Inspiratory Muscle Strength in Asthma

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Augmentation of inspiratory muscle strength (Pmax) represents an adaptive response to airway obstruction. We explore the possibility that respiratory muscle weakness may herald hospital admission during acute bronchospasm. The Pmax measured 81 ± 25 percent of a predicted value in 20 patients with acute bronchospasm (forced expiratory volume in one second, 36 ± 17 percent predicted). Pmax was related to both hyperinflation (functional residual capacity, as percent predicted) and body weight (subjects were 122 ± 29 percent ideal body weight), but not to the degree of airway obstruction per se. Furthermore, measurements of axial (craniocaudal) motion of the rib cage and asynchrony of rib cage and abdominal motions during tidal breathing did not correlate with either the degree of air flow obstruction or Pmax. We conclude that little if any respiratory muscle weakness occurs with bronchospasm. Furthermore, Pmax does not correlate with the degree of airway obstruction and does not explain abnormalities of rib cage and abdominal motion associated with asthma.

To assure ventilation, the respiratory musculature must adapt to the increasing work loads of pulmonary disease. In asthma, such adaptations might include hypertrophy of accessory (e.g., sternocleidomastoid) inspiratory muscles and the persistent use of inspiratory muscles during exhalation.1,2 Respiratory muscle hypertrophy is suggested as an adaptation to chronic airway obstruction, whereas respiratory muscle weakness or fatigue may herald respiratory failure in patients with numerous cardiopulmonary disorders.3,4 The strength of inspiratory muscles has been studied in stable asthmatic patients. Gandevia and McKenzie5 found no impairment of inspiratory or expiratory muscle strength or endurance, whereas Rochester and Arora1 observed a 25 percent increase of inspiratory muscle strength above normal in similar patients. During acute bronchospasm, that is, when bronchospasm is induced in the laboratory setting and muscle strength evaluated immediately thereafter, inspiratory muscle strength appears to be increased. The explanation for this observation is not clear.6 Inspiratory muscle strength has not been measured previously in asthmatic patients presenting to the emergency room during a prolonged attack. Thus, the effect of acute bronchospasm upon respiratory muscle strength in the usual clinical condition whereby asthma presents is not known.

Abnormal motions of the respiratory system (e.g., rib cage or abdomen, or both), often seen in asthma, might reflect adaptation either to increasing airway resistance or to fatigue.4,7 Such motions might include both asynchrony of the rib cage and abdomen during the ventilatory cycle and craniocaudal or axial motion of the rib cage compartment on inspiration.1,9 Asynchrony is known to increase with increasing airway obstruction in asthma. Asynchrony, if not obvious paradox, is observed in both intensive care patients with respiratory muscle fatigue and in stable patients with specific neuromuscular disorders as well.10 Whether or not inspiratory muscle weakness would accentuate asynchrony in asthma is not known. Axial motion might reflect recruitment of sternocleidomastoid muscles with increasing end-expiratory lung volume.11

In the present study, we measure inspiratory muscle strength, rib cage or abdominal asynchrony, or both, in the anteroposterior dimension and axial rib cage motion in 20 unstable asthmatic patients soon after hospital admission. We hypothesize that asynchrony (or axial motion), if quantified, might correlate with both the severity of airway obstruction and the degree of inspiratory muscle weakness, if present.

METHODS

Subjects

Twenty asthmatic subjects were studied soon after arrival in the emergency room with exacerbations of their disease. All satisfied American Thoracic Society criteria for asthma.12 None had evidence of coexistent cardiopulmonary or neuromuscular diseases. None had calcium, phosphorus or other electrolyte abnormality upon admission. As part of the initial clinical assessment and in order to quantify the duration of an attack, two independent observers ascertained answers to the question "when did you last feel well and free from an attack?" In most cases, the two observers were in agreement; the number of days of duration reported for each patient represents the mean of two responses.

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Pulmonary Function Tests

Vital capacity and its subdivisions were measured on a water-sealed Collins spirometer (WE Collins, Braintree, MA). Functional residual capacity (FRC) and airway resistance, corrected for volume, were measured by pressure-variable plethysmography. Special effort was made to prevent rapid panting during plethysmography with its resultant artificial elevation of FRC. To this end, subjects were instructed to pant inward gently two to three times in succession and relax (rather than pant actively) during the expiratory phase of the panting cycle. Total lung capacity (TLC) is the sum of thoracic gas volume (FRC measured by plethysmography) and inspiratory capacity from the spirometer.

Inspiratory Muscle Strength

Inspiratory muscle strength (Pmax) was measured as the maximal subatmospheric mouth pressure developed against an occluded airway from FRC. For this measurement, as well as for evaluation of respiratory system thoracoabdominal motions to follow patients were seated upright. To assure comfort, patients' backs were stabilized with pillows; their arms rested on arm rests. The Pmax reported is the greatest pressure that each patient could sustain for one second. To ensure that the pressures observed were generated by diaphragm and accessory muscles of inspiration rather than the cheeks, a small leak was permitted in the circuit. Patients were encouraged to attempt the inspiratory maneuver many times and to rest momentarily between each inspiratory effort. Pressure was recorded on a time-based oscilloscope (Electronics for Medicine, Pleasantville, NY). The Pmax was reported both as a measured value (cmH2O) and as a percent predicted value. This predicted value, calculated from the equations of Black and Hyatt, was then corrected for the end-expiratory volume at which the measurement was made by equations attributed to Ringqvist. Maximal expiratory pressure (Pmax) was measured from TLC in six subjects.

Abnormal Respiratory System Thoracoabdominal Motions

To quantify thoracoabdominal asynchrony during tidal breathing, we used a previously described method. Calculation of an inspiratory asynchrony angle was made, as shown in Figure 1, from simultaneous tracings of anteroposterior rib cage and abdomen diameters made by magnetometry (NH Peterson, Boston, MA). Rib cage coils were placed at the angle of Louis; abdominal coils, midway between the xiphoid process and the umbilicus. Asynchrony angles were expressed as positive numbers without regard to whether the rib cage preceded or followed the abdomen during the inspiratory cycle. Abdominal expansion preceded rib cage expansion in 17 of the 20 patients.

Axial motion was measured as the change in distance between two coils during tidal breathing; one, placed upon the angle of Louis; the second, affixed to a stationary wooden holder adjacent to the subject's symphysis pubis. Previous authors have used magnetometer coils to measure axial motion of the abdomen in a similar fashion. To test the precision with which axial motion of the rib cage could be measured by this technique, we made multiple simultaneous measurements of axial motion by both magnetometry and video camera using non-anesthetic paramedical laboratory workers as subjects (unpublished observations). We found good correlation between the measurements (r = 0.92; p < 0.001). The standard error of the estimate (4.4 mm) suggested, however, that the method is not appropriate for the detection of small (eg, less than 5 mm) differences.

On admission, arterial gases were obtained in 17 subjects while they inspired room air. Serum theophylline, obtained at the time of function testing in 16 subjects, was assayed by standard methods.

Reproducibility of the Pmax Measurement

We designed a separate protocol to determine whether the increase in Pmax seen after convalescence in some subjects might represent learning of the test procedure rather than an increase in muscle strength per se. To this end, we measured the highest forced expiratory flow measured with a peak flow meter (PEF) and Pmax with portable instruments (a Wright peak flow meter and aneroid manometer, respectively) in nine asthmatic patients during emergency room therapy. Multiple PEF and Pmax determinations were made; maximal values are reported. To evaluate the effect of learning on the Pmax, we then repeated both Pmax and PEF five, 10, and 15 minutes after the initial recordings. Patients were told that both PEF and Pmax might improve with bronchodilation and were encouraged to give maximal effort at all testing times.

Postconvalescence Studies

Nineteen subjects repeated functional studies at the time of discharge from the hospital or after. In no case was this less than 48 hs. Special care was taken to measure Pmax at the same end-expiratory lung volume at which it had been measured during the acute illness. To this end, FRC was measured in the plethysmograph. The difference between FRC during the acute illness and after convalescence was computed (ΔFRC). The subject was then coached to inspire ΔFRC. After the subject was able to perform the maneuver, repeated measurements of Pmax at the volume FRC + ΔFRC were made. It should be noted that in two subjects, FRC + ΔFRC exceeded the TLC measured after convalescence. In those subjects Pmax after convalescence was measured as near to TLC as possible.

Statistical Analysis

Means, standard deviations, chi square analysis, and comparison between two groups were computed by standard methods. Multiple regression analysis was performed with a commercially available statistical package. To evaluate the effect of learning by the nine subjects over time, we used the two-way analysis of variance and the Neuman-Keul's multiple comparisons test.

Results

Pulmonary Function Test Results

Pulmonary function test results on admission appear in Table 1. While TLC is normal (97 ± 29, as percent predicted), FRC is increased (142 ± 52 percent pre-
Table 1—Functional Characteristics of 20 Asthmatic Patients at the Time of Hospital Admission*

<table>
<thead>
<tr>
<th>Function Tests</th>
<th>L (cmH2O) Mean ± SD</th>
<th>% Mean ± SD</th>
</tr>
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<tbody>
<tr>
<td>TLC</td>
<td>6.03 ± 2.00</td>
<td>97 ± 29</td>
</tr>
<tr>
<td>VC</td>
<td>2.33 ± 1.01</td>
<td>58 ± 21</td>
</tr>
<tr>
<td>FRC</td>
<td>4.33 ± 1.77</td>
<td>142 ± 52</td>
</tr>
<tr>
<td>RV</td>
<td>3.69 ± 1.78</td>
<td>215 ± 98</td>
</tr>
<tr>
<td>FEV1</td>
<td>1.17 ± 0.66</td>
<td>36 ± 17</td>
</tr>
<tr>
<td>SRaw (cmH2O s⁻¹)</td>
<td>34 ± 24</td>
<td></td>
</tr>
</tbody>
</table>

*Definitions of abbreviations: TLC = total lung capacity; VC = vital capacity; FRC = functional residual capacity; RV = residual volume; FEV1 = forced expiratory volume in one second; SRaw = specific airway resistance; L = liters; % = percent of a predicted value.

We could not predict Pmax, in cmH2O, from any of the following variables when regression analysis was performed with one variable: airway function (SRaw, FEV1), serum theophylline, arterial blood gas analysis (Po2, PCO2, pH), duration of attack (days), or percentage of ideal body weight (%IBW). When TLC (as percent predicted) or its subdivisions were considered, only FRC could predict Pmax: Pmax (cmH2O) = -87.4 + 0.26 FRC (percent predicted); n = 20; r = 0.616; p < 0.01.

We then performed multiple regression analysis where independent variables other than static lung volumes were entered as second variables. Of all variables, only %IBW could enhance FRC (percent predicted) in the prediction of Pmax: Pmax (cmH2O) = -107 ± 0.29 FRC (percent predicted) + 0.13 %IBW; n = 20; R = 0.637; p < 0.01.

This relationship is illustrated in Figure 2. The greater the end-expiratory lung volume, and the more overweight the subject, the weaker the subject's inspiratory muscles are likely to be. Further analysis of this equation showed that the regression sum of squares explained 41 percent of the total variation of the 20 Pmax values from their mean; 38 percent by FRC, 3 percent by %IBW. As expected, FRC is the major determinant of Pmax. (Of note, when Pmax is entered as percent predicted, the resultant regression coefficients approximate zero; this would be expected because our predicted Pmax takes into consideration the volume at which it is measured.)

Finally, addition of either quantitative measurement of respiratory system asynchrony or axial motion did not enable us to predict FEV1 or SRaw even if Pmax, serum theophylline, or other demographic information

Of interest, axial motion exceeded 1.0 cm in only two subjects; it was, on the average, 4 ± 7 mm for the two patients.

Data for inspiratory muscle strength and the quantification of abnormal respiratory system motions appear in Table 2. The Pmax (81 ± 25 percent predicted), suggested that even when the measured value was corrected for hyperinflation of the lung, mild weakness of inspiratory muscles was apparent in some subjects.
Table 3—Serial Measurement of Highest Forced Expiratory Flow Measured with Peak Flow Meter and Inspiratory Muscle Strength in Nine Asthmatic Patients*

<table>
<thead>
<tr>
<th>Time, Minutes</th>
<th>0</th>
<th>5</th>
<th>10</th>
<th>15</th>
<th>FIM</th>
</tr>
</thead>
<tbody>
<tr>
<td>PEF</td>
<td>Mean ± SEM</td>
<td>163±24</td>
<td>177±27</td>
<td>170±24</td>
<td>170±24</td>
</tr>
<tr>
<td>Pimax</td>
<td>Mean ± SEM</td>
<td>-55±8</td>
<td>-52±6</td>
<td>-60±6</td>
<td>-64±6</td>
</tr>
</tbody>
</table>

*PEF: highest forced expiratory flow measured with peak flow meter; Pimax, inspiratory muscle strength

were known. In some subjects there was obvious breath-to-breath variation in the asynchrony angle. A discernible pattern of respiratory alternans was not apparent for any subject, however. The standard deviations for asynchrony angles measured ten or more times for each of the 20 subjects ranged from 5° to 28°. Standard deviations did not correlate with either the degree of airway dysfunction or Pimax.

The Pimax in the seven overweight subjects (153±25 %IBW) was 79±17 percent of predicted. This was no different from Pimax in the nonoverweight subjects (104±9 %IBW; Pimax, 81±31 percent of predicted). Thus, muscle weakness was not merely a reflection of obesity.

Reproducibility of Pimax

The Pimax did not appear to be wholly reproducible. Table 3 shows that Pimax measured in the final (15th minute) trial was on average, -9 cm H2O greater than that measured initially (FIM = 4.23; p<0.05). Multiple comparisons showed no difference between Pimax at time 0 (control) and time 5 min. The Pimax at time 10 and 15 min were both different from that at time 5 min and from each other. Since PEF did not change during the trials, changes in Pimax over time could not be explained by changes in airway tone or pulmonary function.

Inspection of data from individual patients, however, shows that Pimax at time 15 min was within ±10 percent of Pimax at time zero for five of the nine patients. On the other hand, Pimax at time 15 min was 140±13 SD percent of the time zero value for the other four subjects. Thus, a learning effect was apparent for four of the nine subjects.

Repeat Study After Convalescence

For the 19 subjects studied after convalescence, Pimax after convalescence (-100±8 SEM, in cm H2O) was greater than the -80±6 prior to therapy (paired t = 2.20; p<0.05). Careful observation indicated that Pimax improved markedly in some subjects but little, if at all, in others. Nine of 19 developed Pimax after convalescence with ±10 percent of Pimax during the acute illness. By contrast, Pimax postconvalescence was 167±78 percent of initial Pimax for the other ten subjects. Chi-square analysis suggested that the likelihood of increase of Pimax postconvalescence (when compared to Pimax during the acute illness) was similar to the likelihood that Pimax would improve with repeated measurements (ie, Pimax at time 15 min compared with Pimax at time zero described before).

Finally, there was no relationship between corticosteroid usage, duration of attack (days), or the time that elapsed (days) between acute and convalescent studies and the likelihood that Pimax would increase after convalescence.

**DISCUSSION**

We found that asthmatic subjects in acute exacerbation have either no or only minimal weakness of inspiratory muscles and that Pimax does not correlate with measures of airway obstruction in these patients. At first glance, the observation that Pimax improves slightly (p<0.05) after convalescence, when compared with Pimax recorded in acute exacerbation, might point to an opposite interpretation. We have demonstrated, however, a learning effect when Pimax is measured repeatedly in patients during an acute attack. Comparison of serial measurements of Pimax in the 19 subjects before and after treatment with those repeated measurements made in nine emergency service patients suggests that a learning effect may explain serial changes of Pimax in both groups. The learning effect in these patients appears to be slightly greater than that observed in normal subjects. This conclusion is reasonable, because Pimax is an effort-dependent maneuver requiring cooperation and motivation; it is likely that an ill, uncomfortable patient will have difficulty performing this test. Note also that we used a mouthpiece and pressure transducer different from that of Black and Hyatt. Therefore, use of their prediction equations may not provide a true standard for weakness for our patients. Finally, since airway pressure has been measured in this study, our pressure measurements reflect the collective effort of all inspiratory muscles. This study provides no insight into the contribution of individual muscles or muscle groups to the inspiratory effort.

It is of interest that in this study, Pimax was predicted from measurement of end-expiratory lung volume expressed as a percentage of normal (ie, FRC) and %IBW. The FRC, in turn, was related to the degree of airway obstruction (FEV1/SRaw). By contrast, Pimax was not predicted from any index of airway obstruction or age. It is recognized that inspiratory muscles transform neural drive into a mechanical force, or pressure, most efficiently at low lung volumes. The fact that a decreasing Pimax is associated
with severe hyperinflation suggests that the apparent decrease of Pmax in some of our subjects represents an exaggeration of a normal phenomenon rather than a true abnormality or weakness.

Lastly, weakness of expiratory muscles (Pmax) should be considered, since phasic abdominal muscle recruitment occurs during severe bronchoconstriction. We measured Pmax in only six of our 20 patients. The severe impairment observed (48 ± 10 percent of predicted) suggests that systematic evaluation of Pmax during bronchoconstriction is warranted.

The inclusion of body weight in the multiple variable regression equation was unexpected. The fact that some of our patients were overweight distinguishes them from asthmatic patients evaluated by other authors. Since muscle weakness is distributed equally between heavy and nonheavy subjects, however, it is appropriate to generalize the findings of this study to all asthmatic patients without regard to weight. A relationship between mild obesity and respiratory muscle weakness has not been observed previously. Epidemiologic data suggesting mild obesity and diminished life expectancy coexist may be consistent with this observation. In asthmatic subjects, unlike normal subjects, age is not a predictor of muscle strength.

Thoracoabdominal Asynchrony

Hillman et al show that during severe air flow obstruction, the magnitude of phase lag between anteroposterior motion of rib cage and abdomen during the respiratory cycle reflects the severity of asthma. These authors studied each of eight subjects three or more times during the resolution of a severe attack. Their conclusion was drawn from the fact that within each subject, asynchrony angle diminished as FEV1 increased during convalescence. By contrast, we show that the asynchrony angle, if measured once in each of a group of subjects with severe bronchospasm, does not correlate precisely with their degree of airway obstruction. From data of Hillman et al, however, it can be estimated that asthmatic subjects whose FEV1 is 36 percent of predicted will have an asynchrony angle of 40°. The FEV1 and asynchrony angle are 36 percent and 49°, respectively, in our patients. Therefore, study of a group of patients whose airway function shows greater disparity than that of this group ought to reveal a correlation between FEV1 and asynchrony angle.

Axial (Craniocaudal) Motion

That axial motion was, on the average, only 4 mm when measured by magnetometers was unexpected. Clinical observations suggest that axial motion might be greater. We believe these measurements to be correct because in preliminary experiments (using ourselves as subjects) we measured similar small excursions when attempting “abdominal” breathing. By contrast, we measured 1.0 to 3.0-cm excursions during “accessory muscle” breathing and confirmed these motions with videotape.

That axial motion is smaller, when measured by magnetometry, than it appears to the clinician may be explained by the fact that all inspiratory accessory and expiratory respiratory muscles are recruited in asthma. Expiratory abdominal contraction may displace the rib cage both on the craniocaudal and anteroposterior axes, whereas inspiratory anteroposterior motion of the rib cage during asthma or external resistive loading, or both, may result from intercostal muscle contraction. Therefore, while sternocleidomastoid muscles may move the rib cage along the craniocaudal axis when contracting alone, during bronchoconstriction they function in concert with other respiratory muscle groups. Nevertheless their contraction can easily be observed by visual observation or palpation.

Other authors have noted that a quantitative assessment of airway dysfunction is necessary for the clinician; this study indicates that the clinical observation of thoracoabdominal movements does not help with this assessment. Finally, all of our patients were eucapnic or hypocapnic. Since readily reversible muscle weakness is associated with hypercapnia, our observations cannot be extrapolated to patients with respiratory acidosis.

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