Breath-by-breath measurement of the volume displaced by diaphragm motion

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Breath-by-breath measurements of ΔVdi would allow measurement of work and power output of the diaphragm and may improve assessment of diaphragm function. Measurement of ΔVdi during breathing cannot be made by using CXRs but may be possible with the use of fluoroscopy, if ΔVdi could be accurately measured from a single plane. Two such methods have been proposed. Petroll et al. (7) measured ΔVdi in dogs using anteroposterior fluoroscopy and modeling the subphrenic space and dome of the diaphragm as a truncated cone with a circular cross section and an oblate spheroid, respectively. Verschakelen et al. (11) measured ΔVdi in humans using lateral fluoroscopy to measure sagittal rib cage diameter and the surface area swept by the diaphragm during inspiration, modeling the cross-sectional shape of the abdominal rib cage as a rectangle. The cross-sectional shape of the rib cage used in these models differed substantially from shapes based on studies in humans (4, 8), and neither method corrected the volume swept by the diaphragm for the volume occupied by the spine and paraspinal tissues (Vsp). For these reasons, the methods of Petroll et al. (7) and Verschakelen et al. (11) are likely to give inaccurate estimates of ΔVdi in humans. The accuracy of the biplanar method previously reported by us depends in part on the validity of the geometric shape used to calculate the cross-sectional area of the abdominal rib cage from the coronal and sagittal diameters measured from the PA and lateral CXRs, respectively. We adopted the shape described by Pierce et al. (8) for the pulmonary rib cage. To the extent that this shape may not apply to the abdominal rib cage, our measurements would also be inaccurate.

The aim of this study was to develop a fluoroscopic method for measuring ΔVdi breath by breath, which was accurate in both healthy and hyperinflated subjects. To assess the relative accuracy of various models for estimating the cross-sectional area of the abdominal rib cage, we compared estimated and measured cross-sectional areas of thoracic computed tomography (CT) scans. The accuracy of methods for estimating ΔVdi from a single radiographic plane and lateral fluoroscopy was assessed by comparing results with those

OUR LABORATORY HAS RECENTLY described a radiographic method for measuring inspired volume attributable to diaphragm motion (ΔVdi) using matched posteroanterior (PA) and lateral chest X-rays (CXR) to quantify the change in subphrenic volume during inspirations from residual volume (RV) (9, 10). ΔVdi and the change in lung volume attributable to expansion of the pulmonary rib cage, measured independently, closely approximated inspired volume in healthy controls and subjects with hyperinflation due to emphysema (9). These results suggest that ΔVdi measured with the biplanar method is accurate and defines the volume contributed by the diaphragm to inspiration.

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obtained, in the same subjects, with the previously validated biplanar method. Methods used to estimate \( \Delta V_{di} \) from a single plane were those described by Petroll et al. (7), Verschakelen et al. (11), and a new method that incorporated our findings on the cross-sectional shape of the abdominal rib cage and considered the \( V_{sp} \). We found that the cross-sectional shape of the abdominal rib cage was accurately modeled as one-third the way between an ellipse and a rectangle, as described by Pierce et al. (8) for the pulmonary rib cage, and that the shape of the rib cage changed little with lung volume. We hypothesized that \( \Delta V_{di} \) would be 1) overestimated by the methods of Petroll et al. (7) and of Verschakelen et al. (11) because these methods assumed thoracic shapes that overestimated the actual cross-sectional area of the abdominal rib cage and did not consider the volume occupied by spinal tissues, and 2) most accurately estimated by the proposed new method. Our findings confirmed these hypotheses.

**METHODS**

**Rib cage shape.** To examine the accuracy of various models used to estimate the cross-sectional area of the rib cage (4, 7, 8, 11), CT images of the thorax close to relaxed total lung capacity (TLC) were obtained in 25 healthy subjects and 22 with pulmonary hyperinflation due to emphysema (Table 1). The CT scans were obtained for clinical purposes with consent of the subjects. The internal cross-sectional area of the rib cage at the levels of the xiphoid process (abdominal rib cage) and the carina (pulmonary rib cage) were 1) measured by planimetry and 2) calculated by using the major sagittal and coronal diameters of the rib cage. The following geometric models were used: circles, ellipse, rectangle, a rectangle and two semicircles ("athletic track") as described by Chihara et al. (4), and one-third the way between an ellipse and a rectangle as described by Pierce et al. (8). Separate cross-sectional areas were calculated for circles with diameters equal to the major coronal and sagittal diameters of the rib cage. All measurements were made by using a digitizing palette (Accugrid, Numonics, Montgomeryville, PA).

**Table 1. Characteristics of subjects used to model cross-sectional shape of the rib cage and to measure \( \Delta V_{di} \)**

<table>
<thead>
<tr>
<th></th>
<th>Healthy</th>
<th>Hyperinflated</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cross-sectional shape of rib cage</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( N ) (M/F)</td>
<td>25(25/0)</td>
<td>22(18/4)</td>
</tr>
<tr>
<td>Age, yr</td>
<td>50.4 ± 10.1</td>
<td>61.8 ± 10.4*</td>
</tr>
<tr>
<td>RV/TLC</td>
<td>0.33 ± 0.05</td>
<td>0.62 ± 0.08*</td>
</tr>
<tr>
<td>FEV(_1), %predicted</td>
<td>101.8 ± 10.4</td>
<td>32.3 ± 10.4*</td>
</tr>
<tr>
<td>DL(_{CO}), %predicted</td>
<td>97.2 ± 10.0</td>
<td>39.8 ± 16.9*</td>
</tr>
<tr>
<td>( \Delta V_{di} )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( N ) (M/F)</td>
<td>10(10/0)</td>
<td>9(9/0)</td>
</tr>
<tr>
<td>Age, yr</td>
<td>63.2 ± 5.7</td>
<td>65.3 ± 9.6</td>
</tr>
<tr>
<td>RV/TLC</td>
<td>0.38 ± 0.05</td>
<td>0.65 ± 0.08*</td>
</tr>
<tr>
<td>FEV(_1), %predicted</td>
<td>107.2 ± 10.3</td>
<td>27.0 ± 13.0*</td>
</tr>
<tr>
<td>DL(_{CO}), %predicted</td>
<td>97.7 ± 7.7</td>
<td>46.6 ± 14.8*</td>
</tr>
</tbody>
</table>

Values are means ± SD. \( N \), no. of subjects; M, male; F, female; RV/TLC, ratio of residual volume to total lung capacity; FEV\(_1\), forced expiratory volume in 1 s; DL\(_{CO}\), carbon monoxide transfer factor by single-breath method; \( \Delta V_{di} \), volume displaced by diaphragm motion. Significant difference from healthy: * \( P < 0.001 \) (t-test).

**Radiographic measurements of \( \Delta V_{di} \).** \( \Delta V_{di} \) was measured by the biplanar method (9) in 10 healthy subjects and nine subjects with emphysema and severe pulmonary hyperinflation (Table 1). These results were then used to assess the accuracy of \( \Delta V_{di} \) estimated by various uniplanar methods using the same CXRs. Subpleural volume and the \( V_{sp} \) were estimated from PA and lateral CXRs taken at active RV, functional residual capacity (FRC), one-half inspiratory capacity (½IC), and TLC during a slow vital capacity (VC) inspiration in the erect posture. At each lung volume, \( \Delta V_{di} \) was also measured with the method described by Petroll et al. (7) applied to the right subphrenum on the PA CXRs and to the lateral CXRs, the method of Verschakelen et al. (11), and a new method described below (\( \Delta V_{diS} \)). Informed consent was obtained from each subject, and ethical approval was granted by the Committee for Human Rights, University of Western Australia.

\( \Delta V_{diS} \). Lateral CXR images at RV, FRC, and ½IC were superimposed on images at FRC, ½IC, and TLC, respectively, using the images of vertebral bodies and radiopaque ball bearings adhered to the posterior chest wall. The subpleural space at the lower lung volume was defined by the silhouette of the right hemidiaphragm, a straight line joining the anterior and posterior costophrenic angles at the higher lung volume, a straight line joining the anterior costophrenic angles at each lung volume, and the posterior limit of the lung (Fig. 1A). This volume was divided into a dome (V\(_{dome,L}\)) and a frustrum (V\(_{fr}\)), the latter being represented by the area between the lines joining the anterior and posterior costophrenic angles at each lung volume, and the posterior limit of the lung (Fig. 1A).

The subpleural space at the higher lung volume was taken as the dome of the diaphragm defined by the silhouettes of the diaphragm at each lung volume, the anterior margin of the vertebral bodies, and the posterior limit of the lung (Fig. 1A). The \( \Delta V_{di} \) was calculated by using the following equation

\[
\Delta V_{di} = V_{dome,L} + V_f - V_{dome,H} - V_{sp} \quad (1)
\]

This equation can be represented as follows (see APPENDIX)

\[
\Delta V_{diS} = D_{dome,L} \cdot A_{dome,L} + 0.6(D_{dome,L} + D_{dome,H}) \times A_s - D_{dome,H} \cdot A_{dome,H} - 0.25\pi D_{sp} \cdot A_{sp} \quad (2)
\]

where \( D_{dome,L} \) and \( D_{dome,H} \) are the length or sagittal diameter of the base of the dome at the lower and higher lung volume, respectively; \( A_{dome} \) and \( A_{fr} \) are the areas projected by the dome and frustrum in the sagittal plane, respectively; \( A_{dome,H} \) and \( A_{dome,L} \) are the \( A_{dome} \) at higher and lower lung volume, respectively; \( D_{sp} \) is the sagittal width of the volume of spinal tissues at the level of \( D_{dome,L} \) and \( A_{sp} \) is the area of spinal tissues projected in the sagittal plane (Fig. 1A). 

**Fluoroscopic measurement of \( \Delta V_{diS} \).** To assess the accuracy of \( \Delta V_{di} \) estimated from lateral fluoroscopy, \( \Delta V_{diS} \) was measured by fluoroscopy in the 10 healthy subjects in whom \( \Delta V_{di} \) had been measured with the biplanar radiographic...
The diaphragm and lower rib cage were imaged by lateral fluoroscopy, with a field of vision 16 in. in diameter (Toshiba CAS 8000 DSA, Tokyo, Japan) at a frame rate of 15 per second. Images and time of day were stored by using a VHS video recorder and cassette (Mitsubishi, HS-E82(A) and Fuji, Pro). Radiopaque ball bearings adhered to the chest wall allowed alignment of images at different lung volumes. Each subject was seated with the left chest wall as close as possible to the image intensifier with the arms elevated and with hands resting on the head. Two sequences of two to four tidal breaths followed by an exhalation to RV and an inspiration to TLC were imaged. Inspiratory flow and volume were measured with a pneumotachograph and recorded continuously on computer (Powerlab, ADInstruments, Sydney, Australia). Posture was maintained constant; no attempt was made to control chest wall configuration. Radiation exposure was varied to optimize contrast of the diaphragm silhouette and bony landmarks and was estimated at ~0.1 mSv.

Fluoroscopic images at end expiration and end inspiration during quiet breathing and at RV, FRC, ½IC, and TLC during VC inspirations were identified by interpolating images on video frames and inspired volume. Images of the diaphragm and bony landmarks were traced onto transparent paper. Distortion and magnification of the images were defined by using a precise grid with radiopaque lines at 1-cm intervals placed at the same distance from the image intensifier as the right midclavicular line. The distorted image of the grid, also on transparent paper, was used to replot the position of the diaphragm and chest wall on Cartesian coordinates, thereby correcting for distortion and magnification. ΔVdis was then measured from the replotted images by using the method described above.

Data analysis and statistics. All data are expressed as means ± SD. Characteristics of healthy and hyperinflated subjects were compared by using the Student’s t-test. Paired t-tests and the methods of Bland and Altman (2) were used to examine the relationships between 1) measured and calculated rib cage cross-sectional area and 2) biplanar and uniplanar ΔVdi. Significance was defined as P < 0.05.

RESULTS

Cross-sectional shape of the rib cage. The measured cross-sectional areas of the abdominal and pulmonary rib cage are compared with those calculated using the major sagittal and or coronal diameters and various models of thoracic shape, in Fig. 2. In both healthy and hyperinflated subjects, the cross-sectional areas of the rib cage were underestimated when modeled as an ellipse, overestimated when modeled as a rectangle, and either under- or overestimated when modeled as a circle, depending on whether the major sagittal or coronal diameter was taken to be the diameter of the circle. The cross-sectional areas of the abdominal and pulmonary rib cages were most accurately calculated when modeled as one-third the way between an ellipse and a rectangle or as an “athletic track” (Figs. 2 and 3). The ratios of the major coronal-to-sagittal diameters of the abdominal rib cage were 1.44 ± 0.11 in healthy subjects and 1.36 ± 0.13 in hyperinflated subjects. These results were similar to those obtained with the biplanar method, where the ratios were 1.5 ± 0.08 at RV and 1.36 ± 0.06 at TLC in controls and 1.35 ± 0.13 at RV and TLC in emphysematous subjects (9).

ΔVdi. ΔVdi estimated by the methods of Petroell et al. (7) using PA CXRs, and of Verschakelen et al. (11) using lateral CXRs, exceeded biplanar ΔVdi by 1.98 ± 1.59 and 1.16 ± 0.82 liters, respectively (both P < 0.001). These overestimates increased with volume, and, in many cases, ΔVdi exceeded inspired volume (Table 2, Fig. 4). ΔVdi by the method of Petroell et al. (7) applied to lateral CXRs was reduced (−0.47 ± 0.33 liter, P < 0.001) relative to biplanar ΔVdi (Table 2, Fig. 4). There was no difference between biplanar ΔVdi and ΔVdis measured from lateral CXRs in the healthy and hyperinflated subjects (mean difference 0.06 ± 0.24 liter, P = 0.08) or from lateral fluoroscopy in healthy subjects (mean difference 0.06 ± 0.28 liter, P = 0.30) (Table 2, Fig. 4). If the Vsp had not been considered, ΔVdis measured from lateral CXRs would have ex-

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*Fig. 1. A: schematic illustration of proposed uniplanar method for measuring the volume displaced by diaphragm motion (ΔVdi) from a lateral chest X-ray (CXR) or fluoroscopy. The silhouette of the diaphragm dome, sagittal diameter of the rib cage at the base of the diaphragm dome, and the anterior and posterior walls of the rib cage are represented by solid lines at the lower (L) lung volume and dashed lines at the higher (H) lung volume. ΔVdis was the difference in volume between (DomeL + frustrum) and (DomeH + spine), which are represented by the respective areas abeda, abdea, ahea, and abcha. The sagittal diameter of spinal tissues was taken as distance bg, where the anterior costophrenic angle at the higher volume is cephalad to the costophrenic angle at the lower volume, the volume represented by area fff'df was excluded from analysis, and DomeH is represented by area ab'da. See text for details.*
ceeded biplanar ΔVdi by 0.29 ± 0.27 liter \( (P < 0.001) \) and 0.15 ± 0.29 liter \( (P = 0.03) \) in healthy and hyperinflated subjects, respectively. ΔVdi measured fluoroscopically during tidal breathing was 0.66 ± 0.16 relative to tidal volume. ΔVdi/tidal volume had a coefficient of variation within subjects of 11.6 ± 5.7% (Fig. 5), and the mean value was similar to the ratio of ΔVdi to the volume inspired between FRC and 1/2 IC during VC inspirations in the six subjects, in whom this information was obtained with the biplanar method (0.71 ± 0.14 vs. 0.68 ± 0.12, \( P = 0.66 \)).

**DISCUSSION**

This study found that the ΔVdi in healthy and hyperinflated subjects was measured accurately from lateral CXRs by considering excursion of the diaphragm, sagittal diameter, and cross-sectional shape of the abdominal rib cage and the Vsp. The method enabled accurate breath-by-breath measurements of ΔVdi in healthy subjects by using fluoroscopy. Previously published methods for measuring ΔVdi by fluoroscopy \( (7, 11) \) were found to be inaccurate.

**Assumptions and limitations.** The accuracy of measuring ΔVdi from a single radiographic plane or from fluoroscopy was examined by comparing, in the same subjects, the results of three uniplanar methods with those of a biplanar method using matched PA and lateral CXRs. The validity of our conclusions relies on the accuracy of our biplanar method \( (9) \). Although there is no direct validation of this method, several lines of evidence support its accuracy. First, in healthy subjects at all inspired volumes and in emphysema subjects at intermediate and high lung volumes, the sum of ΔVdi and the change in lung volume attributable to expansion of the pulmonary rib cage, both measured independently by the biplanar method, accurately estimated inspired volume measured by pneumotachograph \( (9) \). Second, the model of the cross-sectional shape of the rib cage used to quantify subphrenic volume was validated in healthy and hyperinflated...
subjects in this study (Figs. 2 and 3). Third, the method assumes that the coronal and sagittal planes determining the radiographic silhouette of the diaphragm remain constant at different lung volumes so that the change in position of the silhouette represents the overall change in diaphragm position. These planes do move slightly as lung volume increases (5, 13). However, the movements are unlikely to significantly influence biplanar estimates of \( \Delta V_{di} \), because our previous results showed that changes in the length of the diaphragm over the VC measured radiographically (9) were consistent with changes in length of the entire diaphragm measured by MRI (5).

The method used by us for measuring \( \Delta V_{di} \) from a single plane entails a number of assumptions. First, we assumed that the cross-sectional shape of the abdomen

### Table 2. Ratio of \( \Delta V_{di} \) to inspired volume for breaths between RV and FRC, between RV and 1/2IC, and between RV and TLC, measured using the biplanar and several uniplanar methods

<table>
<thead>
<tr>
<th></th>
<th>Healthy</th>
<th>Hyperinflated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume</td>
<td></td>
<td></td>
</tr>
<tr>
<td>RV-FRC</td>
<td>0.78 ± 0.22</td>
<td>0.42 ± 0.50</td>
</tr>
<tr>
<td>RV-1/2IC</td>
<td>0.72 ± 0.16</td>
<td>0.46 ± 0.32</td>
</tr>
<tr>
<td>RV-TLC</td>
<td>0.50 ± 0.11</td>
<td>0.22 ± 0.16</td>
</tr>
<tr>
<td>RV-FRC</td>
<td>0.78 ± 0.57</td>
<td>0.32 ± 0.46</td>
</tr>
<tr>
<td>RV-1/2IC</td>
<td>0.42 ± 0.50</td>
<td>0.57 ± 0.42</td>
</tr>
<tr>
<td>RV-TLC</td>
<td>0.16 ± 0.12</td>
<td>0.50 ± 0.46</td>
</tr>
<tr>
<td>RV-FRC</td>
<td>1.50 ± 0.36</td>
<td>1.42 ± 0.57</td>
</tr>
<tr>
<td>RV-1/2IC</td>
<td>1.56 ± 0.49</td>
<td>1.25 ± 0.84</td>
</tr>
<tr>
<td>RV-TLC</td>
<td>2.72 ± 1.52</td>
<td>1.56 ± 0.57</td>
</tr>
</tbody>
</table>
| Values are means ± SD; \( N \), no. of subjects. FRC, functional residual capacity, 1/2IC, one-half inspiratory capacity. \( \Delta V_{di} \) was measured from posteroanterior (PA) and lateral (LAT) chest X-rays (CXRs) (biplanar \( \Delta V_{di} \)); from the method of Petroll et al. (7) (\( \Delta V_{di\_petroll} \)) from PA and LAT CXRs separately; from the method of Verschakelen et al. (11) (\( \Delta V_{di\_verschakelen} \)) from LAT CXRs; and from our proposed method (\( \Delta V_{di\_s} \)) from LAT CXRs and fluoroscopy. Significant difference from biplanar \( \Delta V_{di} \): *\( P < 0.05 \), †\( P < 0.01 \), ‡\( P < 0.001 \) (paired t-test).

**Fig. 4.** Bland and Altman comparisons of the volume displaced by diaphragm motion (\( \Delta V_{di} \)) in 10 healthy and 9 hyperinflated subjects for breaths between residual volume (RV) and functional residual capacity, RV and one-half inspiratory capacity, and RV and total lung capacity, measured from matched posteroanterior (PA) and lateral (LAT) CXRs (biplanar \( \Delta V_{di} \)) and the uniplanar methods of Petroll et al. (7) applied to PA \( \Delta V_{di\_petroll\_PA\_CXR} \) (A) and LAT CXRs \( \Delta V_{di\_petroll\_LAT\_CXR} \); B) separately, Verschakelen et al. (11) applied to LAT CXRs \( \Delta V_{di\_verschakelen\_LAT\_CXR} \); C), and our proposed method (\( \Delta V_{di\_s} \)) applied to LAT CXRs \( \Delta V_{di\_s\_LAT\_CXR} \); D). In 10 healthy subjects, biplanar \( \Delta V_{di} \) was compared with our proposed method applied to LAT fluoroscopy \( \Delta V_{di\_s\_LAT\_Fluoroscopy} \); E). The solid lines are the mean difference, and the dashed lines are the limits of the 95% confidence intervals.
nal rib cage remained constant during inspirations from RV and that spinal tissues had a circular rather than an elliptical cross section, as assumed in the previous biplanar study (9). The ratio of major coronal to sagittal rib cage diameters, obtained during active inspirations from RV to TLC in the erect posture with the use of biplanar CXRs (9), decreased by ~10% in healthy subjects and did not change in those with emphysema. The constant ratio of 1.4 assumed in healthy subjects and did not change in those with emphysema. The constant ratio of 1.4 assumed in the expression used to estimate $\Delta V_{di}$ from uniplanar images (APPENDIX) was within the range of values found in healthy and emphysematous subjects and unlikely to lead to errors of significant magnitude. The finding that, for inspirations between RV and TLC, $\Delta V_{di}$ measured by the uniplanar and biplanar methods were not different supported this conclusion. This finding also suggests that our assumption of a circular cross section of spinal tissues did not cause significant error. On biplanar CXRs, we found no consistent relationship between the coronal and sagittal diameters of spinal tissues and, therefore, adopted the more simple assumption of a circular cross section. Second, we assumed that the change in position of the right hemidiaphragm silhouette in the imaging plane is representative of the overall change in position of the diaphragm. Excursion of the right hemidiaphragm usually exceeds that of the left (3, 5, 9, 10, 13), and this could lead to an overestimation of $\Delta V_{di}$. The error is likely to be small in healthy subjects in whom the mean difference in shortening of the hemidiaphragms over the VC was only ~1% (9). In subjects with hyperinflation, the mean difference was ~14%, and the corresponding overestimation of $\Delta V_{di}$ over the VC would approximate 90 ml. Third, we assumed that the position of the costophrenic angles around the circumference of the rib cage could be represented by a straight line between the anterior and posterior costophrenic angles (Fig. 1). Whitelaw (13) and Gauthier et al. (5) have shown that, in the supine posture, the lateral costophrenic angle lies slightly above this line at low lung volumes and slightly below it at high lung volumes. However, the departure of the costophrenic angles from a straight line around the circumference of the rib cage is small, and we expect the error associated with this assumption to be small. Regarding the assumption that the anterior costophrenic angle moves along a straight line during inspiration, examination of the lateral CXRs showed that this assumption was reasonable for the volume increments used. For larger volume changes, e.g., VC inspirations, departures from this assumption are common, resulting in overestimation of $\Delta V_{di}$.

$\Delta V_{di}$ 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 and elevating the rib cage, but this indirect contribution is believed to be small (6, 9, 12). Diaphragm motion during inspiration is not simply a function of diaphragm action but also of rib cage and abdominal muscle activities and elements and of the mechanical coupling between the diaphragm and chest wall (6). As measured in this study, $\Delta V_{di}$ reflects the volume change of the lung attributable to diaphragm motion, including motion due both to active shortening and to the mechanical properties of the chest wall. Where there is paradox of the pulmonary rib cage, $\Delta V_{di}$ reflects the volume change of the lung and pulmonary rib cage; such behavior was observed in two healthy subjects between RV and FRC.

Implications. The ability to measure $\Delta V_{di}$ breath by breath is likely to be of clinical value. 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 abdominal muscles are developed largely by rib cage and abdominal muscles, respectively. 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. Using biplanar measurements of $\Delta V_{di}$, we have previously shown that decreases in VC in asbestos-related pleural fibrosis were due mainly to reduced expansion of the lower rib cage with relative preservation of $\Delta V_{di}$ (10) and revealed mechanisms by which the function of the diaphragm as a volume pump was preserved in emphysema, despite severe pulmonary hyperinflation (9). The ability to measure $\Delta V_{di}$ from a single plane using fluoroscopy enables dynamic study of the pump function of the diaphragm.

$\Delta V_{di}$ was not accurately measured by the methods of Petrill et al. (7) or by those of Vershakelen et al. (11) (Table 2, Fig. 4). Our data show that this was due, first, to significant departures of actual cross-sectional shape of the abdominal rib cage in humans from the circular and rectangular shapes, respectively, assumed in these models (Fig. 2) and, second, to failure to consider the volume occupied by spinal and paraspinal tissues. The geometric model of Vershakelen et al. (11) assumes that the cross-sectional shape of the abdominal rib cage was rectangular with coronal dimensions.
1.8 times the sagittal diameter; our data show that this ratio was inappropriately high.

In contrast to these methods, ΔVdi measured from lateral CXRs and fluoroscopy, using a method that considered excursion of the diaphragm, actual shape of the abdominal rib cage, and the volume occupied by spinal and paraspinal tissues, did not differ from that measured by the biplanar method (Table 2, Fig. 4), despite the assumptions and limitations discussed above. ΔVdi during tidal breaths in 10 healthy subjects was relatively consistent from breath to breath (Fig. 5), and the ratio of ΔVdi to inspired volume was similar to that during slow inspirations between FRC and 1/3IC. These findings suggest that this method allows accurate dynamic measurements of ΔVdi. In combination with measurements of transdiaphragmatic pressure and the duration of inspiration, fluoroscopic measurements of ΔVdi may allow breath-by-breath estimation of work and power output of the diaphragm and enable a clearer understanding of the role of the diaphragm in pathogenesis of breathlessness, exercise limitation, and the development of respiratory failure in chronic obstructive lung disease.

APPENDIX

Derivation of Proposed Method for Estimating ΔVdi From a Lateral Radiographic/Fluoroscopic Image (ΔVds)

Subphrenic volume was divided into Vdome,L and Vfr and Vdome,H as described in Methods and Fig. 1. If the domes were elliptical in cross section, their volumes (Vdome,ellipse) could be calculated from the equation

\[ V_{\text{dome,ellipse}} = 0.67\pi \cdot 0.5D_{\text{Sag}} \cdot 0.5D_{\text{Cor}} \cdot H_{\text{dome}} \]  

where \( D_{\text{Sag}} \) and \( D_{\text{Cor}} \) are the sagittal and coronal rib cage diameters at the base of the domes, respectively, and \( H_{\text{dome}} \) is the height of the domes. The \( A_{\text{dome}} \) can be calculated from the equation

\[ A_{\text{dome}} = 0.5\pi \cdot 0.5D_{\text{Sag}} \cdot H_{\text{dome}} \]  

Combining Eqs. 3 and 4

\[ V_{\text{dome,ellipse}} = 0.67D_{\text{Cor}} \cdot A_{\text{dome}} \]  

We found that, in health and hyperinflation, the ratio of \( D_{\text{Cor}} \) to \( D_{\text{Sag}} \) was ~1.4. Therefore

\[ V_{\text{dome,ellipse}} = 0.93D_{\text{Sag}} \cdot A_{\text{dome}} \]  

Because the cross-sectional area of the rib cage is best approximated by a shape one-third the way between an ellipse and a rectangle (Figs. 2 and 3), and this area is 1.091 times the area of an ellipse of the same dimensions

\[ V_{\text{dome}} = D_{\text{Sag}} \cdot A_{\text{dome}} \]  

The \( V_{fr} \) can be calculated by dividing it into multiple horizontal slices with a cross-sectional shape one-third the way between an ellipse and a rectangle. The volume of each slice (Vslice) can be calculated as follows

\[ V_{\text{slice}} = H_{\text{slice}}(0.25\pi D_{\text{Sag}} \cdot D_{\text{Cor}} + 0.33 \cdot (D_{\text{Sag}} \cdot D_{\text{Cor}} - 0.25\pi D_{\text{Sag}} \cdot D_{\text{Cor}})) \]  

where \( H_{\text{slice}} \) is the height of each slice. This can be simplified to

\[ V_{\text{slice}} = 0.857H_{\text{slice}} \cdot D_{\text{Sag}} \cdot D_{\text{Cor}} \]  

Assuming that a straight line can represent the lateral walls of the frustrum, \( V_{fr} \) can be approximated by the following equation

\[ V_{fr} = 0.857 \text{ mean } D_{\text{Sag}} \cdot \text{ mean } D_{\text{Cor}} \cdot H_{fr} \]  

where \( H_{fr} \) is the height of the frustrum. The area of each slice of the frustrum projected in the sagittal plane (\( A_{\text{slice}} \)) is

\[ A_{\text{slice}} = D_{\text{Sag}} \cdot H_{\text{slice}} \]  

and the \( A_{fr} \) is approximated by

\[ A_{fr} = 0.5\pi D_{\text{Sag}} \cdot H_{fr} \]  

Combining Eqs. 10 and 12

\[ V_{fr} = 0.857 \cdot \text{ mean } D_{\text{Cor}} \cdot A_{fr} \]  

As the ratio of \( D_{\text{Cor}} \) to \( D_{\text{Sag}} \) is ~1.4, the equation can be expressed as

\[ V_{fr} = 1.2 \text{ mean } D_{\text{Sag}} \cdot A_{fr} \]  

or

\[ V_{fr} = 0.6(D_{\text{dome,L}} + D_{\text{dome,H}})A_{fr} \]  

The \( V_{sp} \) within the volume swept by the diaphragm can be estimated by assuming that this volume is cylindrical, i.e.

\[ V_{sp} = 0.25\pi D_{sp}^2 \cdot H_{sp} \]  

where \( D_{sp} \) is the diameter of the spinal column, and \( H_{sp} \) is the height of spinal mass. The \( A_{sp} \) is

\[ A_{sp} = D_{sp} \cdot H_{sp} \]  

Combining Eqs. 16 and 17

\[ V_{sp} = 0.25\pi D_{sp} \cdot A_{sp} \]  

The \( \Delta Vdi \) can be calculated from the equation

\[ \Delta V_{di} = V_{\text{dome,L}} - V_{\text{dome,H}} + V_{fr} - V_{sp} \]  

Combining Eqs. 7, 15, 18, and 19

\[ \Delta V_{di} = D_{\text{dome,L}} \cdot A_{\text{dome,L}} - D_{\text{dome,H}} \cdot A_{\text{dome,H}} + 0.6(D_{\text{dome,L}} + D_{\text{dome,H}})A_{fr} - 0.25\pi D_{sp} \cdot A_{sp} \]  

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