Respiratory muscle strength training with nonrespiratory maneuvers

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DePalo, Vera A., Annie Lin Parker, Fadi Al-Bilbeisi, and F. Dennis McCool. Respiratory muscle strength training with nonrespiratory maneuvers. J Appl Physiol 96: 731–734, 2004. First published September 26, 2003; 10.1152/japplphysiol.00511.2003.—The diaphragm and abdominal muscles can be recruited during nonrespiratory maneuvers. With these maneuvers, transdiaphragmatic pressures are elevated to levels that could potentially provide a strength-training stimulus. To determine whether repeated forceful nonrespiratory maneuvers strengthen the diaphragm, four healthy subjects performed sit-ups and bicep curls 3–4 days/wk for 16 wk and four subjects served as controls. The maximal transdiaphragmatic pressure was measured at baseline and after 16 wk of training. Maximum static inspiratory and expiratory mouth pressures and diaphragm thickness derived from ultrasound were measured at baseline and 8 and 16 wk. After training, there were significant increases in diaphragm thickness [2.5 ± 0.1 to 3.2 ± 0.1 mm (mean ± SD) (P < 0.001)], maximal transdiaphragmatic pressure [198 ± 21 to 256 ± 23 cmH2O (P < 0.02)], maximum static inspiratory pressure [134 ± 22 to 171 ± 16 cmH2O (P < 0.002)], maximum static expiratory pressure [195 ± 20 to 267 ± 40 cmH2O (P < 0.002)], and maximum gastric pressure [161 ± 5 to 212 ± 40 cmH2O (P < 0.03)]. These parameters were unchanged in the control group. We conclude that nonrespiratory maneuvers can strengthen the inspiratory and expiratory muscles in healthy individuals. Because diaphragm thickness increased with training, the increase in maximal pressures is unlikely due to a learning effect.

METHODS

Eight healthy subjects between the ages of 27 and 61 yr were recruited from hospital personnel. All subjects were male, and all were fit but were not actively involved in body-building exercises. Four served as controls and four trained. The mean age, height, and weight were, respectively, 34.5 yr (range 27–51 yr), 176.3 cm (range 165–180 cm), and 78.3 kg (range 71–91 kg) for the training group and 37.5 yr (range 27–61 yr), 175 cm (range 167–180 cm), and 75.8 kg (range 67–86 kg) for the control group. The study was approved by the institutional review committee, and informed consent was obtained from all subjects.

Pressure measurements. Airway opening pressure, esophageal pressure (Pes), and gastric pressure (Pga) were measured by use of standard techniques (15, 20). The Pes and Pga were measured after placement of balloon catheters (no. 47-9005, ACKRAD Lab, Cranford, NJ) in the distal esophagus and stomach. The esophageal balloon was inflated with 0.5 ml of air, and the gastric balloon was inflated with 2.0 ml of air. The Pdi difference was calculated as the difference between Pga and Pes.

Measurements of diaphragm thickness. The diaphragm was imaged using a 7.5–10 MHz transducer applied over the 8th to 9th intercostal spaces in the midaxillary line (ALT model 3000). The diaphragm was identified as a three-layered structure just superficial to the liver consisting of a relatively nonechogenic muscular layer bordered by echogenic membranes of peritoneum and diaphragm pleura. Images were selected for clarity and parallelism of the three layers of diaphragm structure. Images were obtained at end-expiration. Diaphragm thickness (tdi) was measured as the perpendicular distance between the superficial edge of the diaphragm pleura and the deep edge of the peritoneum to the nearest 0.1 mm (11, 30). All sequential measurements of tdi were obtained at the same external chest wall location for each individual. All measurements were obtained with the subjects standing.

Protocol. Baseline measurements of Pdimax were obtained for all individuals. Pdimax was measured at functional residual capacity (FRC) during a combined Mueller and expulsive maneuver (15). Maximal Pga recorded during the combined maneuver was reported as Pgamax. Maximum static inspiratory pressure (Pimax) was also measured at FRC during maximal static inspiratory efforts (7). The subject was instructed to inhale against an occluded mouthpiece for at least 3 s. Maximum static expiratory pressure (Pemax) was measured at total lung capacity during a maximal Valsalva maneuver. The subject was instructed to forcefully exhale against an occluded mouthpiece for at least 3 s. Visual feedback provided by an oscilloscope was used in each of these maneuvers to maximize effort. Pdimax, Pgamax, Pimax, and Pemax were measured at baseline and after 16 wk of training.

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Nonrespiratory maneuvers for respiratory muscle training

Table 1. Measurements in training and control subjects over time

<table>
<thead>
<tr>
<th></th>
<th>Baseline</th>
<th>8 Wk</th>
<th>%Change</th>
<th>16 Wk</th>
<th>%Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Training</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pdimax, cmH2O</td>
<td>198±21</td>
<td>256±23</td>
<td>30.3%</td>
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<tr>
<td>Pgamax, cmH2O</td>
<td>161±25</td>
<td>212±40</td>
<td>32.6%</td>
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<tr>
<td>Pimax, cmH2O</td>
<td>134±22</td>
<td>171±16</td>
<td>29.4%</td>
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<tr>
<td>PEmax, cmH2O</td>
<td>195±20</td>
<td>222±37</td>
<td>13.5%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>tdi, mm</td>
<td>2.5±0.1</td>
<td>2.8±0.1</td>
<td>11.0%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Biceps, cm</td>
<td>35.4±1.3</td>
<td>36.2±1.5</td>
<td>2.2%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FRC, liters</td>
<td>2.87±0.5</td>
<td>2.99±0.4</td>
<td>4.2%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Control</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pdimax, cmH2O</td>
<td>172±21</td>
<td>171±23</td>
<td>0.0%</td>
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<tr>
<td>Pgamax, cmH2O</td>
<td>151±11</td>
<td>149±10</td>
<td>0.8%</td>
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<tr>
<td>Pimax, cmH2O</td>
<td>128±7</td>
<td>125±8</td>
<td>0.0%</td>
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<tr>
<td>PEmax, cmH2O</td>
<td>198±33</td>
<td>196±33</td>
<td>0.9%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>tdi, mm</td>
<td>2.6±0.3</td>
<td>2.7±0.3</td>
<td>3.9%</td>
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<td></td>
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<tr>
<td>Biceps, cm</td>
<td>37±1.5</td>
<td>39±1.5</td>
<td>5.3%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FRC, liters</td>
<td>2.79±0.4</td>
<td>2.8±0.6</td>
<td>2.1%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Values are means ± SD. Pdimax, maximal diaphragmatic pressure; Pgamax, maximal gastric pressure; Pimax, maximal inspiratory pressure; PEmax, maximal expiratory pressure; tdi, diaphragm thickness; FRC, functional residual capacity. Significance levels: *P < 0.05; **P < 0.01; ***P < 0.001.

Pimax and Pgamax were taken as the highest values sustained for 1 s during the respective maneuvers. Baseline measurements of biceps muscle circumference were obtained with the muscle maximally tensed. FRC was measured by body plethysmography (Collins model no. 001).

Training. Four subjects underwent training, consisting of biceps curls and sit-ups. The biceps curls were performed with dumbbells. The weight progressively increased through the course of the study period as tolerated by the subject, beginning with 15 lbs, and increasing to a maximum of 35 lbs. in two individuals. Biceps training consisted of three sets of 8–10 repetitions. Subjects rested for 5 min between sets. Sit-ups were performed with knees flexed, starting with 20 sit-ups per session, increasing the number as tolerated. Subjects were instructed to inhale as they were raising their torso during this maneuver. The number of sit-ups performed progressively increased. By the end of the 16-wk training interval, subjects were performing between 100 and 150 sit-ups. Each exercise was performed a minimum of 4 days/wk for the course of the study. Training was unsupervised and occurred at home or in a gymnasium. Measurements of Pimax, Pgamax, biceps circumference, and tdi were made at baseline and 8 and 16 wk. Pdimax and Pgamax were measured at baseline and at 16 wk.

Statistics. Data for all baseline measurements were calculated and expressed as means ± SD for the control and the weight-trained groups. Changes in measurements after the training period were expressed as percent of the baseline values. Differences in the effects of weight training on the individual measurement between the control and weight-trained groups were assessed by using analysis of covariance with the percent change in measurement as the dependent variable and the baseline measurement as the covariate. Differences were considered significant for P < 0.05. All analyses were performed by use of Statview (SAS Institute, Cary, NC).

RESULTS

All subjects found the training to be strenuous, and three subjects stopped training soon after the conclusion of the study. Baseline values (means ± SD) for Pdimax, Pgamax, Pimax, PEmax, tdi, FRC, and biceps circumference for each group are given in Table 1. There were no significant differences in any of these baseline parameters between the training and control groups. For the control group, no significant changes in Pimax, Pgamax, or tdi were noted at 8 or 16 wk. Similarly, there were no significant changes in Pdimax or Pgamax during the 16-wk interval for the control group. FRC was unchanged in both the training and control groups.

Training was associated with increases in inspiratory muscle strength. Both Pimax and Pdimax increased to a similar degree. Pgamax increased by 29.4% from 134 ± 22 to 171 ± 16 cmH2O (P < 0.002), and Pdimax increased by 30.3% from 198 ± 21 to 256 ± 23 cmH2O (P < 0.02). This increase in inspiratory muscle strength was accompanied by an increase in diaphragm mass. The tdi increased by 25.8% from 2.5 ± 0.1 to 3.2 ± 0.1 mm (P < 0.001). Strength training with nonrespiratory maneuvers also improved expiratory muscle strength. PEmax increased by 36.4% from 195 ± 20 to 267 ± 40 cmH2O (P < 0.002), and Pgamax increased by 31.2% from 161 ± 5 to 212 ± 40 cmH2O (P < 0.03). There also was a small but significant increase in biceps circumference at 16 wk (35.4 ± 1.3 to 36.4 ± 1.7 cm, P < 0.02). At 8 wk, there were significant increases in Pimax (12.1%) and Pgamax (13.5%) (Fig. 1). The slope of the line between baseline and 8 wk was not significantly different from that between 8 and 16 wk. During this time the training protocol was unchanged.

DISCUSSION

Chronic disease states that affect the respiratory system may adversely impact muscle structure and function leading to respiratory muscle fatigue, weakness, and the development of respiratory failure (17, 18). It follows that improvements in respiratory muscle strength or endurance may help avert respiratory failure, which is often a consequence of severe chronic respiratory disease. To this end, pulmonary rehabilitation with generalized exercise training or specific respiratory muscle training has been shown to be beneficial in patients with respiratory disease (2, 3). However, issues surrounding safety, patient compliance, and the efficacy of varied types of exercise continue to be debated in the literature. We present results demonstrating that nonrespiratory activities involving the trunk and limbs can be used to train the diaphragm as well as the expiratory muscles.
Individuals engaged in physical labor perform repetitive maneuvers that may strengthen the respiratory muscles. In an autopsy series, Arora and Rochester (4) found that diaphragm muscle mass was greater in those who had been regularly engaged in manual labor. They speculated that the diaphragm was recruited in activities involving the trunk. McCool and collaborators (19) extended these observations to a study of individuals who had performed weight-lifting maneuvers for >1 yr. They used ultrasound to assess tdi and measured P\textsubscript{1\text{max}} in 15 muscular weight lifters and 18 healthy volunteers. They demonstrated that the more muscular individuals had greater diaphragm mass and inspiratory muscle strength (19). The increase in diaphragm muscle mass seen in these individuals may be attributed to the physical activity itself, or, in the study of weight lifters, to the use of anabolic steroids (25). These associations between generalized muscularity and diaphragm mass are consistent with previous observations that the strength of the trunk flexors correlated with P\textsubscript{1\text{max}} in a series of healthy individuals (22).

Physical activity can be accompanied by substantial increases in Pdi. The abdominal muscles are often activated during strenuous nonrespiratory activities that involve the trunk. Contraction of this group of muscles will increase intra-abdominal pressure. The benefit of increasing abdominal pressure during weight-bearing activities is that it lessens the axially directed compressive forces on the spine. However, the elevated intra-abdominal pressures are transmitted to the thorax if the glottis is closed and diaphragm relaxed during these maneuvers. Consequently, there may be adverse hemodynamic and central nervous system effects. To avert these complications, the diaphragm may be activated and tensed, thereby minimizing the transmission of pressure from the abdomen to the thorax. We previously found that intrathoracic pressure generally remained subatmospheric even when P\textsubscript{a} values were elevated to levels >100 cmH\textsubscript{2}O during weight-bearing maneuvers (1). Consequently, the increase in Pdi may be as great as 65% of P\textsubscript{di\text{max}}. Activating skeletal muscle to this extent will provide a strength-training stimulus. Accordingly, we postulated that weight-bearing maneuvers may be used to strength train the diaphragm and expiratory muscles.

Performing biceps curls and sit-ups four times weekly resulted in significant increases in P\textsubscript{1\text{max}} after 8 wk of training and further increases at 16 wk. The finding that P\textsubscript{di\text{max}} was also increased suggests that these maneuvers not only strengthened the muscles of the rib cage but also provided a sufficient strength-training stimulus to the diaphragm. This assertion is further supported by the observation that t\textsubscript{di} increased with 8 and 16 wk of training. The increase in t\textsubscript{di} in the present study is consistent with strengthening of the diaphragm and argues against a significant learning effect as an explanation of the increases in P\textsubscript{di\text{max}} or P\textsubscript{1\text{max}}. Our protocol did not distinguish between the benefits of biceps curls or sit-ups; however, we speculate that sit-ups may have had the most pronounced training effect on the diaphragm because the increase in biceps circumference was not as great as the increase in P\textsubscript{1\text{max}} and sit-ups were associated with greater increases in Pdi in our previous study (1).

The 30% increase in diaphragm strength and 26% increase in t\textsubscript{di} that we found with strength training are similar in magnitude to the increase in strength and degree of myofiber hypertrophy induced by strength training the lower extremity. Knee extensor and leg press strength increased by 34 and 53%, respectively, in healthy individuals undergoing lower extremity strength training, and vastus lateralis type I and type II muscle fibers hypertrophied by 26 and 28%, respectively (9). Although strength training leads to myofiber hypertrophy, it does not result in mitochondrial proliferation (8, 9, 27). Mitochondrial density may be reduced by ~13% with strength training (9). These observations suggest that endurance may not be improved with strength training alone. However, inspiratory muscle endurance, as assessed by maximal sustainable pressure, is related to the strength of the inspiratory muscles (23). Alternatively, a combination of strength and endurance training in healthy individuals stimulates mitochondria proliferation and myofiber hypertrophy (10). Our study did not address whether strength training will increase endurance, but, on the basis of the above observations, a combination of both training stimuli may be optimal for improving both inspiratory muscle strength and endurance.

The strength-training maneuvers employed in the present study may have other associated benefits. They may not only strengthen the diaaphragm but also strengthen the muscles of the rib cage, abdominal wall, and upper extremities. The increase in P\textsubscript{1\text{max}} is consistent with a strength training effect on the expiratory muscles of the rib cage and abdomen. The small increase in biceps muscle circumference is consistent with strengthening of the upper extremity muscles. Because the muscles of the rib cage, upper extremity, and abdominal wall are often recruited during breathing in patients with chronic obstructive pulmonary disease (COPD), training with these maneuvers may provide more benefit than training maneuvers that target the inspiratory muscles alone (18).

Typically, the inspiratory muscles are strength trained by using resistive loads such as fixed orifices or by using threshold loads (5, 6, 12, 13, 16, 28, 29). A meta-analysis of inspiratory muscle training in COPD patients described mixed results regarding improvement in P\textsubscript{1\text{max}} and respiratory muscle endurance (24). Analysis by the authors suggested that there might have been improvements in strength and endurance if breathing pattern was controlled. With these maneuvers, inspiratory muscle strength can be increased by >50% (5, 21). However, the resistive loads imposed by such training protocols may be overcome by primarily recruiting the inspiratory muscles of the rib cage rather than the diaphragm (14). Thus the rib cage muscles may undergo more of a training effect than the diaphragm. To specifically train the diaphragm, maneuvers that increase Pdi provide the most favorable training stimuli. Such breathing maneuvers may be learned but are often difficult to perform. The nonrespiratory activities utilized for training in the present study may provide an alternative mean to train the diaphragm because they are easily learned.

The nonrespiratory maneuvers reported in the present study were simple to perform and may be of particular benefit in a pulmonary rehabilitation program. These maneuvers can be used to strength train both inspiratory and expiratory muscle groups and may provide other benefits such as increasing bone density. However, the differences between healthy individuals and patients with COPD may limit the degree to which our results can be extrapolated to these patients. Factors such as poor nutrition and lack of motivation may limit any improvement in inspiratory muscle performance. Furthermore, these individuals have difficulty performing activities involving their
upper extremities, which may preclude the use of biceps curls. Nonetheless, these generalized nonrespiratory maneuvers may be more acceptable for patient compliance than tasks specifically targeting the respiratory muscles.

We conclude that nonrespiratory maneuvers such as biceps curls and sit-ups can improve inspiratory muscle strength, expiratory muscle strength, and diaphragm strength. The effects of weight lifting and sit-ups in a comprehensive pulmonary rehabilitation program remain to be studied.

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