Volume displaced by diaphragm motion in emphysema

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the effect of hyperinflation on the volume displaced by dia-
phragm motion (ΔVdi), we compared nine subjects with em-
physema and severe hyperinflation (residual volume (RV)/
total lung capacity (TLC) 0.65 ± 0.08; mean ± SD) with 10
healthy controls. Posteroanterior and lateral chest X rays at
RV, functional residual capacity, one-half inspiratory capac-
ity, and TLC were used to measure the length of diaphragm
assumed to rib cage (Lap), cross-sectional area of the pulmo-

atory rib cage, ΔVdi, and volume beneath the lung-apposed
dome of the diaphragm. Emphysema subjects, relative to
controls, had increased Lap at comparable lung volumes (4.3
vs. 1.0 cm near predicted TLC, 95% confidence interval 3.4–
5.2 vs. 0–2.1), pulmonary rib cage cross-sectional area (em-
physema/controls 1.22 ± 0.03, P < 0.001 at functional residual
capacity), and ΔVdi/Lap (0.25 vs. 0.14 liters/cm, P <
0.05). During a vital capacity inspiration, relative to controls,
ΔVdi was normal in five (1.94 ± 0.51 liters) and decreased inour (0.51 ± 0.40 liters) emphysema subjects, and volume
beneath the dome did not increase in emphysema (0 ± 0.36
vs. 0.82 ± 0.80 liters, P < 0.05). We conclude that ΔVdi can
be normal in emphysema because 1) hyperinflation is shared
between rib cage and diaphragm, preserving Lap, and 2) the
diaphragm remains flat during inspiration.

hyperinflation; subphrenum; dome; zone of apposition; rib
cage

Aliverti et al. (1) have shown that, in humans, during
exercise the diaphragm contracts nearly isotonically and
acts mainly to generate inspiratory flow, whereas the
increased pressures required to displace the rib cage and
abdomen are developed largely by rib cage and abdomi-
nal muscles. These findings suggest that the contribution
of the diaphragm to inspiration depends not only on its
ability to develop tension, but also on its capacity to
shorten and displace volume. In healthy subjects, the
diaphragm shortens by about a third during a vital ca-

pacity (VC) inspiration (3, 8, 26), and diaphragm motion
accounts for about one-half of inspired volume (24, 26,
28). In emphysema, because of pulmonary hyperinflation
and possibly to remodeling with preferential loss of
longer sarcomeres (27), diaphragm length is reduced,
particularly in the zone of apposition of the diaphragm to
the rib cage (Lap). This limits both the maximum tension
that can be generated by the diaphragm (23) and its
inflationary action on the lower rib cage (9) and could
limit further shortening of the diaphragm and its contri-
bution to inspired volume. The latter has not been exam-
ined in emphysema.

Changes in Lap of the costal diaphragm during inspi-
ration can be measured noninvasively (16) and may be an
accurate surrogate measure of the volume displaced by
diaphragm motion (ΔVdi). However, the relationship be-

tween these two measurements has not been established
in humans. In dogs, ΔVdi correlates better with shorten-
ing of the costal than the crural diaphragm (13) and is not
accurately predicted without simultaneous measurement
of changes in rib cage diameter and diaphragm shape
(19). In humans, our laboratory (26) has previously
shown that when Lap is reduced by costophrenic fibrosis,
the diaphragm can flatten during inspiration and this
augments ΔVdi. Because Lap is also reduced in emphy-
sema, changes in diaphragm shape during inspiration
could make an important contribution to the ΔVdi in this
condition, and the relationship between ΔVdi and ΔLap
in emphysema may be different from that in healthy
subjects.

Our aims were to measure ΔVdi in emphysema and to
evaluate its relationship to diaphragm length and shape
and to rib cage dimensions. We hypothesized that ΔVdi
would be reduced in emphysema and that ΔVdi could be
predicted by measuring ΔLap. However, we found that
ΔVdi during a VC inspiration was similar to that in
health in more than half the subjects with emphysema
and that ΔVdi could not be accurately predicted from
ΔLap alone in either health or emphysema. A normal
ΔVdi during a VC inspiration in emphysema was associ-
ated with hyperinflation of the pulmonary rib cage and
an increased Lap. Our analysis suggests that hyperinfla-

tion of the pulmonary rib cage acts to preserve Lap and
the capacity of the diaphragm to change lung volume.

METHODS

Subjects

Nineteen male subjects participated in this study. Nine
had emphysema and severe pulmonary hyperinflation with
the following criteria: ratio of residual volume (RV) to total
lung capacity (TLC) >0.6, TLC greater than predicted, forced

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expiratory volume in 1 s (FEV$_1$) $<$50% predicted, ratio of FEV$_1$ to forced VC $<$0.5, and single-breath transfer factor (lung CO-diffusing capacity (DL$_{CO}$)) $<$70% predicted. A control group of 10 healthy men matched for age, height, and weight was recruited from local service clubs. Subjects were excluded if they were aged $<$40 or $>$80 yr, were cachectic (body mass index $<$18 kg/m$^2$), had previous lung surgery, or had clinical or plain radiographic evidence of another disorder that could cause abnormal diaphragm motion, including disorders of the pleura, pulmonary interstitium, nervous system, and muscles. Informed consent was obtained from each subject, and ethical approval was granted by the Committee for Human Rights, University of Western Australia.

Pulmonary Function and Respiratory Muscle Strength

Respiratory function was assessed in all subjects as follows: lung volumes by plethysmography (model 09103; Warren E. Collins, Braintree, MA), maximum expiratory flow volume relationship and FEV$_1$ by pneumotachograph (model 400VR; Hewlett-Packard, Waltham, MA), DL$_{CO}$ by the single-breath method (model 1182; PK Morgan, Chatham, Kent, UK), and respiratory muscle strength by peak inspiratory pressures, were expressed as percent predicted using the following reference equations: TLC, Crapo et al. (6); VC, Kory et al. (17); RV, Goldman and Becklake (10); FEV$_1$, Cotes et al. (5); and DL$_{CO}$, Miller et al. (17). VC was measured with shoulders relaxed and repeated with shoulders flexed in the posture adopted for chest radiographs.

Measurements From Chest Radiographs

Diaphragm length, rib cage diameter, subphrenic volume (Vsubph), and lung volume and their changes between RV and TLC were estimated radiographically from posterior-anterior (PA) and lateral chest radiographs taken at RV, functional residual capacity (FRC), FRC plus one-half inspiratory capacity (FRC + $1/2$ IC), and TLC during slow inspirations initiated from RV. Inspiratory flow was measured with a pneumotachograph, integrated to obtain inspired volume and corrected to BTPS. The latter was recorded continuously on a polygraph (Linear Corder Mark VII, Watanabe). To allow alignment of the PA and lateral radiographs, radiopaque ball bearings were adhered to the midline of the chest wall as follows: single anterior bearing at the level of the tenth thoracic vertebra. Radiation exposure for each radiograph was $\sim$150 kV, with a maximal cumulative dose to each subject of $<$0.6 mSv.

Measurement of diaphragm and rib cage dimensions. These were measured from radiographs by use of methods adapted from Braun et al. (3). From each radiograph taken at TLC, the junctions of the diaphragm with the sternum and posterior and lateral chest walls were identified and taken to represent the anatomic insertions of the diaphragm. By using bony landmarks, we identified these insertions on radiographs taken at lower lung volumes. On the lateral radiograph, a line representing the midpoint between the right and left hemidiaphragm silhouettes was taken to represent the sagittal diaphragm silhouette. Measurements at each lung volume were made using a digitizing palette (AccuGrid, Numonics, Montgomeryville, PA) and included diaphragm length (Ldi), lengths of the lateral (midcortonal) and posterior costal zones of Lap, and rib cage diameter at the levels of the insertion of the diaphragm (abdominal) and seventh (mid) and fourth (upper) thoracic vertebrae (Fig. 1A). Diaphragm shape was inferred from the dome shape factor (Kdome) defined as the ratio of length of the lung-opposed diaphragm to abdominal rib cage diameter on the PA radiograph (15), and to the linear distance between the anterior and posterior costophrenic angles on the lateral radiograph.

To correct for magnification due to divergence of the X-ray beam, an individual correction factor was determined for each radiograph by using the distance between the radiographic source and radiograph (300 cm), the distance between the subject and the radiograph (7.0 cm), and diameter and thickness of the rib cage determined from radiographs, as described by Pierce et al. (21). Changes in Ldi and rib cage diameter were expressed as a fractional change from measurements obtained at RV.

Estimating Vsubph and $\Delta$Vdi. Vsubph was measured at RV, FRC, FRC + $1/2$ IC, and TLC by use of methods previously described by our laboratory (26) and adapted from a radiographic method of measuring lung volumes (21). The boundaries of the subphrenum were defined by the dome of the diaphragm cranially and the diaphragm-apposed rib cage laterally and posteriorly. The base of the subphrenum was defined by a horizontal line through the most caudal insertion of the diaphragm into the chest wall, identified by using bony landmarks. The subphrenum was divided into two components: a caudal “frustrum” where both the lateral and posterior costal diaphragm were apposed to the rib cage, and a cephalad “dome” where either the lateral or posterior costal diaphragm were apposed to the lung (19) (Fig. 1A). Change (Δ) in volume beneath the lung-apposed dome of the diaphragm (Vdome) was calculated at all lung volumes above RV.

To measure Vsubph, PA and lateral radiographs at matched lung volumes were first aligned in the vertical axis by use of the radiopaque balls and vertebrae. On the PA radiograph, the volume of the spinal mass within the subphrenum was defined by lines drawn on either side of the vertebral column following the tips of the lateral processes of the vertebrae to take account of associated musculature. On the lateral radiograph, the anterior limit of the spinal mass was drawn 1 cm in front of the vertebral bodies to allow for the great vessels and associated tissue. The combined subphrenic and spinal volume (Vsubph + spine) was then divided into multiple 1-cm horizontal slices. The lengths of the major and minor axes of each slice for Vsubph + spine and spinal volume were measured from PA and lateral radiographs, respectively. The cross-sectional shapes of the diaphragm dome and the spinal mass were assumed to be close to an ellipse (21), and the volume ($V_e$) of each slice was estimated from the equation $V_e = \frac{1}{2} \pi x y h$, where $x$ and $y$ are the major and minor axes and $h$ is the height of the slice (1 cm). The cross-sectional shape of the diaphragm frustrum was assumed to be a third of the way between an ellipse and a rectangle (21), and the volume of each slice was estimated from the equation $V_f = \frac{1}{3} \pi x y h$ + $\frac{1}{2} x y h - \frac{1}{2} \pi x y h$. Vsubph was calculated by subtracting the sum of all spinal volume slices from the sum of all Vsubph + spine slices. All dimensions were corrected for magnification.

The volume displaced by diaphragm motion ($\Delta$Vdi) with inspiration was calculated by using the following equation

$$\Delta V_{di} = V_{subphRV} - V_{subphEI} - V_{axial} + Ve + 0.5 V_f$$

where $V_{subphRV}$ and $V_{subphEI}$ were Vsubphs at residual volume and end inspiration, respectively; Vaxial was that part of the Vsubph at RV that was no longer within the

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diaphragm-apposed rib cage at end inspiration because of cephalad movement of the costal margin during inspiration; Ve was the increase in Vsubph due to inspiratory expansion of the abdominal rib cage; and 0.5 Vf was the lung volume displaced as the diaphragm separated from the expanding abdominal rib cage during inspiration (Fig. 1B).

Radiographic lung volume and rib cage cross-sectional area. Radiographic lung volume was estimated by using the method of Pierce et al. (21) based on the equation

\[ \text{Lung volume} = \text{chest volume} - \text{heart volume} - \text{spinal volume} - \text{subphrenic volume} \]

In each subject, heart volume was assumed to remain constant at all lung volumes. All other structures were divided into multiple 1-cm horizontal slices, and the volume of each slice was calculated by measuring its major and minor axes from the radiographs and by assuming a cross-sectional shape of 1) one-third the way between an ellipse and a rectangle for the chest, and 2) an ellipse for all other structures. The cross-sectional areas of 1) the pulmonary rib cage (Arcp) at each 1-cm interval from the apex to the lateral costophrenic angle and 2) the abdominal rib cage (Arcab) at the level of the lateral insertion of the diaphragm in emphysema and control subjects were compared. The change in lung volume attributable to expansion of the abdominal rib cage, and 0.5 Vf was the lung volume displaced as the diaphragm separated from the expanding abdominal rib cage during inspiration (see text for detail).

Protocol

Each subject was trained to perform a slow inspiratory VC maneuver through a pneumotachograph at a constant flow rate (−1 l/s) and posture. Flow rate was displayed on an analog flowmeter providing visual feedback to the subject. During training maneuvers and when PA and lateral chest radiographs were obtained, the subject stood with his anterior or left chest wall, respectively, against the radiographic plate and with his arms elevated and supported. For each radiograph, the subject exhaled to RV, inhaled to TLC, and then exhaled to RV again. Target lung volumes were marked on the chart recorder, and radiographs were triggered by a
radiographer as close as possible to RV and TLC and to FRC and FRC + 1/2 IC as the patient inspired through these volumes, ensuring that the glottis was open and the diaphragm remained activated. A pulse was delivered to the chart recorder at the time of radiographic exposure, thereby allowing precise matching of radiographic image to lung volume; radiographs were analyzed only if they were successfully triggered close to the target lung volume. No attempt was made to control chest wall configuration.

**Data Analysis and Statistics**

All data were expressed as means ± SD. Linear regression and paired t-tests were used to examine the relationships between 1) targeted and actual lung volumes at which chest radiographs were triggered, 2) inspired volumes for matched PA and lateral radiographs, 3) changes in lung volume measured radiographically and by pneumotachograph, and 4) ΔVdi, ΔVrcp and inspired volume. The ratio of Arcp in emphysema subjects to that in controls was examined over 23 1-cm intervals beginning at the apex by use of a two-way ANOVA. Linear regression was used to examine the relationships between Lap and lung volume/TLC predicted and between ΔVdi and predicted lung volume.

**Table 1. Subject characteristics and lung function**

<table>
<thead>
<tr>
<th></th>
<th>Control (n = 10)</th>
<th>Emphysema (n = 9)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age, yr</td>
<td>63.2 ± 5.7</td>
<td>65.3 ± 9.6</td>
</tr>
<tr>
<td>Height, m</td>
<td>1.76 ± 0.05</td>
<td>1.74 ± 0.08</td>
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<tr>
<td>BMI, kg/m²</td>
<td>26.9 ± 3.0</td>
<td>24.2 ± 3.6</td>
</tr>
<tr>
<td>TLC, % predicted</td>
<td>98.0 ± 8.2</td>
<td>130.4 ± 11.3*</td>
</tr>
<tr>
<td>RV/TLC</td>
<td>0.38 ± 0.05</td>
<td>0.65 ± 0.08*</td>
</tr>
<tr>
<td>VC, % predicted</td>
<td>99.3 ± 8.7</td>
<td>77.4 ± 20.0*</td>
</tr>
<tr>
<td>FRC, % predicted</td>
<td>96.6 ± 19.3</td>
<td>167.2 ± 22.2*</td>
</tr>
<tr>
<td>FEV₁, % predicted</td>
<td>107.2 ± 10.3</td>
<td>27.0 ± 13.0*</td>
</tr>
<tr>
<td>DLCO, % predicted</td>
<td>97.7 ± 7.7</td>
<td>46.6 ± 14.8*</td>
</tr>
<tr>
<td>MIP, cmH₂O</td>
<td>97.6 ± 28.7</td>
<td>86.8 ± 26.5</td>
</tr>
<tr>
<td>MEP, cmH₂O</td>
<td>176.8 ± 44.6</td>
<td>203.1 ± 55.1</td>
</tr>
</tbody>
</table>

Values are means ± SD. BMI, body mass index; TLC, total lung capacity; RV, residual volume; VC, vital capacity; FRC, functional residual capacity; FEV₁, forced expiratory volume in 1 s; DLCO, carbon monoxide transfer factor; MIP and MEP, maximal inspiratory and expiratory pressures, respectively. Significant difference from control: *P < 0.001 (t-test).

![Fig. 2. Diaphragm length (Ldi; A), length of the zone of apposition of the diaphragm to the rib cage (Lap; B), and Kdome (C) during inspiration. Values are means ± SD. Sample size for each mean value is indicated at the base of each column. FRC, functional residual capacity; IC, inspiratory capacity; TLC, total lung capacity; Ldi, diaphragm length. Significant difference from control: *P < 0.05, †P < 0.01, ‡P < 0.001 (t-test).](image-url)
and ΔLap. Backward stepwise and multiple linear regression analyses were used to examine the relationships between the dependent variable Vsubph and independent variables Lap, Kdome, and Arcab. All other data were compared by using unpaired t-tests. Significance was defined as \( P < 0.05 \).

**RESULTS**

**Patient Characteristics, Pulmonary Function, and Respiratory Muscle Strength**

The groups were well matched for age, height, and body mass index (Table 1). Relative to controls, emphysema subjects had severe hyperinflation, reduced FEV\(_1\) and VC, and similar respiratory muscle strength (Table 1).

**Inspired Volume During Collection of Radiographs**

Arm elevation, simulating the posture adopted during radiographs, resulted in no change in mean VC of controls and a small nonsignificant decrease in emphysema subjects. VC during the collection of radiographs was close to that obtained in the laboratory with arm elevation (control 102.9 ± 7.9%, emphysema 105.6 ± 8.9%). Satisfactory radiographs at FRC could not be obtained in two subjects with emphysema and at FRC + \( \frac{1}{2} \) IC in four control and five emphysema subjects. For the remaining radiographs, there was no difference between targeted and actual lung volumes at which they were triggered (\( r^2 = 0.99 \), slope 0.96, intercept 0.18 liters) and between inspired volumes for matched PA and lateral radiographs (\( r^2 = 0.99 \), slope 1.01, intercept −0.05 liters). In both groups, inspired volumes measured radiographically (ΔVL) were higher than those measured by pneumotachograph, and these volumes were closely correlated and linearly related with a slope close to 1.0 (control \( r^2 = 0.97 \), slope 0.94, intercept 0.31 liters, mean difference 0.16 liters; emphysema \( r^2 = 0.95 \), slope 0.91, intercept 0.72 liters, mean difference 0.54 liters).

**Diaphragm Length and Shortening**

Relative to control subjects, Ldi and Lap were reduced in emphysema at RV and FRC in both the coronal and sagittal planes; Lap was also reduced at TLC in the coronal plane (Fig. 2, A and B). Shortening of the diaphragm during inspiration between RV and TLC (ΔLdi) was reduced in emphysema (Table 2). However, at comparable lung volumes, Lap in the coronal (Fig. 3) and sagittal planes was longer in emphysema than in controls and was not eliminated at predicted TLC.

**Kdome**

A decrease in Kdome during inspiration indicates diaphragm flattening, and Kdome = 1.0 indicates a completely flat diaphragm. In both coronal and sagittal planes, the diaphragm was flatter in subjects with emphysema at all lung volumes except FRC in the coronal plane (Fig. 2C). In the coronal plane, between RV and TLC, the diaphragm flattened more in emphysema (control Kdome increased by 0.05 ± 0.08, emphysema Kdome decreased by 0.01 ± 0.04, \( P = 0.03 \)).

**Volume Displaced by Diaphragm Motion**

ΔVdi during a VC inspiration was not different between the groups in either absolute terms (control 1.96 ± 0.50 liters, emphysema 1.30 ± 0.87 liters) or as a fraction of inspired volume (ΔVdi/ΔVL) (control 0.46 ± 0.08, emphysema 0.37 ± 0.25) (Fig. 4A). ΔVdi varied widely in subjects with emphysema and during a VC inspiration was similar to controls in five subjects and reduced in four subjects (Fig. 4B). ΔVdi + ΔVrcp was similar to inspired volume in controls and ex-
ceeded inspired volume in emphysema (mean difference 0.45 liters, \( P < 0.001 \)). In both groups, \( \Delta V_{di} + \Delta V_{rcp} \) was linearly related to inspired volume (control \( r^2 = 0.97 \), gradient 0.85, intercept 0.30 liters; emphysema \( r^2 = 0.94 \), gradient 0.84, intercept 0.76 liters) (Fig. 5). At RV, the volume contained within the diaphragm dome (\( V_{dome} \)) was similar in both groups (control 1.36 \( \pm \) 0.41 liters, emphysema 1.57 \( \pm \) 0.49 liters); however, during inspiration to TLC, \( V_{dome} \) increased in controls and did not change in emphysema (\( \Delta V_{dome} \): control 0.82 \( \pm \) 0.80 liters, emphysema 0 \( \pm \) 0.36 liters, \( P = 0.01 \)).

**Dimensions and Displacement of the Rib Cage and Abdomen**

Relative to control subjects, the cross-sectional areas of the upper and mid rib cage were greater in subjects with emphysema at all lung volumes (Fig. 6), and this was due to increased sagittal diameters (pulmonary rib cage diameter at FRC, upper: control 11.5 \( \pm \) 1.0, emphysema 14.0 \( \pm \) 1.7 cm, \( P < 0.01 \), and mid: control 16.5 \( \pm \) 1.3 cm, emphysema 19.3 \( \pm \) 1.4 cm, \( P < 0.01 \)). Coronal diameters were similar in both groups. At

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**Fig. 4.** A: fraction of inspired volume attributable to diaphragm motion (\( \Delta V_{di}/\Delta V_{L} \)) during inspiration from RV to FRC, to FRC + \( 1/2 \) IC and to TLC. Values are means \( \pm \) SD. Sample size for each mean value is shown in the respective column. Significant difference from control at FRC: *\( P < 0.05 \) (\( t \)-test). B: relationship between \( \Delta V_{di} \) during a vital capacity inspiration and the ratio of RV to predicted TLC in all subjects. Solid and dashed lines represent mean \( \Delta V_{di} \) and limits of 95% confidence interval, respectively, for control subjects.

**Fig. 5.** Relationship between inspired volume and the sum of \( \Delta V_{di} \) and change in lung volume due to expansion of the pulmonary rib cage (\( \Delta V_{rcpul} \)) during inspiration from RV to FRC, to FRC + \( 1/2 \) IC, and to TLC in all subjects.

**Fig. 6.** Cross-sectional areas for upper and mid pulmonary (\( Arc_{p} \)) and abdominal (\( Arc_{ab} \)) rib cage during vital capacity inspiration. Values are means \( \pm \) SD. Sample size for each mean value is indicated at the base of each column. Significant difference from control: *\( P < 0.05 \), †\( P < 0.01 \), ‡\( P < 0.001 \) (\( t \)-test).
FRC, mean Arcp was 1.22 ± 0.03 times greater in emphysema subjects than in controls (P < 0.001). Arcab was not different between the groups (Fig. 6). Relative to control subjects, fractional expansion of the abdominal and mid rib cage during a VC inspiration were reduced in the sagittal plane in subjects with emphysema (Table 2). The ratio of coronal to sagittal diameter of the abdominal rib cage decreased during a VC inspiration in the control group (RV 1.50 ± 0.08, TLC 1.36 ± 0.06, P = 0.0002), indicating movement toward a more circular shape, and did not change in subjects with emphysema (RV 1.38 ± 0.11, TLC 1.38 ± 0.16).

Post Hoc Analysis of Emphysema Subgroups

Relative to subjects with reduced ΔVdi during a VC inspiration, emphysema subjects with preserved ΔVdi had increased Lap, Arcab, and Arcp at RV (Table 3).

Predictors of Subphrenic Volume and Volume Displaced by Motion of the Diaphragm

The coefficient of determination (r²) between ΔVdi and ΔLap was similar at the right lateral and posterior zones of apposition (0.74 and 0.75, respectively) in control subjects and was lower at the right lateral than the posterior zone of apposition (0.58 and 0.70, respectively) in subjects with emphysema. Relative to controls, the gradients of linear regressions between ΔVdi and ΔLap were higher in emphysema (right lateral: controls 0.14 l/cm, emphysema 0.25 l/cm, P < 0.05; posterior: controls 0.22 l/cm, emphysema 0.35 l/cm, P < 0.05). At any lung volume, in each group, Vsubph was best predicted by posterior costal Lap, Arcab, and sagittal Kdome: control Vsubph, liters = 0.31 Lap + 0.012 Arcab + 4.72 Kdome − 8.75 (r² = 0.91, standard error of estimate 0.43), emphysema Vsubph, liters = 0.31 Lap + 0.007 Arcab + 4.84 Kdome − 6.53 (r² = 0.90, standard error of estimate 0.35). In these equations, Lap accounted for 48 and 54%, Arcab for 39 and 27%, and Kdome 4 and 9% of the variability in Vsubph in control and emphysema subjects, respectively.

DISCUSSION

This study found that, during a VC inspiration, the volume change attributable to diaphragm motion in emphysema was similar to that in healthy control subjects despite severe hyperinflation with reductions in Lap and fractional shortening with inspiration. Our results suggest that this was possible because in emphysema Lap was increased at comparable lung volumes and ΔVdi was greater for comparable degrees of diaphragm shortening. We attribute the former to an increase in Arcp and the latter to abnormal diaphragm flattening during inspiration and an increase in Arcab in some subjects with emphysema. Additionally, ΔVdi could not be predicted accurately from shortening in the zone of apposition alone in either healthy subjects or subjects with emphysema because Vsubph was influenced by differences in Arcab and shape of the diaphragm dome. Before discussing these findings and conclusions, we consider the extent to which the methods used allow accurate estimates of chest wall and diaphragm dimensions and volumes and influence interpretation of the results.

Limitations

The conclusions of this study are based on estimates of diaphragm length, rib cage diameter, and volume of the chest and contained structures using measurements obtained from chest radiographs, methods described by Braun et al. (3) and Pierce et al. (21), and modifications of these methods. The major assumptions in these methods have been discussed previously (26). Briefly, in determining changes in diaphragm length, the method of Braun et al. assumes that 1) skeletal structures adjacent to costophrenic angles at TLC are a reasonable approximation of the anatomic insertions of the diaphragm, 2) the coronal and sagittal planes determining the diaphragm silhouette on chest radiographs in each subject remain fairly constant at different lung volumes, and 3) changes in length of these silhouettes are representative of overall length change of the diaphragm. A persistent Lap at TLC or significant movement of the plane determining the

Table 3. Characteristics of emphysema subjects with preserved and decreased ΔVdi

<table>
<thead>
<tr>
<th></th>
<th>Control (n = 10)</th>
<th>Emphysema ΔVdi Preserved (n = 5)</th>
<th>Emphysema ΔVdi Decreased (n = 4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ΔVdi during VC inspiration, liters</td>
<td>1.96 ± 0.50</td>
<td>1.94 ± 0.51</td>
<td>0.51 ± 0.40†</td>
</tr>
<tr>
<td>TLC, % predicted</td>
<td>98.0 ± 8.2</td>
<td>130.2 ± 14.4*</td>
<td>130.6 ± 8.0*</td>
</tr>
<tr>
<td>RV/TLC</td>
<td>0.38 ± 0.05</td>
<td>0.61 ± 0.06*</td>
<td>0.70 ± 0.07*</td>
</tr>
<tr>
<td>Dimensions at RV</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Posterior costal Lap, cm</td>
<td>7.8 ± 1.7</td>
<td>4.5 ± 1.2*</td>
<td>1.4 ± 1.0*†</td>
</tr>
<tr>
<td>Arcab, cm²</td>
<td>362 ± 69</td>
<td>470 ± 30*</td>
<td>364 ± 15†</td>
</tr>
<tr>
<td>Arcp/Arcp control</td>
<td>1.0</td>
<td>1.30 ± 0.10*</td>
<td>1.10 ± 0.06†</td>
</tr>
<tr>
<td>ΔVdome during VC inspiration, liters</td>
<td>0.82 ± 0.80</td>
<td>0.07 ± 0.41</td>
<td>−0.09 ± 0.30</td>
</tr>
</tbody>
</table>

Values are means ± SD. ΔVdi, volume displaced by diaphragm motion; Lap, length of zone of apposition; Arcab, cross-sectional area of the rib cage at the level of the costal insertion of the diaphragm; Arcp, cross-sectional area of pulmonary rib cage at 1-cm intervals; ΔVdome, change in volume of the lung-apposed diaphragm dome. Significant difference from control: *P < 0.05. Significant difference from ΔVdi Preserved: †P < 0.05.

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diaphragm shortening and ΔVdi. The validity of these assumptions in our healthy subjects is supported by the similarity between estimated diaphragm shortening over the range of VC in our study (Table 2) and the study of Gauthier et al. (8) using magnetic resonance imaging. In healthy subjects, the diaphragmatic silhouette on a PA radiograph is produced by its contour at a near midcoronal plane, and this plane moves ventrally with increasing lung volume (8, 31). On a lateral radiograph, the silhouette is produced by the diaphragm contour near the midsagittal line, and there is slight medial movement of this plane during inspiration (8). In our study, diaphragm shape change on the PA radiograph was different between emphysema and controls (Fig. 2C), so that the plane producing the silhouette in emphysema may not have behaved in the same way as controls. Although this could lead to an underestimation of diaphragm shortening in the coronal plane in emphysema, the finding that fractional shortening in the sagittal plane was reduced by a similar degree and that shortening in all zones of apposition to the rib cage (Lap) was reduced (Table 2) supports the finding of reduced shortening of the diaphragm in the coronal plane.

In this study, we estimated ΔVdi by measuring the changes in subphrenic and abdominal rib cage volumes between RV and specified higher lung volumes. Because the change in Vsubph with inspiration is equal and opposite to the change in volume of the peritoneal space subtending the ventral abdominal wall, the sum of the volume changes of the subphrenum and abdominal rib cage is equal to ΔVdi. We assumed that measured ΔVdi defined the contribution of the diaphragm to lung volume change in both control and emphysema subjects. Change in Vsubph was measured with the method of Pierce et al. (21), modified to allow for the volume occupied by the vertebral bodies, spinal muscles, and great vessels. We chose this method because, applied to the thorax, it gave precise estimates of lung volume (21), and alternate methods (19, 28) were considered likely to be less accurate because of their shape assumptions and failure to account for spinal volume (25). Our data and previous work (8, 26) show that in healthy subjects the abdominal rib cage becomes more circular with inspiration from RV to TLC and that, in emphysema relative to healthy subjects, the abdominal rib cage shape was more circular at RV and changed little with inspiration. Despite these differences, the ratio of coronal to sagittal diameter of the abdominal rib cage in emphysema was within the range seen during inspiration in healthy subjects. Inward movement of the pulmonary rib cage may occur during inspiration in which inspiratory impedance is high and, in this circumstance, ΔVdi will overestimate the contribution of the diaphragm to ΔVL by an amount equal to the volume displaced by inward movement of the pulmonary rib cage. Radiographs at intermediate lung volumes between RV and TLC showed no evidence of inward movement of the pulmonary rib cage in emphysema, and its volume increased progressively with increasing lung volume in control and emphysema subjects. Furthermore, ΔVdi plus independently measured ΔVrcp closely approximated inspired volume (Fig. 5). These findings support the accuracy of measured ΔVdi and the assumption that it defines the contribution of diaphragm motion to lung volume change in both control and emphysema subjects. In emphysema, the sum of ΔVdi and ΔVrcp was higher than inspired volume; this could be due to an increase in thoracic blood volume during inspiration and, at intermediate lung volumes, to decreases in alveolar pressure during inspiration. Any systematic difference in measuring radiographic volumes between emphysema and control subjects would apply equally to the pulmonary rib cage and subphrenic space and be eliminated by expressing ΔVdi as a ratio of ΔVL; this ratio was not different between emphysema and control subjects.

ΔVdi as measured in this study could underestimate the total contribution of the diaphragm to inspired volume because it does not include the effect of diaphragm tension in expanding the pulmonary rib cage. This contribution is mediated through distortion of the abdominal and pulmonary rib cages from their relaxation volumes and by consequent development of forces acting to restore the relaxed configuration (11, 30). These forces, measured as pressures, were small during quiet breathing and exercise in the healthy subjects of Kenyon et al. (11) in whom the average value was −2 cmH2O, so that the indirect contribution of the diaphragm to ΔVL would have approximated −0.2 liters. It is unclear whether the indirect effect of the diaphragm in inflating the pulmonary rib cage would be systematically different during a VC inspiration in emphysema and healthy subjects.

Diaphragm motion during inspiration is not simply a function of diaphragm action but also of rib cage and abdominal muscle activity and elastances and the mechanical coupling between the diaphragm and chest wall (11). Similar maximum mouth pressures suggested similar respiratory muscle strength in each group. Systematic differences in the elastance of the chest wall may account for some of the observed differences in behavior of the diaphragm within the emphysema group; however, the mechanical properties of the chest wall were not measured.

The sample size for this study was chosen by using measurements of ΔVdi in five healthy subjects in a previous study (26); we estimated that eight subjects were required to detect a reduction in ΔVdi of 10% in emphysema with a level of significance of 95% and a power of 90%. However, the coefficient of variation of ΔVdi was greater in this study, particularly in subjects with emphysema, reducing the power of this comparison to 50% and increasing the likelihood of a falsely negative result. Nonetheless, during a VC inspiration, ΔVdi was the same as that in controls in five of the nine subjects with emphysema (Fig. 4B). The inability to obtain satisfactory radiographs at FRC in two emphysema subjects and at FRC + ½ IC in four control and five emphysema subjects reduced the statistical power...
of comparisons and increased the likelihood of a falsely negative result at these volumes. In view of this, no conclusions were drawn when there was no difference in results between the emphysema and control groups at these volumes.

Mechanisms and Implications

The similarity in $\Delta V_{di}$ during a VC inspiration between control and emphysema subjects can be attributed first to an increased Lap at comparable lung volumes and second to a larger $\Delta V_{di}$ per unit change in Lap in emphysema. Our data show that Lap was eliminated at predicted TLC in healthy subjects but not in emphysema (Fig. 3). We attribute this to an increase in the Arcp in emphysema (Fig. 6): calculations based on our data suggest that when hyperinflation is shared between the pulmonary rib cage and diaphragm, a zone of apposition is maintained at lung volumes where it would normally be abolished, e.g., near predicted TLC (see APPENDIX). These calculations allow an estimate of the relative magnitude of these structural adaptations and their effect on Lap. At FRC, lung volume was 3.79 liters higher in subjects with emphysema than in control subjects; the rib cage accommodated $\sim$19% of this increased lung volume, and the diaphragm, via a reduction in length, accounted for the remaining 81%. Preservation of Lap by such structural adaptation of the pulmonary rib cage reduces the adverse effect of hyperinflation on the capacity of the diaphragm to displace volume efficiently via shortening of the zone of apposition. Our data and calculations suggest that if such adaptation had not occurred, Lap would have been eliminated at FRC in subjects with emphysema and $\Delta V_{di}$ would have been reduced by $\sim$0.8 liters (see APPENDIX). These conclusions are further supported by our finding that, among subjects with emphysema, Lap at RV and $\Delta V_{di}$ during a VC inspiration were highest in those subjects with the greatest degree of hyperinflation of the pulmonary rib cage (Table 3). Previous radiographic studies into the effect of hyperinflation in emphysema on rib cage structure have produced conflicting results. Kilburn and Asmundsson (12) and Walsh et al. (29) found no change in rib cage diameters in emphysema, which led the latter investigators to conclude that the primary structural adaptation to hyperinflation in emphysema was a lower diaphragm position. In contrast, Cassart et al. (4), using computed tomography, found an increase in sagittal but not coronal diameters such that the rib cage adopted a more circular shape. Our results agree with the findings of Cassart et al. An increase in Arcp is appropriate to the decreased lung elastic recoil in emphysema (7) and consequent change in the balance of forces across the pulmonary rib cage so that its volume increases.

For a given change in Ldi, $\Delta V_{di}$ was greater in emphysema than in controls. Our data suggest that this was due first to maintenance of constant dome volume during inspiration in emphysema and, second, to an increase in Arcab in some emphysema subjects (Table 3). During a VC inspiration, the volume of the dome of the diaphragm increased by a mean of 0.82 liters in control subjects, whereas it did not change in subjects with emphysema. This increase in dome volume in control subjects was due to increases in both Arcab (Fig. 6) and net height of the dome. Considering our data for cross-sectional areas (Fig. 6) and dome volumes at RV and TLC and modeling the dome as an oblate ellipsoid, the net increase in height of the dome was $\sim$2 cm. The changes in Kdome in the coronal and sagittal planes (Fig. 2C) are consistent with this result but suggest that the increased volume was contained beneath the anterolateral part of the dome. These findings and conclusions are concordant with the findings of Gauthier et al. (8). By contrast, in emphysema, dome volume did not change between RV and TLC, and Arcab increased much less than in controls (Fig. 6). Thus net change in dome height was approximately $\sim$0.3 cm, consistent with the abnormal flattening of the diaphragm observed in both coronal and sagittal planes (Fig. 2C). The relative flattening of the diaphragm and decreased expansion of the abdominal rib cage (Table 2, Fig. 6) contributed substantially, $\sim$0.8 liters, to maintaining $\Delta V_{di}$ at near normal levels. The different behavior of the dome and abdominal rib cage in health and emphysema is likely to reflect systematic differences in the forces acting on the diaphragm and lower rib cage in the two groups. First, transdiaphragmatic pressure, which opposes flattening, would be reduced by the decreased lung elastic recoil in emphysema (7). Second, at intermediate volumes, muscle fibers within the dome in emphysema are likely to be longer than near TLC in controls and thus able to generate more axial force, thereby maintaining a flat shape in the face of increasing abdominal pressure. The unchanging Arcab between FRC and TLC in emphysema relative to controls (Table 2, Fig. 6) we attribute to the transversal force developed by an extremely flat diaphragm at sites of insertion anteriorly where Lap may have been eliminated at lung volumes below TLC. Volume change achieved by flattening of the dome of the diaphragm rather than shortening in the zone of apposition could have implications to the efficiency of diaphragm muscle because comparable axial displacement would require disproportionate shortening of muscle fibers in the dome. This could explain the association between a flat diaphragm and a higher oxygen cost of breathing observed by Pitcher and Cunningham (22) in hypercapnic subjects with chronic obstructive lung disease.

The reason why, in some emphysema subjects, the rib cage was not hyperinflated and Lap at RV was much reduced is unclear. A stiffer chest wall and muscle fatigue with decreased tone are possibilities. Whatever the reason, the differences between the emphysema subgroups suggests that hyperinflation of the pulmonary rib cage is essential to maintaining $\Delta V_{di}$ and that, alone, flattening of the diaphragm dome cannot achieve this (Table 3).

The length of the zone of apposition of the diaphragm can be measured at the bedside noninvasively by using ultrasonography (16) and has the potential to repre-
sent diaphragm length and ΔVdi when the diaphragm shortens isotropically. Our data show that although ΔVdi correlates with shortening of Lap, accurate prediction of ΔVdi requires simultaneous measurement of other determinants of Vsubph, viz., cross-sectional area of the rib cage and diaphragm shape, both in healthy subjects and those with emphysema.

**APPENDIX**

*Estimation of the Distribution of Pulmonary Hyperinflation in Emphysema Between the Rib Cage and Diaphragm, and Its Effect on Lap*

At FRC during a slow inspiration, lung volume was 7.08 ± 1.19 and 3.29 ± 0.69 liters in emphysema and control subjects, respectively, and the mean Arcp was 1.22 ± 0.03 times greater in emphysema than in control subjects. These data can be used to calculate the extra volume accommodated by the greater Arcp in emphysema, i.e.,

\[
\text{Arcp}_E / \text{Arcp}_C - 1 \times \text{FRC}_C = 0.72 \text{ liters} \quad (1)
\]

where subscripts E and C indicate values in emphysema and control subjects, respectively. This volume represents 19% of the increase in FRC in emphysema.

In the absence of hyperinflation of the pulmonary rib cage or a change in diaphragm shape, the increase in lung volume in emphysema could be accommodated only by a reduction in Lap with displacement of volume from the abdominal rib cage (Vrcab) below the diaphragm. The effect of hyperinflation of the pulmonary rib cage on Vrcab and Lap can be derived as follows

\[
\text{Vrcab}_E - \text{Vrcab}_C = \text{FRC}_E - (\text{Arcp}_E / \text{Arcp}_C) \times \text{FRC}_C \quad (2)
\]

Because

\[
\text{Vrcab} = \text{Lap} \cdot \text{Arcb}
\]

Equation 2 can be re-expressed as

\[
\text{Lap}_C \cdot \text{Arcb}_C - \text{Lap}_E \cdot \text{Arcb}_E = \text{FRC}_E - (\text{Arcp}_E / \text{Arcp}_C) \times \text{FRC}_C \quad (4)
\]

where Arcb is the cross-sectional area of the abdominal rib cage. Let

\[
\text{Lap}_E = \text{Lap}_C - \Delta \text{Lap}
\]

Substituting Eq. 5 into Eq. 4,

\[
\text{Lap}_C \cdot \text{Arcb}_C - (\text{Lap}_C - \Delta \text{Lap}) \cdot \text{Arcb}_E = \text{FRC}_E - (\text{Arcp}_E / \text{Arcp}_C) \times \text{FRC}_C \quad (6)
\]

and

\[
\Delta \text{Lap} = \frac{\text{FRC}_E - (\text{Arcp}_E / \text{Arcp}_C) \times \text{FRC}_C + \Delta \text{Arcb} \cdot \text{Lap}_C}{\text{Arcb}_E} \quad (7)
\]

where \(\Delta \text{Arcb} = \text{Arcb}_E - \text{Arcb}_C\).

Equation 7 predicts that in emphysema Lap decreases with increases in lung volume or hyperinflation of the abdominal rib cage, and Lap increases with hyperinflation of the pulmonary rib cage. The reduction in Lap with expansion of the lower rib cage has been shown by Petrilli et al. (20). Equation 7 can be used to examine the effect of rib cage hyperinflation on Lap at FRC in our subjects with emphysema where diaphragm shape in the coronal plane was the same as controls (Fig. 2C). Using our data from Figs. 2B and 6, Eq. 7 predicts that in the absence of rib cage hyperinflation, i.e., where \(\text{Arcp}_E / \text{Arcp}_C = 1\) and \(\text{Arcab}_E = \text{Arcab}_C\), Lap in the midcoronal plane would be shortened by 9.6 cm at FRC, resulting in its elimination (Fig. 2B). The data of Gauthier et al. (8) suggest that the ratio of mean Lap around the circumference of the rib cage to mean Lap in the midcoronal plane is ~0.84; thus, in the absence of rib cage hyperinflation, mean Lap in emphysema would be shortened by 8.1 cm. With the degree of rib cage hyperinflation observed in our subjects with emphysema, in whom mean ArcpE/ArcpC = 1.22, ArcabE = 453 cm², and ΔArcab = 57 cm², Eq. 7 predicts that, at FRC, midcoronal Lap would be shortened by 7.9 cm and mean Lap around the circumference of the rib cage by 6.6 cm. Thus the model predicts that modest hyperinflation of the pulmonary rib cage results in an approximate gain in midcoronal Lap of 1.7 cm, close to the observed value (Fig. 2B), and in mean Lap of 1.5 cm.

In control subjects, mean Arcp at TLC relative to FRC was 1.24, i.e., similar to the mean Arcp at TLC relative to FRC in emphysema relative to controls. This suggests that, although the degree of pulmonary rib cage hyperinflation in emphysema was modest, it approached the maximum achievable in healthy subjects. However, without substantial adaptation in inspiratory muscle fiber length and rib structure as found in emphysematous hamsters (27), the net advantage of pulmonary rib cage hyperinflation would be small because acute hyperinflation reduces the ability of parasternal muscles to inflate the lung (18). In the emphysema subjects with a normal ΔVdi, mean Arcp at FRC was 1.3 relative to controls, and the predicted gain in mean Lap was 2 cm. Although the observed increase in Arcp and resultant preservation of Lap appears modest it is functionally important: the data in Fig. 6 suggest that in emphysema, for each centimeter of mean Lap preserved at FRC the diaphragm can contribute ~450 ml to inspired volume.

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