Twitch transdiaphragmatic pressure depends critically on thoracoabdominal configuration

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Chen, Rongchang, Bengt Kayser, Sheng Yan, and Peter T. Macklem. Twitch transdiaphragmatic pressure depends critically on thoracoabdominal configuration. J. Appl. Physiol. 88: 54–60, 2000.—We measured the effect of thoracoabdominal configuration on twitch transdiaphragmatic pressure (Pdi,t) in response to supramaximal, transcutaneous, bilateral phrenic nerve shocks in three thin normal men. Pdi,t was measured as a function of lung volume (Vl) in the relaxation configuration, at functional residual capacity (FRC), and at the same end-tidal Vl 1) during relaxation; 2) with the abdomen (Ab) expanded and the rib cage (RC) in its relaxed FRC configuration; 3) with RC expanded and Ab in its relaxed FRC configuration; and 4) in configuration 3 with an active transdiaphragmatic pressure similar to that required to produce configuration 2. In increasing Vl from FRC to configuration 1, Pdi,t decreased by 3.6 cmH2O; to configuration 2 by 14.8 cmH2O; to configuration 3 by 3.7 cmH2O; and to configuration 4 by 2.7 cmH2O. We argue that changes in velocity of shortening and radius of curvature are unlikely to account for these effects and suggest that changes in diaphragmatic fiber length (Ldi) are primarily responsible. If so, equivalent volume displacements of Ab and RC change Ldi in a ratio of ~4:1. We conclude that Pdi,t is exquisitely sensitive to abdominal displacements that must be rigorously controlled if Pdi,t is to be used to assess diaphragmatic contractility.

abdomen; rib cage; diaphragmatic contractility; phrenic stimulation; diaphragm fiber length

BILATERAL TRANSCUTANEOUS SUPRAXIMAL phrenic nerve shocks with measurement of the resulting twitch transdiaphragmatic pressure (Pdi,t) has been recommended as a means of assessing diaphragmatic contractility (19). Indeed, Pdi,t has become the standard means of measuring the effects of fatiguing tasks on the diaphragm's contractile state. A major reason for this is that, unlike other tests of diaphragmatic contractility, it is the only one affected by low-frequency fatigue (21). Tests such as the power spectrum of the diaphragmatic electromyogram (8), maximum transdiaphragmatic pressure (Pdi) (4), diaphragm relaxation rate (5), and sniff Pdi (6) recover quickly. Thus these tests reflect high-frequency fatigue. Recovery from low-frequency fatigue is much more prolonged and can take longer than 24 h (13). Because of the prolonged effects of low-frequency fatigue on diaphragm contractility, the ability to detect it is important. Pdi,t is useful because it is sensitive to both types (21). Its usefulness would be enhanced if other factors that determine Pdi,t were easy to control. Three obvious ones are fiber length (Ldi), velocity of shortening (Vdi), and radius of curvature (Rdi).

Both Ldi and Pdi,t are linearly related to lung volume (Vl) in the relaxation configuration, (7, 21) and thus Pdi,t and Ldi are linearly related to each other. Thus, provided that the relaxed configuration pertains, one can potentially estimate the effects of Ldi on Pdi,t, if Vdi and Rdi are controlled.

Vdi is a function of the load the diaphragm acts against. Twitch diaphragmatic contraction against a closed airway accelerates the abdomen (Ab) and the rib cage (RC), distorts the lung and RC (3, 11), and displaces the Ab outward and the RC inward. Ab inertia is substantial, and the load it imposes on the diaphragm presumably dominates the inertial loads imposed by other respiratory structures during diaphragmatic twitches. Its effects are transient; once Pdi reaches its peak value, the effects of Ab inertia in decreasing Vdi, in contrast to Pdi measurements, are effectively over (3). Chihara et al. (3) have shown that, initially, Ab displacement lags Ab pressure (Pab); later, the Ab continues its outward displacement as both pleural pressure and Pab fall at nearly constant Pdi. Thus early in a twitch Ab inertial load tends to diminish Vdi, whereas later it facilitates it.

The load imposed by lung distortion should be relatively small. The lung's shear modulus is less than its bulk modulus (14, 15); thus the effect of lung distortion on Vdi is less than the effect of lung inflation during open-glottis twitch contractions and presumably small compared with the chest wall load.

The RC distortion, in contrast, decreases the effective compliance of the RC to a value less than one-third of its undistorted value (3, 11). Therefore, ~70% of the pressure the diaphragm applies to the RC acts to distort it, whereas only the remaining 30% acts to change its volume (11). This RC stiffening combined with Ab compliance (Cab) and inertia are probably the most important factors determining Vdi during twitches against a closed glottis.

Rdi is also a potentially important determinant of Pdi,t. According to the Laplace law, for a given tension developed by the diaphragm, Pdi,t will be inversely proportional to Rdi. In the coronal plane Rdi does not...
change as a function of V_{L}, whereas in the sagittal plane there is a greater rostral displacement of the posterior part of the diaphragm than the anterior part, and R_{di} in this plane decreases as V_{L} increases (7).

At the present time it is not possible to be precise as to how changes in R_{di} and V_{di} affect P_{di}, nor about the influence of L_{di} in unrelaxed thoracoabdominal configurations. They remain as uncontrolled, potentially confounding, variables in an assessment of diaphragmatic contractility by P_{di}.

In the present experiments we have explored the effects of thoracoabdominal configuration on P_{di}. Configuration will influence L_{di} at a given V_{L}, may change the load on the diaphragm and thus influence P_{di}, and may alter R_{di} and thereby influence P_{di}, for any degree of diaphragmatic tension. We found that P_{di} was exquisitely sensitive to increases in Ab dimensions and relatively insensitive to increases in RC dimensions. Thus to use P_{di} as a measure of diaphragmatic contractility, thoracoabdominal configuration must be rigorously controlled.

METHODS

Subjects. The subjects for this experiment were six healthy, nonsmoking male laboratory personnel, who gave informed consent and who were all highly trained in respiratory maneuvers. They were between 37 and 43 yr old and close to their ideal body weight with little subcutaneous fat, thereby minimizing motion artifacts of RC and Ab.

Measurements. Changes in V_{L} were monitored by a bag-in-box system. RC and Ab dimensions were measured by two pairs of magnetometers placed at the front and back in the midline at the level of the third intercostal space anteriorly and 2 cm above the umbilicus. The magnetometers were calibrated by the isovolume method (12). RC vs. Ab displacements were displayed on the y- and x-axes, respectively, of a storage oscilloscope and used to guide the subject in the appropriate respiratory maneuvers.

Phrenic nerve stimulation was performed supramaximally by the method of Bellemare and Bigland-Ritchie (2). Two pairs of electromyographic surface electrodes were placed, one over the sixth intercostal space between the anterior axillary and midclavicular lines and the other immediately caudal to it at the costal margin to measure diaphragmatic action potentials. The compound action potentials were monitored on an oscilloscope and recorded on tape for later analysis. Supramaximal stimulation was assumed when the height of the compound action potential remained constant when the stimulating current was increased. During the experiment we only stimulated supramaximally. The recorded signals were digitized at a 3-kHz sampling frequency. Esophageal and gastric pressures were measured with conventional balloon-tipped catheters coupled to transducers. P_{di} was measured as gastric minus esophageal pressure. Zero P_{di} was taken as the P_{di} at the end of a quiet expiration at functional residual capacity (FRC). It was displayed to the subject on a storage oscilloscope.

All the signals except the action potentials were recorded in a computer via a 12-bit analog-to-digital converter at a sampling rate of 500 Hz.

Experimental procedure. The experiments were conducted with the subjects seated comfortably in an armchair in a fixed posture and with a fixed mouthpiece position to maintain the xyphipubic distance constant. Both P_{di} and thoracoabdominal configuration were displayed on two separate storage oscilloscopes and were monitored by the subject during the various respiratory maneuvers. The operator monitored the compound action potentials on a third oscilloscope. P_{di} was measured during the following conditions: 1) during relaxation at FRC; 2) during relaxation and slow expiration against a high external resistance at different V_{L} values between inspiratory capacity and FRC, with particular attention to the end-tidal V_{L}, which was 350- to 500-ml greater than FRC; 3) in the RC-out configuration after an inspiration to end-tidal V_{L}, followed by an isovolume maneuver with RC expansion and inward Ab displacement to the Ab dimension at FRC (Fig. 1); 4) in the Ab-out configuration after an inspiration to end-tidal V_{L}, followed by an isovolume maneuver with outward Ab displacement and RC deflation to its FRC dimension (Fig. 1); 5) in the RC-out configuration at the same end-tidal V_{L} with an active P_{di} equal to that within condition 4. These configurations were within the limits where RC and Ab behave as compartments with a single degree of freedom, as specified by Konno and Mead (12).

These maneuvers were difficult to perform, particularly the one that required an active P_{di} while the RC-out configuration was maintained. Only three of the six subjects were able to perform all five maneuvers satisfactorily and repeatedly; thus we only report the results in these individuals. The results in all three were closely similar, so we are confident...
that they are reasonably generalizable for normal, nonsmoking, nonobese men between 35 and 45 yr of age. Loring et al. (16) also found similar maneuvers difficult and only studied two subjects in one experiment and three in another.

Data analysis. The data stored in the computer were analyzed with Origin data analysis software. Only Pdi,t results whereby the evoked action potential was at least 95% of the control maximal action potential or greater were included in the analysis. The data were also discarded if the specific thoracoabdominal configuration could not be maintained during stimulation and if the change in VL as estimated by the magnetometers was not within ±15% of the change in VL measured by the bag-in-box. Pdi,t was calculated after ensemble-averaging of 7–10 twitches under each condition.

We first plotted Pdi,t vs. VL during relaxation from one-half inspiratory capacity to FRC. We then plotted Pdi,t obtained with the Ab displacement at constant FRC RC dimensions and with RC displacement at constant FRC Ab dimensions on the same plot, at the VL at which they were measured. Thus, at constant VL, we were able to determine the effect of thoracoabdominal configuration on Pdi,t. The effect of configurational change on Pdi,t could then be estimated, not only as the change at constant VL but also as the change in VL in the relaxation configuration that would be required to produce the same change in Pdi,t. Because Ldi is linearly related to VL in the relaxation configuration (7), this allowed us to estimate the relative length changes produced by the RC and Ab maneuvers, respectively, assuming that neither Vdi nor Rdi played an important role in producing changes in Pdi,t. Finally, because the Ab displacement maneuver required an active contraction of the diaphragm, we evaluated how much twitch occlusion this produced by measuring the Pdi,t during relaxation at the same VL, with the diaphragm relaxed and then contracted at the same Pdi as during the Ab displacement maneuver.

RESULTS

Figure 1 is a Konno-Mead plot (12) of RC vs. Ab dimensions and illustrates the various configurations at FRC and end-tidal VL at which we measured Pdi,t. These were at FRC relaxed, at end-tidal VL relaxed, and at end-tidal VL in the iso RC, Ab-out and the iso Ab, RC-out configurations. For 86% of the trials the specific configurations could be maintained within ±15% of the desired change in VL above FRC. Only the data from these trials were included in the analysis. The end-tidal VL and the volumes displaced by the Ab and RC in AB-out and AB-in configurations are show in Table 1. The amplitude of 92% of the action potentials was within ±10% of its value at FRC.

An example of the measured Pdi,t and its gastric and esophageal pressure components in the relaxation, the Ab-out, and the RC-out configurations are shown in Fig. 2. Figure 3 shows Pdi,t as a function of VL in the relaxation configuration, and at end-tidal VL in the RC-out and Ab-out configurations, in each of the three subjects who was able to perform all maneuvers satisfactorily. As shown in Table 1, the tidal inspiration ranged from 0.31 to 0.62 liters. Table 2 gives the Pdi,t values at FRC and at the three configurations at end-tidal VL. With the RC-out configuration, Pdi,t was, on average 18.9 ± 2.1 (SD) cm H2O, similar to the Pdi,t of 19.0 ± 1.6 cm H2O during relaxation at the same VL.

In the Ab-out configuration, however, Pdi,t was only 7.8 ± 3.0 cm H2O. When, while maintaining the RC-out configuration, the subject voluntarily generated a Pdi similar to that required to produce the Ab-out configuration (far right column), Pdi,t was somewhat increased from 18.9 ± 2.1 to 19.0 ± 2.6 cm H2O. Table 3 gives the baseline Pdi_t (the absolute difference between gastric and esophageal pressures (Pdi,b)) before phrenic shocks in the Ab-out configuration and in the RC-out configuration with the diaphragm relaxed and contracted.

DISCUSSION

Main findings. The main finding of this study was that at a VL of FRC+tidal volume, the Ab-out configuration reduced Pdi,t from a value of 22.6 ± 1.4 at FRC to 7.8 ± 3.0 cm H2O, whereas a similar change in VL in the RC-out and relaxation configurations only decreased Pdi,t to 18.9 ± 2.1 and 19.0 ± 1.6 cm H2O, respectively. The fact that it required an active diaphragmatic contraction to achieve the Ab-out position and that twitch occlusion might therefore decrease Pdi,t in this configuration cannot account for our findings because, in the RC-out configuration at a similar baseline Pdi,t, Pdi,t was 19.0 ± 2.6 cm H2O.

Table 1. Volumes displaced during isovolume maneuvers

<table>
<thead>
<tr>
<th>Subject</th>
<th>Configuration</th>
<th>ΔVL, liter</th>
<th>ΔVab, liter</th>
<th>ΔVrc, liter</th>
</tr>
</thead>
<tbody>
<tr>
<td>SY</td>
<td>Ab out</td>
<td>0.40</td>
<td>0.36</td>
<td>−0.02</td>
</tr>
<tr>
<td></td>
<td>RC out</td>
<td>0.40</td>
<td>0.01</td>
<td>0.38</td>
</tr>
<tr>
<td></td>
<td>BK</td>
<td>0.38</td>
<td>0.02</td>
<td>0.39</td>
</tr>
<tr>
<td></td>
<td>Ab out</td>
<td>0.55</td>
<td>0.51</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>RC out</td>
<td>0.54</td>
<td>0.02</td>
<td>0.54</td>
</tr>
<tr>
<td></td>
<td>RC out</td>
<td>0.61</td>
<td>−0.01</td>
<td>0.55</td>
</tr>
<tr>
<td></td>
<td>Ab out</td>
<td>0.36</td>
<td>0.37</td>
<td>−0.01</td>
</tr>
<tr>
<td></td>
<td>RC out</td>
<td>0.35</td>
<td>0.01</td>
<td>0.35</td>
</tr>
<tr>
<td></td>
<td>Ab out</td>
<td>0.33</td>
<td>−0.02</td>
<td>0.32</td>
</tr>
</tbody>
</table>

ΔVL, volume above functional residual capacity (FRC) at which the isovolume maneuvers took place; ΔVab, abdominal volume change from FRC; ΔVrc, rib cage volume change from FRC; Ab, abdomen; RC, rib cage.

Table 2. Pdi,t configuration

<table>
<thead>
<tr>
<th>Subject</th>
<th>FRC</th>
<th>Relaxation</th>
<th>Ab Out</th>
<th>RC Out</th>
<th>RC Out (Active Diaphragmatic Contraction)</th>
</tr>
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<tr>
<td>SY</td>
<td>24.3</td>
<td>18.6</td>
<td>8.2</td>
<td>19.3</td>
<td>19.7</td>
</tr>
<tr>
<td></td>
<td>23.3</td>
<td>6.4</td>
<td>17.4</td>
<td>16.7</td>
<td></td>
</tr>
<tr>
<td>BK</td>
<td>22.1</td>
<td>20.8</td>
<td>12.7</td>
<td>20.2</td>
<td>22.0</td>
</tr>
<tr>
<td></td>
<td>22.9</td>
<td>9.3</td>
<td>22.2</td>
<td>23.5</td>
<td></td>
</tr>
<tr>
<td>RC</td>
<td>21.2</td>
<td>17.7</td>
<td>4.4</td>
<td>16.7</td>
<td>18.5</td>
</tr>
<tr>
<td></td>
<td>21.9</td>
<td>5.9</td>
<td>17.6</td>
<td>18.9</td>
<td></td>
</tr>
<tr>
<td>Mean + SD</td>
<td>22.6±1.4</td>
<td>19.0±1.6</td>
<td>7.8±3.0</td>
<td>18.9±2.1</td>
<td>19.9±2.6</td>
</tr>
</tbody>
</table>

Pdi,t, transdiaphragmatic twitch pressure.
Previous studies. Our findings contrast with those of Hubmayr et al. (10), who found that RC compression corresponding to a weight of 5 and 9 kg applied to the midsternum had little effect on Pdi,t even with outward Ab displacements of ~0.3 liter, a value similar to those shown in Table 1. The major difference between our study and theirs was the method used to produce changes in thoracoabdominal configuration. We depended on voluntary shifts of volume between RC and Ab compartments, whereas they used external anteroposterior (A-P) compression of the RC. Because they measured thoracoabdominal dimensions with respiratory inductance plethysmography, they could not estimate the effects of A-P compression on A-P and lateral RC dimensions. At constant RC volume, this would increase the lateral dimension and decrease the A-P dimension. If this diminished RC compliance over and above that resulting from the distortions produced by diaphragmatic twitches (3, 11), the elastic load on the diaphragm would increase and this would decrease V_{di}. Although they measured the elastic properties of the RC and Ab and their displacements occurring during twitches, they reported these only during unloaded conditions. Thus it is possible that a decrease in V_{di} resulting from transverse RC-shape distortion tended to offset the effects of a decrease in L_{di} resulting from a shift in volume from RC to Ab.

### Table 3. Baseline Pdi

<table>
<thead>
<tr>
<th>Subject</th>
<th>Pdi,b (Ab)</th>
<th>Pdi,b (RC)</th>
<th>Pdi,b (RC + Di)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SY</td>
<td>25.5</td>
<td>11.7</td>
<td>22.2</td>
</tr>
<tr>
<td>BK</td>
<td>25.0</td>
<td>14.2</td>
<td>16.3</td>
</tr>
<tr>
<td>RC</td>
<td>6.5</td>
<td>0.4</td>
<td>5.9</td>
</tr>
<tr>
<td></td>
<td>5.5</td>
<td>2.1</td>
<td>4.6</td>
</tr>
<tr>
<td>RC</td>
<td>16.2</td>
<td>6.4</td>
<td>15.3</td>
</tr>
<tr>
<td></td>
<td>22.3</td>
<td>6.9</td>
<td>21.3</td>
</tr>
</tbody>
</table>

Pdi,b, baseline Pdi. Shown are Pdi,b in the Ab-out, RC-out, and RC-out with diaphragm (Di) in relaxed and contracted configuration.

Fig. 2. Twitch transdiaphragmatic (Pdi,t), esophageal (Pes), and gastric pressures (Pga) in RC-out position (A) and at same lung volume in Ab-out configuration (B). Tracings during a quiet breath are shown before phrenic stimulation. To produce Ab-out configuration, a Pdi of ~12.5 cmH_{2}O was required.

Fig. 3. Pdi,t as function of lung volume in all 3 subjects (A-C, respectively). Only Ab-out configuration produced a Pdi,t that was different from that in relaxed configuration. In particular when baseline Pdi before phrenic stimulation was increased while RC-out configuration was maintained to equal that required for Ab-out configuration (Pdi,b-m), there was no significant twitch occlusion.
In addition, a decrease in $R_{di}$ in the sagittal plane might also have counterbalanced the effects of a decrease in $L_{di}$. For a given $L_{di}$, $R_{di}$ in the sagittal plane should be a function of the A-P RC dimension at the costal margin where the diaphragm is attached but not the Ab dimension. Thus $R_{di}$ should decrease systematically with a decrease in RC A-P dimension. To the extent that the decrease in $L_{di}$ with volume displacement from the RC to the Ab was offset by a reduction in $R_{di}$, $P_{di}$, it would tend to be preserved.

With the voluntary volume shifts between RC and Ab in our experiments, the RC distortions and decrease in $R_{di}$ should be systematically less than in the experiments reported by Hubmayr et al. (10) for the same compartmental volume shifts. Thus we suggest that the counterbalancing effects of a decrease in $V_{di}$ and $R_{di}$ that likely influenced their results had a smaller effect in our experiment.

Thoracoabdominal configuration and $L_{di}$. We believe that a reduction in $L_{di}$ is the principle cause of the decrease in $P_{di}$, t we measured in the Ab-out configuration. Although this configuration decreased A-P RC dimension (Fig. 1) and therefore $R_{di}$ in the sagittal plane, this, if anything, would have minimized the effect of a decrease in $L_{di}$, as discussed above.

The effect of configurational change on $V_{di}$ is more difficult to predict. This should not have a significant effect on inertial loads as the masses of the structures accelerated would be unchanged. Therefore, any influence of thoracoabdominal configuration on $V_{di}$ is most likely mediated by changes in RC compliance and Cab. Outward displacement of Ab decreases Cab, which would act to diminish $V_{di}$ and preserve $P_{di}$, t. However, a reduction in the area of apposition might minimize the effects of distortion on RC compliance, increasing it more than the decrease in Cab and therefore increasing $V_{di}$. We think this is unlikely for two reasons.

Hubmayr et al. (10) found that $V_{di}$ had no influence on the displacements of RC and Ab with diaphragmatic twitches so that, in their experiments in the undistorted configuration, reductions in the area of apposition had no influence on the relative displacements of RC and Ab. This suggests that the relative compliances of these two structures were unaltered by changes in the area of apposition. As Cab presumably decreased with outward Ab displacement, unloading of the diaphragm by an increase in RC compliance should not have occurred.

However, as illustrated in Fig. 2, the Ab-out configuration decreased the change in pleural pressure ($P_{pl}$) more than it did $P_{di}$. The potential reasons for this are analyzed below. If this were also the case in the experiments of Hubmayr et al. (10), it is possible that RC compliance did increase, but this was offset by a reduction in the pressure applied to the RC, so that RC displacement (and presumably $V_{di}$) remained unchanged.

Chihara et al. (3) have analyzed the factors that determine the change in the $P_{pl}$-to-$P_{di}$ ratio ($\Delta P_{pl}/\Delta P_{di}$) when the diaphragm is the only muscle contracting. To do this they used the model of Ward et al. (20), in which the RC is divided into a lung-apposed or pulmonary compartment (RCp) and a diaphragm-apposed or Ab compartment (RCa). The pressure on the inner surface of RCp is $P_{pl}$ over the surface of the lung, assumed to equal esophageal pressure, whereas the pressure on the inner surface of RCa is $P_{di}$ in the area of apposition, assumed to equal $P_{ab}$ (17, 18) and measurable by gastric pressure. By equating the volume displacements of the two compartments, and of the Ab with the product of the pressure acting on each compartment and its effective compliance during diaphragmatic twitches, they showed that

$$\Delta P_{pl}/\Delta P_{di} = C_{rc,p}(C_{rc,p} + Cab)$$

where $C_{rc,p}$ is dynamic compliance of RCp and is defined as ratio of change in RCp volume/$\Delta P_{pl}$ during phrenic twitches.

They found minimal or no change in volume of RCa during twitches, a finding confirmed by Kenyon et al. (11). As the compliance of RCa was effectively zero it dropped out of the equation. The result shows that $\Delta P_{pl}/\Delta P_{di}$ tends toward zero as Cab diminishes and/or as $C_{rc,p}$ tends toward infinity. This was only ~30% of its value during relaxation conditions (3, 11) because, with isolated diaphragm contraction against a closed airway, the bending stiffness of the RC hinders the inward displacement of RCp and effectively prevents the outward movement of RCa despite the increase in $P_{ab}$ and the insertion action of the diaphragm at the costal margin.

Chihara et al. (3) did not report the effects of lung volume on $C_{rc,p}$ and dynamic compliance of RCa, but they did show that as $V_{di}$ increased, RC distortability remained unchanged or decreased (3). As the major determinant of distortability is the bending stiffness of the RC, bending stiffness either remained the same or increased. As bending stiffness is also the major determinant of the difference between the compliance of RCp during relaxation and that during phrenic twitches (3), we think that it is unlikely that $C_{rc,p}$ increased with a decrease in the area of apposition. Thus we believe that $\Delta P_{pl}/\Delta P_{di}$ decreased in the Ab-out condition due to the known decrease in Cab rather than a hypothetical increase in $C_{rc,p}$.

To the extent that this belief is correct, the Ab-out configuration increased the load on the diaphragm, and as a result $V_{di}$ decreased. The net effect of changes in both $R_{di}$ and $V_{di}$ would be to mask the effects of $L_{di}$ on $P_{di}$, t in the Ab-out configuration.

A similar argument can be made about the RC-out configuration. Here $R_{di}$ in the sagittal plane should have increased due to the increase in RC A-P dimension. This would tend to potentiate any reduction in $P_{di}$, t due to shortening of $L_{di}$ secondary to RC expansion. However, the effect on $V_{di}$ should depend on which muscles were recruited to produce the configurational change. If it were the Ab muscles, Cab would decrease and $V_{di}$ would decrease with it. If it were RC muscles, Cab and $V_{di}$ would increase. In the former situation the effects of a decrease in $L_{di}$ would be masked, but the
effects of $R_{di}$ and $V_{di}$ would tend to cancel. In the latter, the effect of a reduced $L_{di}$ would be magnified.

Finally, all phrenic stimulation in the present study was either performed against a closed airway or a sufficiently high resistance so that the documented increases in $V_L$ resulting from diaphragmatic twitches were $-2.5\%$ or less and were almost entirely due to alveolar gas decompression. The effects of this on our results are sufficiently small that they can be neglected.

For these reasons we believe that the Ab-out configuration produced a substantially greater reduction in $L_{di}$ than either the relaxation or RC-out configurations. Because the relationships between $L_{di}$ and $V_L$ and between $P_{di,t}$ and $V_L$ in the relaxed configuration are linear, we can estimate the relative degrees of shortening in inspiring from FRC to the same $V_L$ in the three different configurations, assuming that the effects of $V_{di}$ and $R_{di}$ can be neglected. If they are more important than we assume, the effects of Ab configurational change on $L_{di}$ are presumably underestimated.

The mean change in $P_{di,t}$ in the relaxation configuration was 3.6 cmH$_2$O from FRC to the end-tidal $V_L$ at which we made our measurements; in the RC-out configuration, it was 3.7 cmH$_2$O; and in the Ab-out configuration it was 14.8 cmH$_2$O. Thus the ratio of $L_{di}$ shortening in Ab-out to that in the relaxation and RC-out configurations was on the order of 14.8:3.7 or 4:1. At constant $V_L$, the change from the relaxation to the RC-out configuration produced no detectable change in $P_{di,t}$, whereas from the relaxation to Ab-out configuration the reduction in $P_{di,t}$ of 11.2 cmH$_2$O accounted for 11.2/14.8 or $-76\%$ of the shortening of the diaphragm in inspiring from FRC to the Ab-out shape.

Our results are consistent with those obtained by Grassino et al. (9) and agree with those of Loring and co-workers (16, 18), in that they show that RC displacements affect $L_{di}$ as well as do Ab displacements. They estimated that 85-90\% of the diaphragm shortening that took place with a tidal inspiration close to the relaxation configuration also occurred with the same increase in $V_L$ produced by the RC only. Our data confirm that there is little difference in $\Delta L_{di}$ produced by the same $\Delta V_L$ in these two configurations. However, we found that Ab displacements affect $L_{di}$ relative to equivolume RC displacements considerably more than they estimated. Their theoretical estimate that the ratio of $\Delta L_{di}$ in the Ab-out configuration to that in the RC-out configuration was 3:2 and their experimental finding that it was 1.8:1 are far smaller than our value of 4:1. The reasons for this discrepancy are not clear. However, they did not study the same thoracoabdominal configurations as we did. To measure the effects of Ab displacement on $L_{di}$ at constant RC volume, they started with an Ab-in position and then displaced the Ab outward approximately to the relaxation configuration. Our subjects, on the other hand, displaced the Ab beyond the relaxation configuration to arrive at the Ab-out configuration. Furthermore, Loring et al. (16) estimated $L_{di}$ by X-rays and assumed (possibly incorrectly) that the diaphragmatic contour was always in the same sagittal or coronal plane. Finally, they only obtained posteroanterior (P-A) and lateral X-rays in one subject, and this P-A subject's lateral X-ray was assumed to apply to the other two subjects, whereas his P-A film was assumed to apply to one of the other subjects. It is possible that the assumptions used in measuring $L_{di}$ from X-rays, the incompleteness of the X-ray information, and the fact that they did not study the Ab-out configuration led them to underestimate the effects of outward Ab displacement on $L_{di}$.

That Loring et al. (16) may have underestimated the influence of Ab displacement on $L_{di}$ is also suggested by recently reported work using a sophisticated respiratory-motion-analysis system combined with ultrasound to measure the upper boundary of the area of apposition and the thoracoabdominal configuration during exercise in normal humans (1). From the data obtained they estimated $L_{di}$ in the area of apposition (which is tightly linked to total $L_{di}$; Ref. 7) as a function of thoracoabdominal configuration. Using multiple stepwise regression analysis, Aliverti et al. (1) concluded that RC displacements only accounted for $-6\%$ of the change in $L_{di}$ in the area of apposition. Ab displacements had much larger effects, accounting for $86\%$. Together, RC and Ab configuration accounted for $92\%$ of the variation of $L_{di}$ in the appositional zone (A. Aliverti and P. Macklem, unpublished observations).

Diagnostic usefulness of $P_{di,t}$. Our results apply to magnetic as well as electrical stimulation of the diaphragm. In the former in most studies it is unclear what configuration the chest wall takes, as the neck must be flexed in an unnatural position for the magnet to be properly placed. Furthermore, it is well recognized that magnetic stimulation activates an undetermined number of inspiratory RC muscle motor units. What is of greater concern is that magnetic stimulation presumably activates an equally undetermined number of expiratory motor units as well and thus introduces at least two more uncontrolled variables compared with electrical stimulation.

Our data indicate that a displacement of $\sim 300$ ml from the thoracic to the Ab compartment may lead to a 60\% decrease in $P_{di,t}$. It follows that thoracoabdominal configuration must be rigorously controlled if one wishes to use $P_{di,t}$ as a clinical test of diaphragmatic contractility. If the relationship between $P_{di,t}$ and Ab displacement is linear, a mere 50 ml of Ab displacement would lead to a 10\% decrease in $P_{di,t}$. It would be difficult to prevent such small changes in thoracoabdominal configurations during the course of an experiment. This observation sheds serious doubt on the use of $P_{di,t}$ as a clinical diagnostic tool.

In summary, we have demonstrated that $P_{di,t}$ is highly sensitive to Ab displacement but less to RC displacement. Therefore, if $P_{di,t}$ is ever to be clinically useful as a measure of diaphragmatic contractility to detect weakness and fatigue, Ab dimensions must be tightly controlled. Under the clinical conditions under which it would be useful to do this, we doubt that this degree of control can be achieved by using either electrical or magnetic stimulation. Some other method of measuring force output may be required. Phonomyog-
raphy has the advantage of being noninvasive, in contrast to Pdi measurements, and only requires unilateral stimulation. Furthermore, it might be considerably less sensitive to thoracoabdominal configuration.

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