Decrease in functional residual capacity during inspiratory loading and the sensation of dyspnea

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KIKUCHI, YOSHIHIRO, WATARU HIDA, TATSUYA CHONAN, CHIYOHIKO SHINDOH, HIDETADA SASAKI, AND TAMOTSU TAKISHIMA. Decrease in functional residual capacity during inspiratory loading and the sensation of dyspnea. J. Appl. Physiol. 71(5): 1787-1794, 1991.—The purposes of the present study were to determine the changes in functional residual capacity (FRC) during inspiratory loading and to examine their mechanisms. We studied seven normal subjects seated in a body plethysmograph. In both graded inspiratory elastic (35, 48, and 68 cmH2O/l) and resistive (21, 86, and 192 cmH2O·L−1·s) loading, FRC invariably decreased from control FRC and phasic expiratory activity increased. The reduction in FRC was greater with greater loads. A single inspiratory effort against an inspiratory occlusion at three different target mouth pressures (−25, −50, and −75 cmH2O) and durations (1, 2, and 5 s) also resulted in a decrease in FRC with an increase in respiratory electromyogram activity in the following expiration. The decrease in FRC was greater with greater target pressure and duration. This decrease in FRC is qualitatively similar to that during inspiratory loaded breathing, and we suspect that the same mechanisms are at work. Because neither vagal nor chemoreceptor reflex can account for these responses, we suspect conscious awareness of breathing or behavioral control to be responsible. In an additional study, the sensation of discomfort of breathing during elastic loading decreased with a decrease in FRC. These results suggest that the reduced FRC may be due to behavioral control of breathing to reduce the sensation of dyspnea during inspiratory loading.

Methods

Seven healthy male subjects between the ages of 28 and 35 yr were studied. All subjects were experienced in respiratory maneuvers and had normal spirometry and lung volumes; however, three of the subjects had had no previous experience of breathing through inspiratory loads before this experiment and were unaware of the purpose of the study. All gave their informed consent. All measurements were performed while the subject was seated in a pressure compensated volume displacement body plethysmograph for measurement of lung volume. Thoracoabdominal configuration was monitored with linearized magnetometers (18). The anteroposterior (A-P) diameter of the lower rib cage (RC) was measured with a pair of magnetometer coils placed over the sternum at the level of the fifth intercostal space and over the spine at the same level. The A-P diameter of the abdomen (AB) was measured with a pair of magnetometer coils placed 1 cm above the umbilicus and over the spinous process at the same level. The two outputs were displayed on the vertical (RC) and horizontal (AB) axes of an X-Y storage oscilloscope (Tektronix 5111). The magnetometer was calibrated using the isovolume technique of Konno and Mead (18) while the subject was seated in the body plethysmograph.

Electrical activity of the respiratory muscles was recorded with surface electrodes placed over the seventh intercostal space in the anterior axillary line. This signal contains mainly diaphragm activity but also sometimes contains inspiratory intercostal activity. The same electrodes can detect expiratory intercostal activity as well. The raw electromyogram (EMG) signal was processed using an amplifier (model 1117, NEC Sanci, Japan), band-pass filtered (model FV-604T, 100-2,000 Hz, variable filter, NF Circuit Design, Japan), and rectified by band-pass filtered (model FV-604T, 100-2,000 Hz, variable filter, NF Circuit Design, Japan), and rectified by

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before it was passed through a leaky integrator with a time constant of 100 ms.

Esophageal pressure was used as an index of pleural pressure (Ppl) and was measured with a thin-walled balloon catheter in the lower third of the esophagus. The balloon was connected via a polyethylene catheter to a differential pressure transducer (model 267B, Hewlett-Packard). Mouth pressure (Pm) was also monitored at the mouthpiece with a differential pressure transducer (model 267B, Hewlett-Packard). In three subjects, expired CO2 was monitored using a mass spectrometer (model 200 MGA, Centronics). Lung volume change, filtered EMG, integrated EMG, Ppl, and Pm were recorded on a hot pen recorder (Recti-Horiz 8K, NEC-Sanei) and magnetic tape for later playback and analysis.

Three experimental protocols were as follows.

Protocol I. We first examined the effects of various inspiratory elastic and resistive loads on changes in FRC, thoracoabdominal configuration, and respiratory muscle activity. The inspiratory elastic load was applied by having the subject inspire from a rigid airtight container, which was vented to the atmosphere via a three-way valve during each expiration. The magnitude of the elastic load was varied by changing water volume of the container: 35 (EL1), 48 (EL2), and 68 cmH2O/l (EL3). The inspiratory resistances were 21 (R1), 86 (R2), and 192 cmH2O · l−1 · s (R3), measured at a flow rate of 0.5 l/s. After a period of quiet tidal breathing during which variations in breathing pattern were allowed to stabilize, either the elastic or the resistive load was applied in a random order to the inspiratory port of a Hans-Rudolph valve attached to the mouthpiece. A screen was used to hide the inspiratory portion of the valve and the load from the subject. No instructions were given to the subject on how to breathe against the loads. Because a steady state was usually achieved after 10–15 loaded breaths, the load was not applied for more than 15 breaths. Thereafter the load was removed, and unloaded breathing was repeated. Each load was applied at least two times in each subject, and the values of the change in the FRC from the quiet tidal breathing level were averaged. Tidal volume (VT) and ventilatory timing duration (Ti, inspiratory duration; Te, expiratory duration) were determined from the tracings of lung volume, Ppl, and Pm. The last four loaded breaths in each measurement were chosen for analysis, and the values were averaged.

Protocol II. On the same day and after protocol I, we examined the effect of a single inspiratory effort on FRC. The subject made an inspiratory effort to produce a specified target Pm against an occlusion at control FRC. Pm of -25 and -50 cmH2O were held for 1, 2, or 5 s, and Pm of -75 cmH2O was held for 1 s. After the effort, the subject relaxed. Such maneuvers were performed while the subject watched a trace of Pm on the storage oscilloscope. The change in FRC was calculated at the next expiration followed by an inspiratory effort. Each subject repeated each inspiratory effort at least four times, and the values were averaged.

Protocol III. Because in protocol I the FRC invariably decreased during inspiratory loading and the sensation of discomfort of breathing, or the sensation of dyspnea, always accompanied inspiratory loaded breathing, we examined the relation between lung volume and the respiratory sensation during inspiratory loaded breathing. On separate days, the sensation of dyspnea or discomfort was measured on a visual analog scale (VAS) while the subject breathed through the severe inspiratory elastic load (EL3) at control FRC, at FRC + 0.5 liter, or at FRC − 0.5 liter. The VAS was displayed on the vertical axis of the storage oscilloscope screen. The lower and upper ends of the scale were designed “none at all” and “most intense imaginable” and were given numerical values of 0 and 100, respectively. EL3 was applied at the inspiratory port of the Hans-Rudolph valve while the subject watched the lung volume trace on the oscilloscope screen and breathed at resting FRC or after inspiration or expiration of 0.5 liter from the control FRC. The subject was asked to breathe and maintain these lung volume levels to the extent possible during a period of 20 breaths, after which the subject rated the intensity of the sensation of dyspnea on the VAS. Each lung volume was selected randomly, and measurements were repeated at least twice for each lung volume. The averaged values of the VAS score were used for analysis. Breathing parameters including VT and breathing frequency (f) were calculated from the traces of lung volume.

Data analysis. Data were statistically analyzed by one-way analysis of variance (ANOVA) and the Student's t test. All data are expressed as means ± SE. Differences were considered statistically significant for P < 0.05.

RESULTS

FRC decreased during inspiratory elastic and resistive loading in all subjects. Figure 1 shows a representative recording made when one naive subject was breathing against an inspiratory resistive load (R2). When the load was applied, the FRC usually decreased in the following expiration and continued to decrease in subsequent breaths, becoming stable after 10–15 breaths. With the reduction in FRC, phasic EMG activities during the expiratory and the inspiratory phases gradually increased after application of the load. Simultaneously, end-expiratory Ppl shifted to positive. With the resumption of quiet tidal breathing, FRC, EMG activities, and Ppl gradually returned to control levels. The relation between peak expiratory EMG activity and the magnitude of reduction in FRC in a representative subject is shown in Fig. 2. During both resistive and elastic loadings, the decreased volume of FRC was related to the peak expiratory EMG activity in an exponential fashion.

Figure 3 is a plot of RC vs. AB A-P diameter (Konno Mead diagram) during quiet tidal breathing and during elastic loaded (EL3) breathing in one subject. The end-expiratory position (FRC) is shifted from the relaxation line during elastic loaded breathing. Although both A-P diameters decreased, AB A-P diameter decreased more than did RC A-P diameter. Paradoxical movements between RC and AB during loaded breathing are also shown in Fig. 3; i.e., early in inspiration, AB A-P diameter increased whereas RC A-P diameter decreased. Although these paradoxical movements were typically found at the largest elastic load, similar motions were
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start

stop

FIG. 1. Representative tracing obtained in 1 naive subject who breathed through a moderate resistive load (R2). Changes in mouth pressure, averaged EMG, band-pass filtered EMG, lung volume, and pleural pressure are shown. Load was applied at point marked “start” and removed at “stop.” After application of load, functional residual capacity (FRC) started to decrease at the following expiration, and magnitude of reduction grew as breathing proceeded. With reduction in FRC, EMG activity during expiratory, as well as inspiratory, phases gradually increased. Sometimes found during severe resistive (R3) and moderate elastic loadings (EL2).

Figure 4 shows the decreased volumes from quiet tidal breathing levels during inspiratory resistive (Fig. 4A) and elastic loaded breathing (Fig. 4B) in all subjects. With both kinds of loads the decreased volume increased with an increase in intensity of the load in each subject. There was no difference in the decreased volume between naive and experienced subjects. Mean values of decreased lung volume were 0.05 ± 0.02, 0.24 ± 0.06, and 0.66 ± 0.04 (SE) liter in R1, R2, and R3, respectively, and 0.40 ± 0.06, 0.59 ± 0.07, and 0.80 ± 0.09 liter in EL1, EL2, and EL3, respectively. These values differed significantly among the intensities of resistive and elastic loads employed (ANOVA, P < 0.01 in both resistive and elastic loads).

Table 1 shows breathing parameters during loaded breathing in all subjects. Mean values of end-tidal fraction of CO2 (FE\textsubscript{CO2}) in three subjects are also shown in Table 1. During resistive loading, VT increased and f decreased significantly compared with control resting breathing (paired t test). However, minute ventilation (VE) did not differ significantly from control. Ti increased and TE decreased with an increase in the resistive load. Mean inspiratory flow (VT/Ti) decreased significantly from control during moderate (R2) and severe (R3) resistive loadings. During elastic loading, on the other hand, VT significantly decreased with a significant increase in f, and consequently VE did not differ significantly from the control value. Ti tended to decrease during elastic loading, although these values did not reach statistical significance. TE decreased significantly during EL2 and EL3 loadings, and VT/Ti also decreased significantly during severe elastic loading. FE\textsubscript{CO2} in three subjects ranged from 4.7 to 6.0% during resistive and elastic loaded breathing, and, on the average, there was a slight tendency of FE\textsubscript{CO2} to increase during severe resistive and elastic loadings. These changes, however, were not significant (paired t test).

Figure 5 shows a representative tracing obtained when one subject performed an inspiratory effort against an occluded inspiratory line at FRC. FRC decreased from the quiet tidal breathing level at the next expiration after the subject discontinued the inspiratory effort. The decrease in lung volume was always accompanied by increased lower RC EMG activities. Figure 6A shows mean values of reduced volume at the target Pm of -25, -50, and -75 cmH\textsubscript{2}O during expiration. The decrease in FRC was significantly increased with an increase in the magnitude of the target Pm with a duration of 1 s (ANOVA, P < 0.05). The effect of holding time for -25 and -50 cmH\textsubscript{2}O target pressures is shown in Fig. 6B. Increased duration at both -25 and -50 cmH\textsubscript{2}O target pressures also significantly increased the reduction in lung volume (ANOVA, P < 0.05 in both).

The VAS scores during EL3 breathing at FRC + 0.5 liter, at control FRC, and at FRC - 0.5 liter are shown in Fig. 7. In all subjects, the VAS scores decreased with a decrease in lung volume, and the mean values were significantly different (ANOVA, P < 0.01). Student's paired t test also revealed a statistical significance in the mean VAS values among three lung volumes (P < 0.01 in each pair). Table 2 shows the mean values of VE, VT, and f during these measurements. VT decreased and f increased significantly with an increase in lung volume, and the Student’s paired t test revealed a statistical significance in the mean VE values between FRC - 0.5 liter and FRC + 0.5 liter breathing.

DISCUSSION

The present study confirms that FRC decreases in response to external inspiratory loading in conscious hu-
man subjects and that the magnitude of reduction increases with an increase in the severity of the load. The reduction in lung volume was always associated with the increase in expiratory muscle activity. A single inspiratory effort against an occlusion similarly resulted in a decrease in FRC with an increase in expiratory EMG activity in the following expiration. In an additional study we also found that the sensation of dyspnea during g

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FIG. 2. Relationship between FRC reduction and peak expiratory
EMG activity (arbitrary units) during inspiratory resistive (top) and
elastic (bottom) loaded breathing. Each point represents 1 breath dur-
ing loaded breathing. Note that decreased volume from control FRC is
related to expiratory EMG activity in an exponential fashion.

Changes in FRC and pattern of breathing during inspira-
tory loading. Our observation that FRC decreases during inspiratory loading is consistent with the findings of Martin et al. (21), who first demonstrated a substantial reduction in FRC during inspiratory resistive and elastic loading in normal human subjects. However, most other studies (4, 5, 12, 13, 19, 26, 27) have reported either no change or a small reduction (<200 ml) during inspiratory loading. One reason that previous workers could find no reduction in lung volume may be the methods used for measuring changes in lung volume. In most studies changes in end-expiratory lung volume were measured by electronic integration of the mouth flow (26, 27, 29) or

with an inductance plethysmograph or a magnetometer (12, 19). These methods may not be reliable when small changes in lung volume are measured during inspiratory loading because of drift or change in posture during the inspiratory effort. On the other hand, the volume dis-
placement body plethysmograph was used in the present study and in the study of Martin et al. (21). A second reason may be the severity of the loads used, because several studies (4, 10, 15, 23) using body plethysmogra-
phy or spirography demonstrate no substantial reduc-
tion in lung volume. The magnitudes of the loads in most studies were <20 cmH$_2$O·l$^{-1}$·s resistance (12, 15, 19) and <25 cmH$_2$O/l elastance (10), whereas Martin and De Troyer (22) used a severe resistance (140 cmH$_2$O·l$^{-1}$·s) and elastance (90 cmH$_2$O/l). Because previous studies did not examine the effect of load severity, we used three graded resistances and elastic loads in this study and demonstrated that FRC decreased progressively with load severity.

With the reduction in FRC, breathing pattern also changed. During resistive loading subjects took deeper slower breaths without a significant change in VE. Because VT/TI decreased with an increase in the resistive load, the increase in VT was mainly due to an increase in TI. During elastic loading, on the other hand, subjects took shallower more rapid breaths while maintaining VE. These changes in breathing pattern during both types of loading were qualitatively similar to those obtained in awake human subjects (7, 24).

We also found that RC A-P diameter decreased during the early part of severe elastic and resistive loaded inspira-
tion, whereas AB A-P diameter increased. These para-
doxical movements of RC A-P diameter during loaded inspiration have been previously reported by several in-
vestigators (1, 27). Agostoni and Mognoni (1) showed

FIG. 3. Changes in rib cage and abdomen A-P diameters (Konno-
Mead plot) occurring during quiet breathing (at rest) and under severe
elastic loading (Load+) in a representative subject. Solid line, relax-
ation curve; dashed curves, isovolume lines. Closed circles, FRC; open circles, end-inspiratory lung volume. FRC decreased and shifted from
relaxation line during elastic loaded breathing. Note that although both abdominal and rib cage A-P diameters decreased with reduction of
FRC, decrease in abdomen appears to be much larger than that in rib
cage. Paradoxical movement between rib cage and abdomen occurs
during loaded breathing. VC, vital capacity; RV, residual volume.
that the RC becomes more elliptical in shape when normal subjects inspire through a high resistance or perform static inspiratory efforts at FRC; RC A-P diameter becomes smaller and RC lateral diameter becomes larger. Although Agostoni and Mognoni did not measure AB A-P diameter, Sampson and De Troyer (27) showed that some of their subjects (4 of 6 subjects) increase their AB A-P diameter with a decrease in RC A-P diameter and an increase in RC lateral diameter during severe elastic and resistive loaded inspirations. Unfortunately RC lateral diameter was not measured in this experiment; however, the paradoxical movement we found appears to be compatible with these two findings.

**Possible mechanisms of decrease in the lung volume.** A number of possibilities can be discarded when an explanation is sought for the reduction in FRC in response to inspiratory loading. First, a vagally mediated reflex through stretch receptors is unlikely, because these receptors are usually activated by lung inflation (3, 9) and they would not likely be activated during inspiratory loading. Second, stimulation of medullary or peripheral chemoreceptors is also unlikely to be responsible for our observations, because the reduction in FRC started in the first expiration after the addition of the loads, and \( F_{ETCO_2} \) did not greatly increase in three subjects during loading (Table 1). Also we could find no relationship between \( F_{ETCO_2} \) values and the reduced volumes in this experiment. Third, segmental reflexes from the chest wall also do not seem to be responsible for the active expiration, because it is believed that these reflexes contribute little to respiratory compensation for external mechanical loads (7, 20, 28). Fourth, respiratory responses to ventilatory loading can be modified in conscious individuals by anticipation and previous experience (7). To exclude these effects, three naive subjects who had no previous experience of inspiratory loaded breathing were examined. Also, care was taken to prevent the subjects from seeing the application of the loads. Because the decrease in lung volume in the naive subjects were qualitatively and quantitatively similar to those of the experienced subjects, it seems unlikely that the reduction in lung volume might result simply from anticipation and experience.

Finally, given the difficulty in attributing the FRC decrease to the reflexes above, we speculate that cortical influences might be responsible. Because several studies have shown that inspiratory activity is increased by ventilatory loading in conscious but not in anesthetized humans and experimental animals (2, 16, 29), we speculate that the rise in expiratory activity with inspiratory loads observed in the present study likewise depends on consciousness. This would suggest that input from higher brain centers is necessary for the increased response. Gothe and Cherniack (12) observed increased inspiratory activity as well as expiratory activity during expiratory loaded breathing in conscious subjects. They suggested that such an increased response to expiratory

**TABLE 1. Respiratory parameters during inspiratory resistive and elastic loaded breathing**

<table>
<thead>
<tr>
<th></th>
<th>Control</th>
<th>R1</th>
<th>R2</th>
<th>R3</th>
<th>EL1</th>
<th>EL2</th>
<th>EL3</th>
</tr>
</thead>
<tbody>
<tr>
<td>( V_E, l/min )</td>
<td>8.86±0.33</td>
<td>9.34±0.52</td>
<td>8.89±0.35</td>
<td>8.61±0.40</td>
<td>9.16±0.33</td>
<td>8.89±0.91</td>
<td>8.65±0.64</td>
</tr>
<tr>
<td>( V_T, liter  )</td>
<td>0.59±0.04</td>
<td>0.69±0.05*</td>
<td>0.65±0.05*</td>
<td>0.68±0.06*</td>
<td>0.53±0.06</td>
<td>0.51±0.06</td>
<td>0.46±0.04*</td>
</tr>
<tr>
<td>( f, \text{min}^{-1} )</td>
<td>15.42±0.97</td>
<td>14.30±0.88*</td>
<td>13.94±0.81*</td>
<td>13.96±0.77†</td>
<td>17.88±1.70*</td>
<td>18.30±1.89*</td>
<td>19.21±1.57†</td>
</tr>
<tr>
<td>( T_I, s )</td>
<td>1.58±0.11</td>
<td>2.00±0.17*</td>
<td>2.23±0.15†</td>
<td>2.70±0.21†</td>
<td>1.61±0.15</td>
<td>1.57±0.15</td>
<td>1.43±0.11</td>
</tr>
<tr>
<td>( T_E, s )</td>
<td>2.42±0.17</td>
<td>2.33±0.19</td>
<td>2.17±0.16†</td>
<td>2.04±0.18†</td>
<td>2.02±0.34</td>
<td>1.96±0.30*</td>
<td>1.85±0.95†</td>
</tr>
<tr>
<td>( V_T/T_I, l/min)</td>
<td>0.37±0.02</td>
<td>0.34±0.02</td>
<td>0.29±0.01*</td>
<td>0.25±0.01†</td>
<td>0.30±0.01</td>
<td>0.32±0.02</td>
<td>0.32±0.03*</td>
</tr>
<tr>
<td>( F_{ETCO_2}, % )</td>
<td>5.30±0.15</td>
<td>5.18±0.28</td>
<td>5.33±0.18</td>
<td>5.42±0.16</td>
<td>5.37±0.29</td>
<td>5.45±0.38</td>
<td>5.50±0.26</td>
</tr>
</tbody>
</table>

Values are means ± SE; \( n = 7 \), except for \( F_{ETCO_2} \) where \( n = 3 \). \( V_E \), minute ventilation; \( V_T \), tidal volume; \( f \), breathing frequency; \( T_I \), inspiratory duration; \( T_E \), expiratory duration; \( V_T/T_I \), mean inspiratory flow rate; \( F_{ETCO_2} \), end-tidal \( CO_2 \) fraction. * \( P < 0.05 \); † \( P < 0.01 \), significant difference from control by paired \( t \) test.
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FIG. 5. Representative tracing obtained when 1 subject performed an inspiratory effort of -50 cmH2O mouth pressure at FRC against an occluded inspiratory line. Note that FRC decreased with an increase in lower rib cage EMG activity immediately after subject discontinued inspiratory effort.

loading is related to conscious sensations, because this response cannot be considered a simple reflex. Although the load used in this experiment was inspiratory rather than expiratory, our finding that inspiratory loading activated expiratory, as well as inspiratory, activity appears similar to the response obtained by Gothe and Cherniack (12).

We also found the expiratory muscle activation and the reduction in FRC after a single inspiratory effort against occlusion. These findings were so similar to those observed during inspiratory loaded breathing that the same mechanism appears to be related to both. Because none of the reflexes mediated by the vagus, chemoreceptors, or proprioceptors can be held responsible for the effect of a single inspiratory effort on FRC, it seems possible to attribute the FRC reduction after single inspiratory effort to cortical influences. Furthermore, in our preliminary experiments with three anesthetized dogs, FRC did not decrease, even with severe inspiratory resistive or elastic loads, if FET, was kept <7% (unpublished observations). This also suggests that higher brain centers mediate the response we observed. Although we could not determine the nature of the signals received by higher brain centers in the present study, studies of the perception of inspired volume suggest that sensory information from the respiratory muscles is of primary importance in the subjective assessment of thoracic displacement (30). Moreover, a recent report by Gandevia and Macefield (11) also provides clear evidence for a direct projection to the human cerebral cortex of low-threshold muscle afferents from the parasternal and lateral intercostal muscles. Thus it seems possible that higher brain centers might detect the inspiratory load through signals from mechanoreceptors in the respiratory muscles.

Why do subjects change their respiratory muscle activation to reduce lung volume? One possible explanation lies in the respiratory optimization theory proposed by Cherniack (6). He hypothesized that the breathing pattern might be optimized so as to minimize conscious pain or discomfort. Although Cherniack did not refer to changes in lung volume, it seems appropriate to extend "the optimization theory" to changes in FRC and breathing pattern that may affect the discomfort of breathing. Theoretically, there are two main advantages

FIG. 6. Effect of a single inspiratory effort against an occluded inspiratory line on FRC reduction. A: effect of magnitude of target negative pressure with a duration of 1 s. FRC significantly decreased with an increase in magnitude of target pressure (ANOVA, P < 0.01). B: effect of duration of inspiratory efforts. Open circles and open triangles, data obtained when target pressure was -25 cmH2O and -50 cmH2O, respectively. One-way ANOVA revealed a significant difference in values of reduced volume between durations (P < 0.05 in both target pressures). *P < 0.05; NS, not significant by paired t test. Values are means ± SE of 7 subjects.
in a reduced FRC during inspiratory loading. First, active expiration stores elastic energy so that part of the subsequent inspiration can be achieved without use of the inspiratory muscles, thereby lessening inspiratory work done. Second, with a reduction in FRC the diaphragmatic muscle fibers would be lengthened so that they could generate more pressure for a given neural output (13, 25). Because of these advantages the inspiratory motor command would be smaller at lowered lung volume. If, as is postulated, the sensation of dyspnea is correlated with the level of motor command to the respiratory muscles, thereby lessening inspiratory muscle endurance. Indeed we found that the sensation of dyspnea was reduced at lowered FRC during EL3 loaded breathing. Although breathing pattern also changed with a change in the FRC, these pattern changes themselves do not seem to be a primary cause of the difference in the sensation of dyspnea. This is because the mean VE value was rather higher at FRC - 0.5 liter than that at FRC + 0.5 liter, and it is postulated that the sensation of dyspnea increases with an increase in VE (8). It appears that these pattern changes would rather indicate the mechanical advantages of the reduced FRC during inspiratory loaded breathing. Furthermore, our finding that the FRC reduction after single occluded inspiration increased with an increase in inspiratory effort (target pressure and duration) suggests that a close relationship may exist between the decrease in FRC and the sensation of dyspnea. We would thus propose that FRC may be optimized by higher brain centers to minimize the intensity of dyspnea in the awake human.

Although direct evidence supporting this hypothesis is lacking, it seems worthy to note that Henke et al. (14) suggested that the reduced FRC was “selected” to optimize diaphragm length during exercise. Because sensation of dyspnea possibly increases during exercise, their finding also appears to be explained by the same mechanism. However, because the association of changes in FRC with alterations in the intensity of dyspnea cannot be considered direct evidence that the lung volume changes are mediated behaviorally, further studies, especially in anesthetized or sleeping subjects, are needed to elucidate the role of the respiratory sensation, as well as the behavioral response, on the control of FRC.

In summary, the present study has shown that end-expiratory lung volume decreases during inspiratory resistive or elastic loading in a load magnitude-dependent manner in conscious humans. Because this response cannot be explained by a simple reflex and the reduced FRC decreased the sensation of dyspnea, we believe that it is primarily the result of a behavioral control of breathing to reduce the unpleasant sensation produced by the load. Although it is well known that the efficiency of the respiratory muscles varies with changes in lung volume, it has not been clarified whether the FRC is only passively determined by a mechanical change and/or a chemical drive or is also actively altered to an advantageous position through a cortical response. Our results suggest that FRC (end-expiratory lung volume) may be actively selected during loaded breathing through cortical response to reduce sensation of dyspnea and that this mechanism may be important and beneficial in overcoming inspiratory loading such as that in restrictive impairment.

We thank Dr. Hiroshi Miki for expert technical assistance, Dr. Stephen H. Loring for helpful criticism, and Dr. Ron Scott for assistance in the preparation of the manuscript.

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Received 11 June 1990; accepted in final form 14 June 1991.

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