
Chest wall kinematic determinants of diaphragm length by optoelectronic plethysmography and ultrasonography

MOST OF THE AVAILABLE INFORMATION on chest wall kine-

matics is based on the two-compartment chest wall model of Konno and Mead (12) composed of rib cage and abdomen (AB), with each behaving with a single degree of freedom, so that changes in volume of each compartment can be measured by a single dimension. Because the movable parts of the AB are the antero-
lateral abdominal wall and the diaphragm, the volume of abdominal contents (Vab) displaced from under the diaphragm must be equal and opposite to the volume displaced by the anterolateral abdominal wall (ΔVabw, where Δ is change). Thus diaphragmatic displacements are closely linked to abdominal wall displacements, and it had been assumed that diaphragm fiber length (LDi) would be simply related to displacements of the AB and nearly unrelated to rib cage displacements. This assumption was supported by the studies of Goldman et al. (8) and Grassino et al. (9), who found that length-tension behavior of the diaphragm was much less sensitive to changes in rib cage diameter than to displacements of the abdominal wall.

Subsequent studies have shown that displacements of the abdominal contents under the diaphragm are more complex than those measured simply by displacements of the anterior abdominal wall. An analytic approach to these complexities was developed in an important paper by Mead and Loring (14). They put forward the concept that displacements of the lower part of the rib cage where the diaphragm is apposed to its inner surface, along with displacements of the AB, are important determinants of LDi and provided experimental evidence to support their theoretical analysis (14). However, in preliminary studies, our laboratory found that >80% of the variance in LDi in the area of apposition (Aab) during exercise was accounted for by abdominal displacements (3). These findings are in agreement with those of Chen et al. (6), who found that twitch diaphragmatic pressure in response to supra-

maximal, transcutaneous, bilateral phrenic nerve stimulation was exquisitely sensitive to abdominal dis-

placements and relatively insensitive to rib cage dis-

placements. These studies suggest that LDi is more closely linked to abdominal displacements and less to rib cage displacements than has generally been thought. In this paper, we develop a method to assess factors determining LDi using optoelectronic plethys-
mography (OEP) (5) to measure volume displacements of the rib cage (ΔVrc) and ΔVabw, combined with ultrasound measurements of changes in LDi in the area of apposition (ΔAab) (5) (5) (5). We hypothesized that it would be possible to predict ΔAab from ΔVabw during quiet breathing and exercise, with and without expiratory flow limitation.
The im-

**THEORY**

In this section, we develop the relationship between abdominal and diaphragmatic displacements following the approach of Mead and Loring (14). To do so, we develop equations that are similar, but not identical, to those they used. They assumed, quite reasonably, that the Vab is constant and that it is composed of three compartments, all of which can change their contribution to the total volume during breathing. The three compartments are displaced during breathing by motion of the diaphragm dome apposed to the lung, by motion of the rib cage in Aap, and by displacement of the anterolateral abdominal wall. Thus

\[ \text{Vab} = \text{Vab}_L + \text{Vab}_\text{rc} + \text{Vab}_w = \text{constant} \quad (1) \]

and

\[ \Delta \text{Vab}_L + \Delta \text{Vab}_\text{rc} + \Delta \text{Vab}_w = 0 \quad (2) \]

where Vab_L is the Vab in the diaphragm dome; Vab_rc is that part of Vab contained between the surface separating the dome from the cephalad limit of Aap and the surface separating the costal margin from the rest of the abdominal contents, Vab_w; and \( \Delta \) is changes in the volume of the three compartments. If xiphic-pubic distance is constant so that the cephalad border of \( \Delta \text{Vabw} \) does not move relative to the pelvic floor, changes in the third compartment are equal to \( \Delta \text{Vabw} \).

\( \Delta \text{Vab}_\text{rc} \) has two components: the first is \( \Delta \text{Vab} \) in the Aap of diaphragm to rib cage, and the second is \( \Delta \text{Vab} \) in the part of the rib cage caudal to the insertion of the costal part of the diaphragm (the obligatory ring). Mead and Loring (14) estimated the fraction of the internal surface of the rib cage at functional residual capacity occupied by Aap (fapp) to be \( \sim 0.25 \), whereas the fraction occupied by the obligatory ring (fobr) was estimated to be \( \sim 0.15 \). Mead and Loring assumed that “in the resting tidal range fapp decreases only modestly during inspiration, and 0.41 is a reasonable average value of (fapp + fobr).” Thus they estimated \( \Delta \text{Vab}_\text{rc} \) by

\[ \Delta \text{Vab}_\text{rc} = (\text{fapp} + \text{fobr}) \Delta \text{Vrc} \]

Substituting for \( \Delta \text{Vab}_\text{rc} \) in Eq. 2 yields

\[ \Delta \text{Vab}_L + (\text{fapp} + \text{fobr}) \Delta \text{Vrc} + \Delta \text{Vabw} = 0 \quad (3) \]

Equation 3 requires that the middle term, the Vab contained within Aap, be always positive if the rib cage expands, and ignores the consequences of a decrease in Aap. Using this approach, they calculated that the Vab displaced from the diaphragmatic dome during inspiration was “more than twice the contribution based solely on anterolateral abdominal expansion.” The implication they drew is that diaphragmatic shortening could be considerably greater than that estimated by measuring abdominal wall motion alone, because the diaphragmatic contribution to tidal volume includes the middle term of Eq. 3, which is always positive with rib cage expansion. This is not measured by \( \Delta \text{Vabw} \), but it can be estimated by measuring \( \Delta \text{Vrc} \). The problem with this conclusion is the use of an average value of fapp that remains constant during inspiration. If one allows fapp to change during inspiration rather than taking an “average” value, a quite different result is obtained.

Substituting \( (\text{fapp} + \text{fobr}) \) Vrc for \( \text{Vab}_\text{rc} \) in Eq. 1 gives Vab at the beginning of inspiration

\[ \text{Vab} = \text{Vab}_L + (\text{fapp} + \text{fobr})\text{Vrc} + \text{Vabw} \quad (4) \]

At the end of inspiration

\[ \text{Vab} = \text{Vab}_\text{w} + (\text{fapp} - \Delta \text{fapp} + \text{fobr}) \times (\text{Vrc} + \Delta \text{Vrc}) + \text{Vab}_\text{w} \quad (5) \]

where \( * \) indicates a new value at end inspiration. Subtracting Eq. 4 from Eq. 5

\[ \Delta \text{Vab}_L + \Delta \text{Vrc}(\text{fapp} + \text{fobr}) - \Delta \text{fapp} \text{Vrc} - \Delta \text{fapp} \Delta \text{Vrc} + \Delta \text{Vabw} = 0 \quad (6) \]

The difference between Eqs. 6 and 3 is the inclusion of \( - \Delta \text{fapp} \text{Vrc} - \Delta \text{fapp} \Delta \text{Vrc} \) in Eq. 6. Thus, according to Eq. 6, the \( \Delta \text{Vab} \) contained within Aap

\[ \Delta \text{Vrc} (\text{fapp} + \text{fobr}) - \Delta \text{fapp} \text{Vrc} - \Delta \text{fapp} \Delta \text{Vrc} \]

This can be either positive or negative, depending on the relative values of \( \Delta \text{Vrc}, \text{Vrc}, \Delta \text{fapp}, \text{and fapp}. \)

If one assumes a breath of 500 ml in which fapp decreases from 0.25 to 0.20, fobr remains constant at 0.15, \( \Delta \text{Vrc} = 375 \text{ ml}, \frac{1}{2} \Delta \text{Vab} = 125 \text{ ml}, \Delta \text{Vab} \text{ in Aap becomes} (150 - 0.05 \text{ Vrc} - 6.25) \text{ ml}. A reasonable value for the internal volume of the rib cage measured by OEP (5) (a new technology described in detail below) is 5 liters (A. Aliverti, personal communication). Thus the \( \Delta \text{Vab} \text{ in Aap} \) is a negative value of \(-106.25 \text{ ml} \text{ compared with} +150 \text{ ml} \text{ calculated by using the Mead and Loring equation.} \)

Thus the predictions arising from Eq. 6 are quite different from those arising from Eq. 3. Equation 6 does not predict that the \( \Delta \text{Vab} \text{ in Aap} \) is necessarily positive. It can increase, decrease, or stay the same, depending on the relative magnitudes of rib cage expansion and decrease of the Aap. The sum of \( \Delta \text{Vab}_L \) and \( \Delta \text{Vab}_\text{rc} \) gives the \( \Delta \text{Vab} \text{ contained within the diaphragm, and this sum is equal and opposite to \( \Delta \text{Vab} \text{. The assumption that the Vab contained within Aap always increases with rib cage expansion cannot be correct when Aap decreases. As a result, because \( \Delta \text{fapp} \text{Vrc} \) can be estimated, and to the extent that \( \Delta \text{Vab}_\text{rc} \text{ and } \Delta \text{Vab}_L \text{ carry information about diaphragmatic shortening, } \Delta \text{Vab} \text{ can potentially be used to estimate L}. \)\text{)} \)

Clearly, how much fapp changes with a breath is crucial to the understanding of the diaphragm’s contribution to breathing. Mead and Loring’s (14) use of a constant average fapp must introduce substantial errors. Although it is true that their measurements (13) tended to support their theoretical analysis (14), not all measurements were made in all subjects, and some
questionable assumptions tend to make their data open to reinterpretation (see Ref. 6 for further discussion). It would seem that Mead’s earlier calculations of the effect of thoracoabdominal configuration on $L_{di}$ [made with Goldman et al. (8) and Grassino et al. (9)] may have been closer to the truth than his later calculations.

**METHODS**

**Subjects**

We studied four healthy normal men 42 ± 3 (SD) yr old, with anthropometric and functional respiratory characteristics shown in Table 1. They were all laboratory personnel trained in respiratory maneuvers.

**Protocol**

Each subject was studied on two occasions while seated on a cycle ergometer with the arms supported away from the trunk. On both, the subjects breathed spontaneously for 3 min and then performed an incremental exercise test starting at 0 W and increasing by 25 W every 4 min until exhaustion. The incremental exercise tests were performed under control conditions (Ex,c) and with a Starling resistor in the expiratory port of the valve, which separated inspiratory and expiratory flow. We measured maximal power output under Ex,c and Ex,s. Reports of the determinants of exercise limitation and dynamics of breathing during these experiments have previously been published (2, 10). During Ex,s, the subjects breathed through a mouthpiece, which was attached to a Hans Rudolph valve, which separated inspiratory and expiratory flow. Flow limitation was achieved by putting the Starling resistor on the expiratory port of the valve. A 2-liter jar was placed in parallel with the Starling resistor, which acted as a capacitance, so that, at the beginning of expiration, flow was somewhat greater than 1 l/s, whereas, at the end, it was somewhat less (see Ref. 10, Fig. 1). Data were gathered during the last 40 s of each workload. We randomized the order in which these two exercise tests were performed.

**Measurements**

**OEP.** Figure 1A shows a general overview of the measurement system. Chest wall kinematics and compartmental volumes were measured by OEP, as previously described, and validated at rest and during exercise (1, 5, 11). Eighty-nine reflecting markers were placed front and back over the chest wall from clavicles to pubis. Each marker was tracked in three dimensions (3D) by four video cameras: two in front of the subject and two behind. A dedicated image processor measured the position of each marker at 50 Hz. For volume computation, chest wall surface was approximated by 182 triangles connecting the markers. Then, using Gauss’ theorem, the volume of the chest wall (Vcw) and of its compartments was calculated. We modeled the chest wall as a three-compartment system, comprised of the pulmonary or lung-apposed rib cage (RCP), the abdominal or diaphragm-apposed rib cage (RCA), and the AB (5, 15). The sum of the volume of each compartment equaled the Vcw: 

$$Vcw = Vrc,p + Vrc,a + Vab,$$

where $Vrc,p$ is pulmonary rib cage volume and $Vrc,a$ is abdominal rib cage volume.

**Ultrasonography of the diaphragm.** Diaphragm motion was visualized by a general-purpose echo camera (Aloka Echocam Camera), equipped with a linear probe (3.5 MHz, 128 mm). As the intrapulmonary air greatly attenuates the transmission of ultrasound waves, the resulting abrupt discontinuity in the image at the level at which the diaphragm reflects from the chest wall and the lung intervenes was used to identify the position of the cephalic margin of the zone of apposition (Fig. 1B). The caudal border was measured by markers along the costal margin.

The probe was placed in a plastic frame fixed to the skin by adhesive tape and manually kept in a fixed position during the experiments. The probe was aligned approximately axially and placed between the two markers defining the right lateral border of the RCA. Three additional markers were placed on the probe and tracked by the OEP cameras to measure its position and orientation.

Ultrasonographic images were synchronized with the motion analyzer by generating a trigger signal that created a symbol at a frequency of 0.5 Hz on the ultrasonic image and that was recorded on a analog-to-digital card (RTI800, Analog Devices, Norwood, MA) synchronized with the motion analysis system. The ultrasonic images were then recorded on a standard video recorder and successively digitized by a frame grabber (Screen Machine II, Fast Electronic) in motion JPEG format at 10 frames/s with a resolution of $320 \times 240$ pixels. When the first symbol and the first trigger appeared, respectively, on the image and the digitized signal, the sequence of echographic images and OEP volumes (down-sampled at 10 Hz) was aligned to be in synchrony and automatically maintained synchronous for the duration of the measurement by a specifically developed software. Small movements of the margin of the zone of apposition could be easily detected, even if sometimes the margin was obscured by a rib at the initial or final position.

**Data Analysis**

$L_{di}$ in the $A_{xp}$. Changes in $A_{xp}$ were estimated by measuring axial motion of its cephalic margin in the echographic images of the right hemidiaphragm. On each image, the cephalic extremity was manually selected. Successively, the two-dimensional coordinates were mapped into 3D space by using the information on the position and orientation of the probe. For each image, the transverse plane at the level of the xiphisternum was estimated by computing the regression plane outlined by the markers placed at the xiphoid level.

**Table 1. Anthropometric characteristics of subjects**

<table>
<thead>
<tr>
<th>Subject</th>
<th>Age, yr</th>
<th>Weight, kg</th>
<th>Height, cm</th>
<th>TLC, liters</th>
<th>VC, liters</th>
<th>FRC, liters</th>
<th>RV, liters</th>
</tr>
</thead>
<tbody>
<tr>
<td>II</td>
<td>28</td>
<td>94</td>
<td>184</td>
<td>7.70</td>
<td>5.70</td>
<td>3.58</td>
<td>2.00</td>
</tr>
<tr>
<td>KB</td>
<td>44</td>
<td>69</td>
<td>168</td>
<td>7.61</td>
<td>5.25</td>
<td>4.27</td>
<td>1.76</td>
</tr>
<tr>
<td>SP</td>
<td>42</td>
<td>88</td>
<td>180</td>
<td>5.96</td>
<td>4.61</td>
<td>3.20</td>
<td>1.35</td>
</tr>
<tr>
<td>YS</td>
<td>45</td>
<td>56</td>
<td>162</td>
<td>6.30</td>
<td>4.70</td>
<td>2.90</td>
<td>1.60</td>
</tr>
<tr>
<td>Mean</td>
<td>42</td>
<td>75</td>
<td>173</td>
<td>6.9</td>
<td>5.1</td>
<td>3.5</td>
<td>1.7</td>
</tr>
<tr>
<td>SD</td>
<td>3</td>
<td>19</td>
<td>10</td>
<td>0.9</td>
<td>0.5</td>
<td>0.6</td>
<td>0.3</td>
</tr>
</tbody>
</table>

TLC, total lung capacity; VC, vital capacity; FRC, functional residual capacity; RV, residual volume.

*J Appl Physiol* • VOL 94 • FEBRUARY 2003 • www.jap.org
Fig. 1. A: schematic diagram of the measurement, data processing, and analysis system. B: representative example of an echographic image obtained from the right lateral abdominal rib cage. The shadowed area at the top corresponds to the lung, whereas the lighter area at the bottom corresponds to the liver. The arrow indicates the point P where the diaphragm reflects from the chest wall and the lung intervenes. This point was used to identify the position of the cephalic margin of the zone of apposition. 2D, two-dimensional; 3D, three-dimensional.
Finally, the \( D_{ap} \) to the upper border of \( A_{ap} \) was computed as reported in detail in the APPENDIX and in Ref. 4.

**Regression analysis.** For each test, four to five breaths were analyzed at a sampling rate of 10 Hz. Successively, a linear regression analysis between \( D_{ap} \) and \( V_{rc,p} \), \( V_{rc,a} \), \( V_{ab} \), and \( V_{cw} \) was performed, and the results were expressed as squared linear regression coefficient (\( r^2 \)) and slope of the regression line.

**Analysis of variance.** To study the repeatability on different days and experiments and the differences between subjects on \( r^2 \) and slope values, we applied a one-way ANOVA on repeated measures to four different tests of quiet breathing.

---

**Fig. 2.**

**A:** representative example of tracings obtained during quiet breathing. \( \Delta \), Change; \( V_{rc,p} \), volume of lung-apposed rib cage compartment; \( V_{rc,a} \), volume of diaphragm-apposed rib cage compartment; \( V_{ab} \), volume of abdomen; \( D_{ap} \), axial motion of cephalic margin of the diaphragm in the area of apposition. **B:** correlations between \( \Delta D_{ap} \) and \( V_{rc,a} \), \( V_{rc,p} \), \( V_{ab} \), and chest wall volume (\( V_{cw} \)) for the data shown in **A**.
To study the effect of the presence of Starling resistor (factor 1), of different compartments (factor 2), and of different workloads (factor 3) on $r^2$ and slope values, we applied a three-way ANOVA on repeated measures to all of the tests.

For factor 3, we considered quiet breathing at rest, 25 W, maximum workload (Wmax) during exercise with EFL, and Wmax/2 (half-maximal control exercise workload; Wmax,s, maximal exercise workload with expiratory flow limitation).

$$D_{ap} = B_0 + B_1 \cdot Vab + B_2 \cdot Vrc,a + B_3 \cdot Vrc,p \quad (7)$$

where $B_0$ is the intercept and $B_1$, $B_2$, and $B_3$ are the linear coefficients. With the use of stepwise multiple regression, the relative contributions of each component in Eq. 7 were determined for the different subjects during the different exercise workloads (from quiet breathing to Wmax) with and without EFL. The goodness of fit, $r^2$, was used to quantify the percentage of variation in $D_{ap}$ that is explained by Vab, Vrc,a, and Vrc,p. Results obtained from all of the subjects were then averaged in three different situations: quiet breathing, Ex,c, and EFL exercise.

### RESULTS

#### Linear Correlation Analysis

Figure 2A shows tracings of $\Delta Vcw$ and its three compartments (Vrc,p, Vrc,a, and Vab) during quiet breathing. The **bottom** trace is the $\Delta D_{ap}$. The time variations of the volumes of the different chest wall compartments were approximately in phase, and the inspiratory decrease of $D_{ap}$ was in the order of 2.5 cm. Figure 2B shows the results of the linear regression

$$SLOPE = \frac{\text{Slope}}{\text{Slope}}$$

$D_{ap}$, the chest wall, and its compartments as a function of exercise workload for both control and flow-limited exercise. Values are means $\pm$ SE.
analysis (slope and $r^2$), computed between $\Delta D_{ap}$ and $V_{rc,p}, V_{rc,a}, V_{ab},$ and $V_{cw}$, corresponding to the same data reported in Fig. 2A. $\Delta D_{ap}$ was well correlated with the volume variations of each chest wall compartment and with those of the total chest wall. However, the highest value of $r^2$ was obtained for $V_{ab}$. The slopes of the linear regressions simply reflect the volume of each compartment because $D_{ap}$ is common to all.

Analysis of Variance

Figure 3 confirms the importance of abdominal wall displacements in predicting $\Delta D_{ap}$. The $r^2$ values on the ordinate reveal how much of the variance in $\Delta D_{ap}$ is accounted for by the volume displacements of each of the three compartments and the whole chest wall during quiet breathing and as a function of exercise workload. Each bar contains pooled control and EFL breaths in all subjects. Mean $r^2$ values were again highest for the AB and were lower for the two rib cage compartments. The post hoc Scheffé test showed no significant differences between the $r^2$ of the two rib cage compartments ($P > 0.95$) or between the AB and the chest wall ($P > 0.80$), with significant differences for all other comparisons ($P < 0.01$ for all).

Table 2 gives the results of the one-factor analysis of variance in which we looked for possible differences among repeated measures and different subjects. The values of $P$ level reported in Table 2 ($r^2$ and slope) demonstrate the repeatability of this method and the independence of $r^2$ from confounding variables, such as weight, height, age, etc., with the possible exception of $D_{ap}$ vs. $V_{ab}$, where the data approach statistical significance. In contrast, each subject had a characteristic slope as shown by the $P$ values, all of which showed statistically significant differences in slope between subjects.

As shown in Table 3, there were two significant effects for $r^2$: the main effect for compartment and the interaction between compartment and workload. In contrast to the analysis of $r^2$, Table 3 shows that there are many significant factors that affect slope: the main effect for compartment and workload, the interaction between compartment and workload, the interaction between...
displacement of the two rib cage compartments improved this by only 1%.

**DISCUSSION**

$L_{di}$ is determined by thoracoabdominal configuration. Our results demonstrate that, under the conditions in which we measured $\Delta D_{ap}$ near the midaxillary line, abdominal displacement was its best predictor. Is $\Delta D_{ap}$ a measure of change of $L_{di}$? It may be possible with rib cage expansion for the diaphragm to peel away from the rib cage without a change in fiber length. However, Gauthier et al. (7) showed in humans that changes in the axial dimension of the $A_{ap}$ were excellent estimates of fiber length in the supine position. No similar data exist in the upright posture in humans. Assuming that determinants of $L_{di}$ are the same in upright and supine, our measurements of $\Delta D_{ap}$ are estimates of changes in costal $L_{di}$.

As illustrated in Fig. 2, we found substantial shortening of diaphragmatic fibers during quiet breathing, so that Mead and Loring's (14) use of an average value of the $A_{ap}$ during quiet breathing does not seem justified either theoretically (as developed above) or from an experimental point of view.

One might expect that fiber length would be well-correlated with displacements of the RCa from which the costal fibers originate and with which they are in direct contact in the $A_{ap}$. In fact, Loring et al. (13) have provided evidence that this is the case, although we were unable to confirm their findings. However, it should be realized that we only measured the determinants of $L_{di}$ when

---

**Table 4. Significance of differences (P) between compartments**

<table>
<thead>
<tr>
<th></th>
<th>$r^2$</th>
<th>Slope</th>
</tr>
</thead>
<tbody>
<tr>
<td>RCp vs. RCa</td>
<td>0.962231</td>
<td>0.000144</td>
</tr>
<tr>
<td>RCp vs. AB</td>
<td>0.001209</td>
<td>0.049675</td>
</tr>
<tr>
<td>RCp vs. CW</td>
<td>0.003923</td>
<td>0.000966</td>
</tr>
<tr>
<td>RCa vs. AB</td>
<td>0.002242</td>
<td>0.000009</td>
</tr>
<tr>
<td>RCa vs. CW</td>
<td>0.007694</td>
<td>0.000001</td>
</tr>
<tr>
<td>AB vs. CW</td>
<td>0.808966</td>
<td>0.078492</td>
</tr>
</tbody>
</table>

AB, abdomen; CW, chest wall.

The presence of EFL and workload, and the interaction among presence of EFL, workload, and compartment.

The results of the post hoc Scheffé’s test for the effect of workload on slope are shown in Fig. 4. As shown in this figure, the two rib cage compartments and the chest wall had higher slopes during exercise compared with quiet breathing, and the slope for the chest wall was significantly greater at maximal power output with EFL than at 25 W. Only the abdominal compartment showed no change in slope from quiet breathing to exercise.

The presence of EFL did not significantly affect either $r^2$ or slope within a compartment, as shown in Fig. 5. Table 4 shows, as does Fig. 3, that there were no significant differences between the two rib cage compartments, or between the AB and the chest wall, but both $r^2$ and slope were significantly less for the rib cage than for the chest wall and AB. Therefore, Figs. 3–5 demonstrate that the correlation between $\Delta D_{ap}$ and the change of compartmental volumes is significantly better for the AB and total chest wall than for the rib cage compartments, and, considering both $r^2$ and slope, the AB is somewhat better than the chest wall in predicting $\Delta D_{ap}$. Presumably, this is because the chest wall contains both rib cage compartments, which diminishes its ability to predict $\Delta D_{ap}$.

---

**Table 5. Results of multiple stepwise linear regression analysis**

<table>
<thead>
<tr>
<th>Workload</th>
<th>Subject</th>
<th>$r^2$</th>
<th>Change</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>AB</td>
<td>RCa</td>
<td>RCp</td>
</tr>
<tr>
<td>QB</td>
<td>II</td>
<td>0.9366</td>
<td>0.0029</td>
</tr>
<tr>
<td></td>
<td>KB</td>
<td>0.9255</td>
<td>0.0000</td>
</tr>
<tr>
<td></td>
<td>SP</td>
<td>0.9686</td>
<td>0.0014</td>
</tr>
<tr>
<td></td>
<td>YS</td>
<td>0.7251</td>
<td>0.0299</td>
</tr>
<tr>
<td></td>
<td>Mean ± SE</td>
<td>0.89 ± 0.06</td>
<td>0.01 ± 0.00</td>
</tr>
<tr>
<td>25 W</td>
<td>II</td>
<td>0.8940</td>
<td>0.0034</td>
</tr>
<tr>
<td></td>
<td>KB</td>
<td>0.9597</td>
<td>0.0000</td>
</tr>
<tr>
<td></td>
<td>SP</td>
<td>0.9305</td>
<td>0.0000</td>
</tr>
<tr>
<td></td>
<td>YS</td>
<td>0.9267</td>
<td>0.0177</td>
</tr>
<tr>
<td></td>
<td>Mean ± SE</td>
<td>0.93 ± 0.01</td>
<td>0.01 ± 0.00</td>
</tr>
<tr>
<td>Wmax/2</td>
<td>II</td>
<td>0.9485</td>
<td>0.0023</td>
</tr>
<tr>
<td></td>
<td>KB</td>
<td>0.9685</td>
<td>0.0000</td>
</tr>
<tr>
<td></td>
<td>SP</td>
<td>0.9606</td>
<td>0.0094</td>
</tr>
<tr>
<td></td>
<td>YS</td>
<td>0.9565</td>
<td>0.0118</td>
</tr>
<tr>
<td></td>
<td>Mean ± SE</td>
<td>0.96 ± 0.00</td>
<td>0.01 ± 0.00</td>
</tr>
<tr>
<td>Wmax,s</td>
<td>II</td>
<td>0.9494</td>
<td>0.0051</td>
</tr>
<tr>
<td></td>
<td>KB</td>
<td>0.9674</td>
<td>0.0014</td>
</tr>
<tr>
<td></td>
<td>SP</td>
<td>0.9913</td>
<td>0.0000</td>
</tr>
<tr>
<td></td>
<td>YS</td>
<td>0.9378</td>
<td>0.0023</td>
</tr>
<tr>
<td></td>
<td>Mean ± SE</td>
<td>0.96 ± 0.01</td>
<td>0.00 ± 0.00</td>
</tr>
</tbody>
</table>

QB, quiet breathing; Wmax/2, half-maximal control exercise workload; Wmax,s, maximal exercise workload with EFL.
there was prominent abdominal motion. Before the rib cage can be excluded as an important determinant, it would be necessary to show that the diaphragm is quasi-isometric during an inspiration without any abdominal displacement. We have not studied such breaths.

To further examine the relationship between the contributions of the $RC_p$, $RC_a$, and $AB$ to tidal volume and their relationship to $D_{ap}$, we correlated the fractional contributions of these chest wall compartments to tidal volume on one hand and $\Delta D_{ap}$ on the other. The results are shown in Fig. 6. The $r^2$ values for all chest wall compartments are small, and neither relationship is significant, although statistical significance is approached for the $RC_p$ ($P = 0.54$).

Loring et al. (13) showed that, when abdominal motion was minimal, the diaphragm could shorten. They studied three subjects to evaluate the dependence of $L_{di}$ on lung volume and thoracoabdominal configuration and suggested that $L_{di}$ was closely coupled to rib cage displacement, as well as to ventral abdominal wall displacement. In their analysis, they considered the whole rib cage as a determinant of the $L_{di}$. They argued that, because the costal fibers originate at the costal margin, a diaphragmatic contraction should displace the rib cage cranially, entailing diaphragm shortening independent of abdominal motion. Nevertheless, the diaphragm and abdominal wall form a compartment of nearly constant volume. The volume swept by the abdominal wall must be equal and opposite to the volume swept by the diaphragm. If diaphragm fibers can shorten at constant $V_{ab}$, then the diaphragm must decrease its surface area at constant volume. This can only occur if the diaphragm's configuration changes from a less spherical to a more spherical shape.

Despite the possibility of diaphragmatic shortening during a breath with no abdominal displacement, we have shown that abdominal displacements alone, measured by OEP, are sufficient to estimate changes in $L_{di}$ in healthy subjects during quiet breathing and exercise, with and without externally applied EFL.

Before attempting such measurements, it would be necessary to calibrate the relationship between $\Delta D_{ap}$ and abdominal displacement in each subject on each occasion that measurements are made. The results of the ANOVA shown in Table 2 reveal highly significant differences in slope of the $D_{ap}$-$V_{ab}$ regression between subjects. Therefore, the relationship between the two variables in each subject must be known before $\Delta V_{ab}$

---

Fig. 6. Relationship between the percent contributions to tidal volume of the chest wall compartments and $\Delta D_{ap}$. A: $\Delta V_{rc,p}$. B: $\Delta V_{rc,a}$. C: $\Delta V_{ab}$.

Fig. 7. Geometrical transformation between the coordinate system of the echographic probe (axes $x$, $y$, and $z$) and the coordinate system of the laboratory where the markers placed on the chest wall and on the probe are measured (axes $X$, $Y$, $Z$). $M_1$, $M_2$, and $M_3$: points corresponding to the markers placed on the probe; $d$, distance between the markers $M_1$ and $M_2$ and the skin.
can be used as a measure of \( \Delta D_{ap} \). Furthermore, the differences in \( D_{ap} \) vs. \( V_{ab} \) between repeated measures approaches statistical significance. This probably reflects slight differences in posture and marker placement in different experiments. Nevertheless, it indicates the need to calibrate the \( D_{ap} \)-\( V_{ab} \) regression each time a subject is studied. Finally (again as shown in Table 2), the between-subject difference in \( r^2 \) also approached statistical significance. Therefore, we cannot exclude the possibility that there are individuals in whom \( r^2 \) of the \( D_{ap} \)-\( V_{ab} \) regression is not sufficiently high to allow good estimates of \( L_{di} \).

**APPENDIX: \( D_{ap} \) ESTIMATION**

For each acquired frame, the position of the point \( P \) of coordinates \( x_P, y_P \), corresponding to the cephalic margin of the zone of apposition (see Fig. 1B), was selected in the echographic image (plane of axes \( xy \)) and then geometrically transformed by a rototranslation into the point \( P' \) of coordinates \( x_{P'}, y_{P'}, z_{P'} \) in the laboratory reference system (3D space of axes \( XYZ \)), in which the markers placed both on the chest wall surface and on the probe were acquired (Fig. 7).

The coordinate system of the probe was defined by using the 3D coordinates of the markers placed on the probe (\( M_1, M_2, \) and \( M_3 \)), and the three axes \( x, y, z \) were defined as follows: \( x \)-axis parallel to the straight line passing through points \( M_1 \) and \( M_2 \) at a distance \( d \), equal to the distance between the markers \( M_1 \) and \( M_2 \) and the skin; the \( z \)-axis as the vector product between \( x \) and \( y \); \( y \)-axis was obtained as the vector product between \( x \) and \( z \).

Points \( P \) were then rototranslated into the 3D space by the following equation

\[
\begin{bmatrix}
    P' \\
    1
\end{bmatrix} = \begin{bmatrix}
    R & T \\
    Zs & 1
\end{bmatrix} \begin{bmatrix}
    P \\
    1
\end{bmatrix}
\]  

(8)

where \( P' \) is the coordinate vector (3 \( \times \) 1) of the point \( P' \); \( P \) is the coordinate vector (3 \( \times \) 1) of the point \( P (x_P = 0) \); \( R \) is the rotation matrix (3 \( \times \) 3), whose components are the direction cosines of the three axes \( x, y, \) and \( z \); \( T \) is the coordinate vector (3 \( \times \) 1) of the origin of the probe coordinate system, defined by the point \( M_1 \) and the distance \( d \); and \( Zs \) is a row vector (1 \( \times \) 3) of zeros.

The distance between the point \( P \) and the \( D_{ap} \) was computed as follows: 1) by estimating the regression plane \( \pi \) among the markers placed at the xiphoid level, of equation

\[
Z = b_0 + b_1 X + b_2 Y
\]

(9)

\[
\begin{bmatrix}
    b_1 \\
    b_2
\end{bmatrix} = \begin{bmatrix}
    \sum (X_i - X_m)^2 & \sum (X_i - X_m)(Y_i - Y_m) & \sum (X_i - X_m)(Z_i - Z_m) \\
    \sum (X_i - X_m)(Y_i - Y_m) & \sum (Y_i - Y_m)^2 & \sum (Y_i - Y_m)(Z_i - Z_m) \\
    \sum (X_i - X_m)(Z_i - Z_m) & \sum (Y_i - Y_m)(Z_i - Z_m) & \sum (Z_i - Z_m)^2
\end{bmatrix}^{-1} \begin{bmatrix}
    \sum (X_i - X_m)Z_i \\
    \sum (Y_i - Y_m)Z_i \\
    \sum (Z_i - Z_m)Z_i
\end{bmatrix}
\]  

(10)

\[
b_0 = Z_m - b_1 X_m + b_2 Y_m
\]

(11)

where \( b_1 \), \( b_2 \), and \( b_0 \) are identified in Eqs. 10 and 11; \( X_m, Y_m, \) and \( Z_m \) are the mean values of the coordinates of the body markers at the xiphoid level; and \( X_i, Y_i, \) and \( Z_i \) are the values of their different coordinates; and 2) by computing the distance \( D_{ap} \) between the point \( P' \) (of coordinates \( X_{P'}, Y_{P'}, Z_{P'} \)) and the xiphoid plane \( \pi \) as

\[
D_{ap} = \frac{b_0 + b_1 X_{P'} + b_2 Y_{P'} - Z_{P'}}{\sqrt{(b_1^2 + b_2^2 + 1)}}
\]

(12)

---

We gratefully acknowledge E. Orsi for software development and G. Scano, R. Duranti, I. Iandelli, G. Misuri, and B. Kayser for valuable help in preparing and performing the experiments.

**REFERENCES**


