)	Weight (kg)	VC (l)	%VC (%)	FEV_1 % (%)
1	31	175	74	5.1	106	82.6
2	31	164	64	5.6	121	80.3
3	34	171	71	4.4	109	90.3
4	30	177	62	5.3	107	81.8
5	26	162	57	4.1	96	86.9
6	29	165	65	4.8	111	82.0
7	30	163	70	5.0	119	82.9
Mean±SE	30±0.9	168±2.3	66±2.2	4.9±0.2	110±3.2	83.8±1.3

Abbreviations: VC, vital capacity; %VC, percentage of vital capacity to predicted value; FEV_1%, forced expiratory volume in one second divided by VC.

(83.8±1.3%), which were considered as being within normal ranges. Table 2 shows the effect of positions on respiratory function. There were no significant differences in VC or FEV_1 between positions of sitting and supine control (no restrictions). In the supine position, VC in Restrict-abd and Restrict-rib, and FEV_1 in Restrict-rib were significantly less than those in sitting and supine control, these decreases being caused by rib-cage or abdominal restriction. However, it is noteworthy that there were no significant differences in VC or FEV_1 in Restrict-rib and Restrict-abd in the supine position.

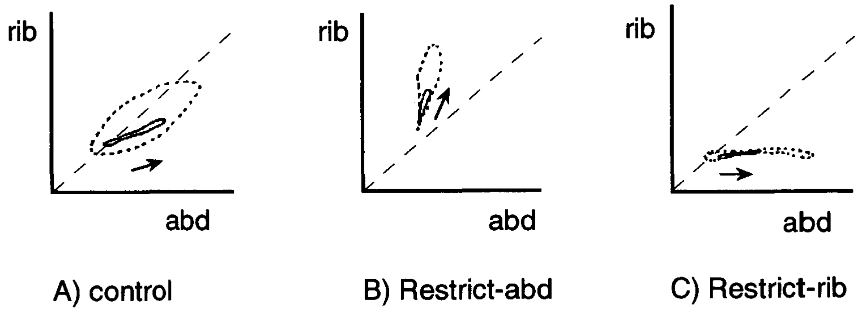
Figure 2 shows the Konno-Mead diagram of the three breathing modes in one subject (No. 1). Each panel shows that the subject maintained his control FRC level by matching rib-cage and abdominal-movement signals at end expiration of the isovolume FRC level. The abdominal movements are expressed by the x-axis and the rib-cage movements are expressed by the y-axis. In the control (no restriction), the movements of the rib cage and abdomen are expressed along an approximately 45-degree line (Fig. 2A). The Restrict-abd showed the limitations of abdominal movement, and thus only rib-cage movement existed (Fig. 2B). The Restrict-rib showed the limitations of rib-cage movement, and thus only abdominal movement existed (Fig. 2C). The solid lines are at the baseline, and the dotted lines are at the end point of the measurement of oxygen consumption of respiratory muscles.

Figure 3 shows the relationship between logarithm of $\dot{V}_{O_2}$ (log $\dot{V}_{O_2}$) and $\dot{V}_E$ in the three modes of breathing in the same subject (No. 1). The log $\dot{V}_{O_2}$ correlated approximately linearly with $\dot{V}_E$ in each breathing mode, and there were also good linear correlations in all subjects (r = 0.85-

Table 2. Effects of position on spirometric data

	Sitting	Supine		
		control	Restrict-abd	Restrict-rib
VC (l)	4.89±0.19	4.68±0.18	4.25±0.17*	4.20±0.18*
FEV_1 (l/sec)	4.34±0.17	4.38±0.17	3.74±0.15	3.61±0.15*

Values are means±SE. Abbreviations: control, without restriction; Restrict-rib, restriction of rib cage; Restrict-abd, restriction of abdomen; VC, vital capacity; FEV_1, forced expiratory volume in one second. *$p<0.05$, significantly different between sitting and supine control.



A) control B) Restrict-abd C) Restrict-rib

Fig. 2. A) control, B) Restrict-abd, and C) Restrict-rib show three breathing modes in a subject (No. 1). The solid and dotted lines of Konno-Mead diagram represent baseline and end point in the measurements of oxygen consumption of respirator muscles, respectively.

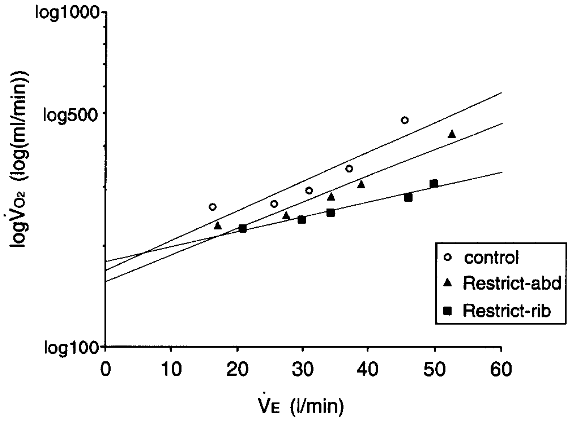


Fig. 3. Relationships between log $\dot{V}_{O_2}$ and $\dot{V}_E$ among the three breathing modes were shown with semi-log regression lines in a subject (No. 1). Open circles, closed triangles and closed squares represent control, Restrict-abd and Restrict-rib, respectively.

0.98). The slope of each semilog regression line (Δlog $\dot{V}_{O_2}/\Delta\dot{V}_E$) was used for a representative parameter of oxygen consumption of respiratory muscles to compare the three modes of breathing, and the Δlog $\dot{V}_{O_2}/\Delta\dot{V}_E$ of Restrict-rib was the smallest slope among the three modes of breathing.

The mean data of seven normal subjects in the three breathing modes are shown in Figure 4. The mean values for Δlog $\dot{V}_{O_2}/\dot{V}_E$ were 0.0085±0.0014 (log(ml/min)/(l/min)) in the control, 0.0084±0.0011 (log(ml/min)/(l/min)) in the Restrict-abd and 0.0054±0.0006 (log(ml/min)/(l/min)) in the Restrict-rib, respectively. The mean slope of Restrict-rib was significantly smaller than those of the other two breathing modes ($p<0.05$) (Fig. 4A). This means that the Restrict-rib breathing mode (i.e., diaphragm- and abdominal-muscle-dominant breathing) had the smallest oxygen consumption rate of respiratory muscles of the three breathing modes. The mean values for $\dot{V}_{O_2}$met were 163±12.1 (ml/min) in the control, 162±9.5 (ml/min) in the Restrict-abd and 181±6.8 (ml/min) in the Restrict-rib, respectively, the values of which did not differ significantly among the three modes of breathing (Fig. 4B). This means that metabolic oxygen consumption except that of respiratory muscles did not differ in the three breathing modes.

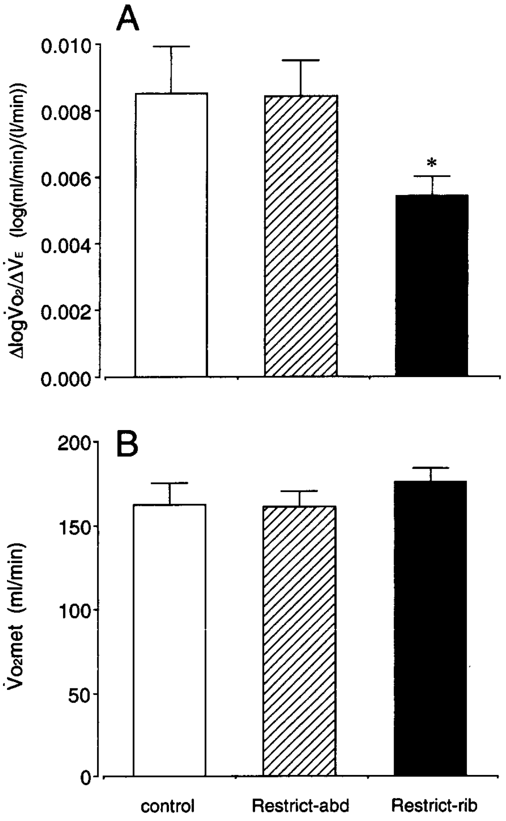


Fig. 4. A. Mean slopes (Δlog $\dot{V}_{O_2}/\Delta\dot{V}_E$) of regression lines of the three breathing modes. Δlog $\dot{V}_{O_2}/\Delta\dot{V}_E$ in Restrict-rib was the smallest in the three breathing modes (*$p<0.05$). B. $\dot{V}_{O_2}$met of the three breathing modes did not significantly differ.

Table 3 summarizes changes of respiratory parameters in the three modes of breathing at the baseline and end point during the measurement of oxygen consumption of respiratory muscles. The tidal volume (V_T) of Restrict-rib and Restrict-abd tended to decrease at the end point compared with the control, but there were no significant differences between the two in either group. The breathing frequency (f) in Restrict-rib and that in Restrict-abd were

Table 3. Respiratory parameters and endurance time in the three modes of breathing

		control	Restrict-abd	Restrict-rib
V_T (l)	Baseline	0.96±0.13	0.87±0.06	0.87±0.04
	End point	2.64±0.39	2.14±0.20*	1.83±0.33*
f (min^{-1})	Baseline	15.7±1.0	19.1±0.9*	18.0±1.1*
	End point	19.5±3.3	29.6±4.6*	31.8±5.7*
$\dot{V}_E$ (l/min)	Baseline	15.7±2.3	16.7±1.1	16.2±1.5
	End point	47.8±5.4	56.6±10.6*	58.8±9.5*
$\dot{V}_{O_2}$ (ml/min)	Baseline	281±23.7	270±20.8	271±16.1
	End point	363±16.1	362±13.2	349±14.6†
Endurance time (min)		9.8±1.1	6.2±2.2*	7.1±1.7*†

Values are means±SE. Abbreviations: control, without restriction; Restrict-abd, restriction of abdomen; Restrict-rib, restriction of rib cage; V_T, tidal volume; f, breathing frequency; $\dot{V}_E$, minute ventilation; $\dot{V}_{O_2}$, oxygen consumption. *$p<0.05$, significantly different from control. $^\dagger p<0.05$, significantly different from Restrict-abd.

significantly increased compared with the control at the end point, but there were no significant differences between the two in either group. Consequently, $\dot{V}_E$ (i.e., $V_T \times f$) at the end point was not significantly different in Restrict-rib and Restrict-abd. Baseline values of $\dot{V}_{O_2}$ among the three modes of breathing did not differ significantly, but at the end point, $\dot{V}_{O_2}$ of Restrict-rib showed a significant decrease from the control and Restrict-abd. Because $\dot{V}_{O_2}$ was less in Restrict-rib than in Restrict-abd, the slopes of $\Delta\log \dot{V}_{O_2}/\Delta\dot{V}_E$ were smaller than those of Restrict-abd. The endurance time of Restrict-rib and that of Restrict-abd were significantly shorter compared with that of control, and that of Restrict-rib was significantly longer than that of Restrict-abd. Hence, it may be concluded that the Restrict-rib breathing mode consumes less energy and is more tolerable than the Restrict-abd breathing mode.

Discussion

Oxygen consumption of respiratory muscles was measured under three breathing modes, namely, Restrict-rib (restriction of rib cage), Restrict-abd (restriction of abdomen), and control (without restriction) breathing by applying continuously increasing external dead space. Our results showed that the slope ($\Delta\log \dot{V}_{O_2}/\Delta\dot{V}_E$) of Restrict-rib was less than those of Restrict-abd and control. In Restrict-rib, rib-cage respiratory muscles were restricted so that the diaphragm and abdominal muscles were recruited to increase minute ventilation. Hence, the diaphragm- and abdominal-dominant breathing indicates less oxygen consumptive breathing at corresponding minute ventilation. On the other hand, in Restrict-abd, the movement of the diaphragm and that of the abdominal muscles were restricted and the rib-cage respiratory muscles were recruited, which indicates more oxygen conservative breathing than in Restrict-rib.

Concerning the separate restrictions of the rib cage or abdomen, a few studies on ventilatory responses to CO_2 inhalation[7,10] and in exercise[11] have been previously done. The effects of restrictions of the abdomen or rib cage on ventilation, which were induced by applying a block of wood fitted to the abdominal contour or by a board held rigidly against the sternum were reported. Tidal volume (V_T) and electrical activity of the diaphragm (Edi) were not found to change significantly in abdominal restriction, while the Edi in rib cage restriction increased to about twice that with no restriction, without any significant change in V_T7). It was also reported that P_{100}/P_{ACO_2}, which indicates the inspiratory motor output of the neuronal respiratory center to unit alveolar P_{CO_2}, was greater in selective elastic strapping of the rib cage than that in abdominal strapping or in the control10). Furthermore, it was reported that the restriction of rib cage induced a greater increase of Edi than that in the restriction of the abdomen or in the control during exercise11). These previous reports consistently agree that the recruitment of the diaphragm occurs corresponding with Edi in the restriction of rib-cage respiratory muscles.

However, because the restriction of the rib cage may induce diaphragm- and abdominal-muscle recruitment to maintain minute ventilation ($\dot{V}_E$), the augmentation of diaphragm-muscle Edi seems to be an expected phenomenon. Even though the diaphragm muscle or rib-cage muscle might be facilitated by neuronal respiratory centers to the same degree (i.e., same $\dot{V}_E$) during these restricted breathing modes, the oxygen consumption of each respiratory muscle may differ depending on the performance of each respiratory muscle. Our results indicate that Restrict-rib (i.e., diaphragm- and abdominal-muscle-dominant breathing) is about 64% of Restrict-abd (i.e., rib-cage respiratory-muscle-dominant breathing) with regard to oxygen consumption. This result seems to be contrary to the previously reported augmentation of Edi, however, we strongly speculate that the differences in oxygen consumption might result from the differences of energy efficiencies between the diaphragm muscle and the rib-cage muscles. Therefore, our results show that the diaphragm muscle consumes less oxygen than the rib cage respiratory muscles at the same $\dot{V}_E$.

As shown in Table 2, VC decreased significantly in Restrict-rib and Restrict-abd compared with the control, and this decrease in VC by restriction was related to the decrement of minute ventilation ($\dot{V}_E$). It has been reported that the head-down position in patients with pulmonary emphysema induced an increase of PaO_2 and a decrease of $PaCO_2$ despite a 20 to 30% decrease in $\dot{V}_E$2). The maximal minute ventilation was elicited in the range of 50-60 l/min during the measurements of oxygen consumption in this study, and that was relatively smaller than the value of 75 l/min in the previous study5). The differences of maximal minute ventilation between the two studies may be explained as being due to the differences of positions (supine in the present study vs. sitting in the previous one) and restrictions of the rib cage or abdomen.

It is an interesting finding that the endurance time of Restrict-rib was longer than that of Restrict-abd. It is suggested that shorter endurance times in Restrict-abd or Restrict-rib compared with that in the control also corresponded to the restrictions of the rib cage and abdomen. These restrictions induced a decrease in V_T, but an increase in breathing frequency (f) in the measurements of oxygen consumption, and resulted in a rather higher increase in $\dot{V}_E$ than that of the control. On the other hand, the oxygen consumption ($\dot{V}_{O_2}$) at end point was almost the same in the control and Restrict-abd, but was less in Restrict-rib. This suggests the possibility that less oxygen consumption (i.e., energy expensiveness) may be related to the longer endurance time in Restrict-rib.

Even though this study was done on only normal subjects, our results may be extended to respiratory diseases. In COPD (chronic obstructive pulmonary disease), especially in pulmonary emphysema, the hyperinflation of the lungs produces shortening of the diaphragm muscle (i.e. diaphragm flattening) and reduces force generation of the diaphragm due to a leftward shift in the length-tension relationship[12]. We have recently reported that the oxygen consumption of respiratory muscles in COPD patients was larger than that of age-matched normal subjects[6], and it has been reported that the cost of breathing increased at a high lung volume[13]. To prevent such high oxygen consumption of respiratory muscles, which decreases an the utility of oxygen in organs except the respiratory muscles, training in diaphragm- and abdominal-muscle dominant breathing in COPD patients seems to be an important issue to decrease dyspnea.

In conclusion, this study is the first report of oxygen consumption of respiratory muscles in partitioning of breathing. It clarified that Restrict-rib, hence abdominal dominant breathing, is a less energy consumptive breathing mode in normal subjects. Because diaphragm- and abdominal-dominant breathing reduces oxygen consumption of respiratory muscles, such breathing is proposed as a beneficial breathing mode for treatment and rehabilitation of COPD patients.

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