Measurement of Tidal Breath by Determination of Chest Wall Volume Displacement in Patients with Airflow Obstruction*

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We compared tidal volume (Vt) measured from the integrated airflow signal of a pneumotachygraph (PNTG) in ten patients, seated comfortably, with airflow obstruction to Vt, recorded simultaneously, by three chest-wall volume-displacement methods: two-channel magnetometer, isovolume calibration (mag-isov); respiratory inductance plethysmograph, isovolume calibration (rip-isov); and, inductance plethysmograph, least squares calibration (rip-l sq). There was no difference between Vt measured without PNTG, with each of the methods. When mouthpiece, noseclips, PNTG, and finally, dead space were included in a breathing circuit, Vt increased to approximately one and one-half times that measured without the mouthpiece. Inspiratory volumes were measured with similar error by each method (mag-isov, 8.61±5.73 percent SD; rip-isov, 9.30±6.12 percent SD; rip-l sq, 8.43±6.27 percent SD). We conclude that in airflow obstruction patients seated in a constant position, over the range of inspiratory volumes studied, error associated with chest wall volume-displacement methods is no greater than in normal subjects.

Measurement of the tidal breath (Vt) by summation of rib cage and abdominal volume displacements, unlike that measured by spirometry, is not influenced by either conscious behavior (eg, the mouthpiece effect) or addition of external dead space.1 In normal subjects, the summation of these volumes agrees closely with simultaneous measurement of volume obtained by integration of flow measured by pneumotachygraph and thus has been used to quantify respiration.2-4 It is not certain, however, that the calibration methods for conversion of either magnetometer or respiratory inductance plethysmograph signal to estimates of volume displacement are appropriate for patients with respiratory disease. Nevertheless, such measurements have been published from studies of both intubated intensive-care patients and stable subjects with various pulmonary disorders.5-7 While a single position calibration technique for the respiratory inductance plethysmograph has been proposed to overcome major disadvantages of other calibration methods, this technique has not been verified over a wide range of volumes.8

We have quantified Vt in ten patients with airflow obstruction. We have examined the precision of two mechanical apparatuses (two-channel magnetometer; inductance plethysmograph) and two calibration techniques (isovolume maneuver; least-squares method). To study a range of volumes, we have recorded Vt first with no facial apparatus, again with mouthpiece and flow meter, and finally with mouthpiece, flow meter, and additional dead space. Where possible, measurements derived from rib cage and abdominal displacements are compared to simultaneously recorded pneumotachygraph volumes.

METHODS

Ten patients (eight men and two women) participated in this study. Eight met the diagnostic criteria of the American Thoracic Society for asthma.9 Two had chronic airflow obstruction. Evaluation at the time of study included spirometry (Collins water-seal spirometer) and plethysmographic determination of functional residual capacity (pressure-variable plethysmograph).

Equipment

A two-channel magnetometer and an inductance plethysmograph were used to measure Vt. The former monitors anteroposterior diameters of rib cage and abdomen during the respiratory cycle; the latter, cross-sectional area. Our method for placement of magnetometer (mag) coils and processing magnetometer signals has been described.9 Rib cage coils were placed approximately at the level of the second intercostal space where anterior motion could be most easily observed during quiet breathing.

The rib cage respiratory inductance plethysmograph (rip) coil was placed such that the upper edge of each belt passed just underneath both axillae. The abdominal coil was placed at the umbilicus well below the costal margins. To secure the coils, a tight elastic net was worn by each subject. The electrical outputs of each coil and their sum signal were recorded on a four-channel recorder.

Calibration

Both apparatuses were calibrated by the isovolume maneuver (isov) described by Konno and Mead.10 Outputs were adjusted so that the equivalent rib cage and abdominal displacements gave equivalent signals. To calibrate these signals, tidal breathing was then recorded simultaneously on the rip or magnetometer recorders and the water sealed spirometer. The isovolume maneuver was...
performed in the seated position in which VT was recorded throughout the study.

The rip was also calibrated by the least squares method (I sq) described by Chadha et al. For this method, the subject breathed through a pneumotachygraph. The integrated flow signal was displayed on the four-channel recorder. Pneumotachygraph and rip signals were recorded in both the seated and supine positions. Rib cage/pneumotachygraph and abdomen/pneumotachygraph ratios were calculated and plotted on x-y coordinates. The best line through these points was computed by linear regression. Scaling factors for the rib cage and abdomen signals were then derived from the x- and y-intercepts of the line.

Protocol

After calibration, subjects sat comfortably in a constant posture and breathed quietly throughout the study. Not all subjects performed all portions of the protocol. In four subjects, a lengthy period of quiet breathing was observed after calibration by each of the three methods (mag-iso, rip-iso, rip-I sq) without mouthpiece and flow meter. When a steady-state breathing pattern appeared, ten or more breaths were recorded without respiratory apparatus at the airway to measure VT during quiet resting ventilation.

Eight subjects breathed through the mouthpiece and pneumotachygraph after having calibrated both magnetometers and rip by the same isovolume maneuver. When a steady-state was achieved, ten or more tidal breaths were recorded simultaneously by rip, magnetometer, and flow meter for analysis. A small dead space comprised of 90 ml of wide-bore tubing then was added to the flow meter. Data collection was repeated. Eight subjects, six of whom had participated in the isovolume-calibration trial, performed the protocol with the impedance plethysmograph calibrated by the rip-I sq method. In seven subjects, a second, larger dead space (160 ml) was added. Ten or more simultaneous measurements of VT by flow meter and chest wall displacement methods were again recorded for analysis.

Data Analysis

Student's paired-\(t\) test and regression coefficients were used to compare pneumotachygraph VT with simultaneously collected chest wall displacement volumes. For comparisons of data collected by the three calibration techniques, the one-way analysis of variance was used.

**RESULTS**

Anthropometric and functional data for ten subjects appear in Table 1. The FEV\(_1\) was 0.91 ± 0.51 (SD) L, or 37 ± 13 percent of a predicted value. Total lung capacity was 6.62 ± 1.55 (SD) L, or 109 ± 22 percent of predicted. These data demonstrate severe airway obstruction at the time of study.

Tidal volume VT measurements without the flow meter appear in Table 2. There is no significant difference between VT measured by magnetometer, rip-iso, or rip-I sq.

Comparisons of VT recorded by pneumotachygraph with each corresponding breath measured by the chest wall displacement method appear in Table 3. When VT was measured by an apparatus calibrated by the isovolume maneuver, regardless of whether the rip or magnetometer was used, there was, on the average, no difference between flow meter and chest wall volume displacement VT. By contrast, VT measured by flow meter (626 ± 65 ml SEM) was greater than that measured by rip-I sq (591 ± 63; paired-\(t\) = 2.63; \(p<0.05\)). This difference appeared greater when both small (paired-\(t\) = 3.18; \(p<0.02\)) and large (paired-\(t\) = 4.05; \(p<0.01\)) dead spaces were added to the pneumotachygraph.

The differences between each calibration technique and the corresponding flow meter breath, expressed as a percentage, appear in Table 4 and Figure 1. With the differences expressed without regard to sign, the precision of the three methods is identical (F 2.66 = 0.13). Furthermore, from Figure 1, it appears that as the tidal breath is increased by addition of dead space, there is no corresponding increase in the percentage error of the chest wall volume displacement methods when compared to the pneumotachygraph. Graphic illustrations depicting the mean and standard error of the mean for breaths measured simultaneously by flow meter and chest wall volume displacement appear in Table 3.
Table 4—Percent Difference Between Tidal Volume Measured by Three Chest Wall Volume Displacement Calibration Techniques and Corresponding Breath Measured by Pneumotachygraph

<table>
<thead>
<tr>
<th></th>
<th>Mag-Pntg</th>
<th>RipIsov-Pntg</th>
<th>RipL sq-Pntg</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>8.61±5.73 SD</td>
<td>9.30±6.12</td>
<td>8.43±6.27</td>
</tr>
</tbody>
</table>

Figure 2. Each data point represents the mean of ten or more simultaneous tidal volume measurements. On the average, with each volume displacement method, there is good agreement between flow meter and volume displacement measurement. Nevertheless, the standard error bars demonstrate great variability between individual breaths and the line of identity.

We sought relationships between the degree of functional impairment of the ten patients and the percentage error, expressed as an absolute value. We observed low correlation coefficients for FEV₁ as percent predicted (independent variable) with either magnetometer (r=0.18), rip-isov (r=0.01) and rip-l sq (r=0.02) percentage error, respectively. Similarly, no significant correlations appeared between FRC, as percent predicted, and percent error by each chest wall displacement method (r=0.26, 0.13, and 0.12, respectively).

Breathing Frequency

Serial measurements of breathing frequencies in all study conditions for seven subjects recorded by respiratory inductance plethysmograph during l sq calibration appear in Table 5. Two-way analysis of variance indicated that neither the mouthpiece nor dead space influenced the respiratory rate (F₁,₉ = 0.85). Identical data were obtained during magnetometer, rip-isov, and rip-l sq studies.

Discussion

The spirometer with mouthpiece and noseclips (MPC/NC) provides a simple, precise technology for the measurement of maximal pulmonary volumes and flow rates. The MPC/NC provides an artificial milieu for the measurement of resting ventilation (Ve), however. As such, MPC/NC stimulate change in the breathing pattern, for Vt measured by spirometer exceeds that measured noninvasively by 15 percent in normal subjects.7,12 One might expect that determination of Vt in disease states, and most important to the clinician, the determination of change in Vt induced by therapy, will be affected by MPC/NC as well.7

Alternate techniques quantify Ve by the summation of rib cage and abdominal volume displacements. Two such devices, the two-channel magnetometer (which measures the change in anteroposterior diameter of each compartment during tidal breathing) and the respiratory inductance plethysmograph (which measures change in cross-sectional area) were used in this study. To calibrate these devices, it is assumed that change of either diameter or cross-sectional area measured in any one plane is representative of the diameter or area change of the entire rib cage and abdominal compartments during quiet breathing. Stated in a different way, it is assumed that neither compartment changes shape during respiration. When body position is fixed, both compartments do maintain a constant shape during quiet breathing in normal subjects. One may therefore quantify Vt by estimation of chest wall volume displacement in normal subjects.

By contrast, the shape of either compartment may change either during change in position (eg, from seated to supine) or during tidal breathing in patients with airway obstruction. This study was designed to examine the precision with which Vt can be measured by chest wall volume displacement methods in such patients. The three methods we selected for comparison included two standard calibration techniques (isovolume, least squares) and the two most available apparatuses. One might postulate that rip, which measures area, would provide a more accurate approxi-
imimation of volume displacement than would magnetometry. Change in anteroposterior diameter as measured by the magnetometer would appear to provide a tenuous estimate of volume displacement if either rib cage or abdominal compartment were to change shape during the ventilation cycle.

**Calibration Technique**

Error is inherent in both calibration techniques employed. The lsq calibration requires that the patient breathe quietly in two positions. \( V_T \) is measured in one of the calibrating positions. The lsq is valid, therefore, only if the shapes of both rib cage and abdominal compartments remain constant throughout quiet breathing in both calibrating positions. This may not be so, however. The volume-to-motion (V-M) coefficients of both compartments change with position change in normal subjects. These physiologic events must affect the precision of \( V_T \) measurement by the lsq method. Conceivably, such changes in V-M coefficients with change in position do not occur in patients with airway obstruction. The observation that end-expiratory lung volume decreases when a normal subject (but not a patient with airway obstruction) assumes the supine position supports the possibility that neither the shape of rib cage or abdomen nor their V-M coefficient change with position change in airway obstruction patients.

The isovolume technique, unlike the least squares method as used in this and other studies to date, requires only one position for both calibration and \( V_T \) measurement. The major disadvantage of the iso-

**Table 5—Breathing Frequency, Seven Subjects in Four Conditions: No Facial Apparatus; Mouthpiece Alone; Mouthpiece with Small Dead Space; Mouthpiece with Larger Dead Space**

<table>
<thead>
<tr>
<th>Frequency</th>
<th>No Mpc</th>
<th>Mpc</th>
<th>Mpc + DS₁</th>
<th>Mpc + DS₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>18</td>
<td>17</td>
<td>17</td>
<td>17</td>
</tr>
<tr>
<td>± SD</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>

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volume technique is the patient cooperation requirement. The subject must close his mouth and nose (or glottis), and permitting only minimal change in pressure within both rib cage and abdominal cavities, shift an equal volume back and forth between the two compartments. This maneuver is often difficult for patients with severe airflow obstruction to perform and to reproduce. Bellia et al28 have suggested that the precision of any calibrating technique depends upon the subject's ability to produce a wide range of randomly occurring Vr, rib cage and abdominal relationships during the calibrating procedure. It would appear difficult for the airway obstruction patient to produce an average of these relationships during such a brief and difficult calibrating procedure.

Rib Cage Shape

A change of rib cage shape during respiration would likely affect the calibration by magnetometer, and possibly rip, as well. Ringel et al24 have shown in asthma, the anteroposterior diameter of the thorax, when measured high on the rib cage, increases at a constant rate throughout inspiration. Thus, placement of the anterior magnetometer coil in the second intercostal space, as in our study, maximizes the possibility that the magnetometer signal will be proportional to rib cage volume change during tidal breathing in the asthmatic subjects. Retraction of intercostal spaces on inspiration, seen in some chronic airway obstruction patients, might also affect the precision of volume calibration.17

To minimize both asynchrony between anteroposterior and lateral rib cage motions and discoordination between rib cage and abdominal motions during breathing, we selected a comfortable position for the study. Patients were seated, in a slightly forward position, arms and trunks stabilized with pillows as necessary. Patients with either chronic airflow obstruction or asthma often choose this position to minimize both asynchrony of chest wall movements, and, therefore, breathing work.17,18 Coincidentally, this position should minimize error when Vr is measured by chest wall displacement methods.

Precision of Volume Measurements

We found little difference in the precision with which Vr could be measured by each of the three methods. Comparison of Vr measured with (Table 3) to that without (Table 2) MPC/NC demonstrates that each method identifies the augmentation of Vr by the respiratory apparatus. Similarly, each method identifies the increment of Vr induced by addition of dead space to the circuit. The errors for each method when expressed without regard to direction were similar and small, when presented as pooled averages of many breaths, as shown in Figure 1. By contrast, perusal of

Figure 2 suggests that for individual breaths, the differences between volume-displacement and pneumotachygraph methods are greater than implied by comparison of the mean values.

Two recent studies indicate that VT may be accurately measured in airway obstruction patients when the inductive plethysmograph is calibrated by either two-body position least-squares or isovolume method.19,20 This study extends those observations by stimulating Vr with addition of an external dead space to the mouthpiece. We show that during quiet tidal breathing and when respiration is stimulated so as to increase Vr to approximately one and one-half times that measured without mouthpiece (as with mouthpiece, noseclips, and added dead space), each of three methods measures Vr with, on the average, less than 10 percent error when compared to simultaneous flow meter volume estimates. Measurement of chest wall volume displacement provides a valid semiquantitative determination of tidal volume in patients with airflow obstruction.

Breathing Frequency

Frequency was not affected by the addition of mouthpiece or dead space. The fact that neither intervention influences frequency has been demonstrated previously in asthmatic subjects when studied during episodes of acute airway obstruction but not in chronic airway obstruction patients.3

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REFERENCES

7 Freedman AR, Mangura BT, Lavietes MH. Minute ventilation in asthma, enhancement by mouthpiece and depression by oxygen administration. Am Rev Respir Dis 1983; 128:800-05

Measurement of Tidal Breath (Dadzie, Simpson, Lavietes)
Respir Dis 1962; 85:762-68


