LUNG protective strategies to minimize lung injury and promote recovery from acute respiratory distress syndrome (ARDS) have sought to minimize both volutrauma (barotrauma) due to overdistension as well as cyclic alveolar collapse from underexpansion, both of which promote lung injury. Esophageal manometry can be used to guide ventilator management in severe ARDS, and this strategy was shown to improve oxygenation and lung compliance, and possibly improve survival, when compared with standard practice. Other therapeutic approaches including paralysis, nitric oxide, recruitment maneuvers, and prone positioning have shown benefits, but also have the potential to cause injury.

Our discussion will focus on prone positioning, which was first proposed in the 1970s as a tool to improve lung oxygenation and mechanics in patients with hypoxic respiratory failure. The mechanism of benefit in prone positioning remains incompletely understood. Proposed mechanisms include optimization of lung recruitment and a more even distribution of perfusion that result in improved oxygenation and increases in functional residual capacity. Additionally, gravitational forces on the abdominal contents may be one mechanism for the observed clinical benefit with prone positioning.

What We Already Know about This Topic
- Prone positioning improves oxygenation and survival in adult respiratory distress syndrome, but it is seldom employed, perhaps in part because of uncertainty in the mechanism of action

What This Article Tells Us That Is New
- In healthy patients during general anesthesia, switching from the supine to the prone position was associated with an increase in end-expiratory transpulmonary (distending) pressure and lung volume, which may account for its benefit in acute respiratory distress syndrome

Effects of Prone Positioning on Transpulmonary Pressures and End-expiratory Volumes in Patients without Lung Disease

Abirami Kumaresan, M.D., Robert Gerber, B.S., Ariel Mueller, M.A., Stephen H. Loring, M.D., Daniel Talmor, M.D.

ABSTRACT

Background: The effects of prone positioning on esophageal pressures have not been investigated in mechanically ventilated patients. Our objective was to characterize effects of prone positioning on esophageal pressures, transpulmonary pressure, and lung volume, thereby assessing the potential utility of esophageal pressure measurements in setting positive end-expiratory pressure (PEEP) in prone patients.

Methods: We studied 16 patients undergoing spine surgery during general anesthesia and neuromuscular blockade. We measured airway pressure, esophageal pressures, airflow, and volume, and calculated the expiratory reserve volume and the elastances of the lung and chest wall in supine and prone positions.

Results: Esophageal pressures at end expiration with 0 cm H$_2$O PEEP decreased from supine to prone by 5.64 cm H$_2$O (95% CI, 3.37 to 7.90; $P < 0.0001$). Expiratory reserve volume measured at relaxation volume increased from supine to prone by 0.15 l (interquartile range, 0.25, 0.10; $P = 0.003$). Chest wall elastance increased from supine to prone by 7.32 (95% CI, 4.77 to 9.87) cm H$_2$O/l at PEEP 0 ($P < 0.0001$) and 6.66 cm H$_2$O/l (95% CI, 3.91 to 9.41) at PEEP 7 ($P = 0.0002$). Median driving pressure, the change in airway pressure from end expiration to end-inspiratory plateau, increased in the prone position at PEEP 0 (3.70 cm H$_2$O; 95% CI, 1.74 to 5.66; $P = 0.001$) and PEEP 7 (3.90 cm H$_2$O; 95% CI, 2.72 to 5.09; $P < 0.0001$).

Conclusions: End-expiratory esophageal pressure decreases, and end-expiratory transpulmonary pressure and expiratory reserve volume increase, when patients are moved from supine to prone position. Mean respiratory system driving pressure increases in the prone position due to increased chest wall elastance. The increase in end-expiratory transpulmonary pressure and expiratory reserve volume may be one mechanism for the observed clinical benefit with prone positioning.

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regional diaphragm mechanics and change its motion, resulting in improvement of ventilation-perfusion mismatch.\textsuperscript{11} We hypothesized that a postural reduction in pleural pressures and corresponding increase\textsuperscript{12} in the transpulmonary pressure would accompany an increase in lung volumes. This effect has been demonstrated in awake spontaneously breathing subjects.\textsuperscript{13}

To our knowledge, the use of esophageal manometry in prone ventilated patients during general anesthesia has not been described. The objective of this study was to characterize effects of prone positioning on esophageal pressure, transpulmonary pressure, and lung volume at end exhalation in patients during general anesthesia, thereby assessing the potential utility of esophageal pressure measurements in setting positive end-expiratory pressure (PEEP) in prone patients with ARDS.\textsuperscript{14} The use of esophageal pressure measurements to titrate PEEP in the prone position may further promote lung protection within the operating room and elsewhere.\textsuperscript{15}

**Materials and Methods**

**Patients**

In this nonrandomized observational physiologic study, we enrolled a convenience sample of patients without lung disease who were scheduled for elective spine surgery. Patients were enrolled from 2014 to 2015. Subjects provided written, informed consent using a protocol approved by the Committee on Clinical Investigations at Beth Israel Deaconess Medical Center (Boston, Massachusetts). No formal power calculation was performed \textit{a priori}. As this is a physiology study, we chose a convenience sample of 18 patients, and we were able to obtain measurements from 16 eligible participants. This value is similar to the sample sizes used in previous studies looking at the prone position and oxygenation by both Pelosi \textit{et al.}\textsuperscript{4} (N = 16) and Guerin \textit{et al.}\textsuperscript{16} (N = 12).

Patients were initially anesthetized, pharmacologically paralyzed, intubated, and mechanically ventilated in the supine position. Airway pressure\textsuperscript{17} was measured at the endotracheal tube,\textsuperscript{17} esophageal pressure was measured using an esophageal balloon-catheter filled with 1.0 ml air, and flow was measured with a Fleisch pneumotachograph (Hans Rudolph Inc., USA) and later integrated to obtain volume change. Transpulmonary pressure was calculated as peak airway pressure minus esophageal pressure.

**Physiologic Measurements**

The esophageal balloon was advanced to approximately 30 cm from the incisors. Proper balloon position was confirmed by the presence of cardiac artifact and by demonstrating similar increases in esophageal pressure and peak airway pressure during external compression of the chest wall during airway occlusion. Patients were initially ventilated with tidal volumes of 6 ml/kg ideal body weight with 0 cm H\textsubscript{2}O PEEP.

The protocol was designed to measure changes in the lung volume at resting functional residual capacity (relaxation volume) caused by a change in posture by measuring the expiratory reserve volume in both positions, the position-dependent difference in expiratory reserve volume indicating the change in relaxation volume. We achieved relaxation volume by allowing subjects to exhale to atmospheric pressure. We then applied a negative transpulmonary pressure sufficient to cause exhalation to residual volume, thereby measuring expiratory reserve volume. Exhalation to expiratory reserve volume would normally be achieved by active exhalation, raising the pleural pressure to a highly positive value. In our paralyzed subjects, this was not possible, so exhalation was achieved by reducing airway pressure by 25 cm H\textsubscript{2}O (mechanically equivalent to raising pleural pressure to 25 cm H\textsubscript{2}O at residual volume). The substantially negative transpulmonary pressure causes exhalation to the minimum air volume of the lung, at which time all the airways are collapsed and the alveoli are isolated from the pressure in the endotracheal tube. The alveolar pressure in this situation is determined by the parenchymal stress, and is roughly the same as pleural pressure. (Note that in this situation, the static transpulmonary pressure and the elastic recoil pressure of the lung are not the same.)

The protocol was as follows. After seven tidal breaths with PEEP 0 cm H\textsubscript{2}O, the patient was detached from the ventilator for 15 s, and a steady negative pressure of –25 cm H\textsubscript{2}O was applied to the airway for 5 s by aspirating air with a 2-l syringe from the breathing circuit fitted with an inverted PEEP valve (Ambu, Denmark). The volume expired during the application of negative pressure was measured as the expiratory reserve volume. The patient was then placed back on the ventilator with PEEP 7 cm H\textsubscript{2}O, and the measurements above were repeated. Finally, the patient was turned prone, and all measurements at both PEEP concentrations were repeated. Pressure and flow signals were digitized and recorded for subsequent analysis (Dataq Instruments, USA; fig. 1).

**Analysis**

Esophageal pressure, transpulmonary pressure, peak airway pressure, and flow were recorded continuously. We averaged these values at end-expiration and a brief (0.5 s) end-inspiratory plateau during five tidal breaths and in two maneuvers at relaxation volume. Tidal volumes were used to calculate elastances of respiratory system, lung, and chest wall using the appropriate end-inspiratory and plateau pressures. Mean driving pressure of the respiratory system was calculated as the change in peak airway pressure from end expiration to end-inspiratory plateau, and the transpulmonary driving pressure was calculated from transpulmonary pressure at the same time points. Expiratory reserve volume was calculated by integrating flow during the application of negative airway pressure from relaxation volume to residual volume.

**Statistics**

Differences in measurements between supine and prone positions were assessed using a paired \textit{t} test or Wilcoxon signed-rank test using SAS 9.4 (SAS Institute Inc., USA). Normality was assessed with the use of the Shapiro-Wilk test. Results are reported as mean ± SD or median (interquartile
range) depending on distribution. All two-sided \( P \) values < 0.05 were considered statistically significant.

**Results**

Our subjects were 16 American Society of Anesthesiologists physical status class I or II patients without respiratory disease presenting for elective spine surgery. Two other subjects had been excluded because of inadequate tests of balloon position (chest push). Our study population included nine males and seven females. Two were of African-American descent, one was of Hispanic descent, one patient did not wish to identify, and the remainder were white. The average balloon position was 33.8 cm with SD of 2.8 cm. Please refer to the Supplemental Digital Content (http://links.lww.com/ALN/B668) for a full table of results.

End-expiratory esophageal pressures were measured at relaxation volume at PEEP 0 and 7 in both supine and prone positions (table 1). End-expiratory esophageal pressure decreased from supine to prone position. During tidal ventilation at PEEP 0 and PEEP 7, the mean end-expiratory esophageal pressure decreased (table 1). The mean difference was –5.64 at PEEP 0 and –5.07 at PEEP 7, \( P = 0.0001 \) and \( P = 0.0002 \), respectively. Esophageal pressure was also lower in the prone position at relaxation volume (fig. 2).

There was a corresponding increase in transpulmonary pressure (transpulmonary pressure = peak airway pressure – esophageal pressure) at end expiration from supine to prone position at PEEP 0. Similar results were observed at PEEP 7. Expiratory reserve volume increased from supine to prone; median expiratory reserve volume was 0.20 l (interquartile range, 0.15, 0.41) supine and 0.37 l (interquartile range, 0.29, 0.66) prone, with a median difference of 0.15 l (\( P = 0.003 \); table 1; fig. 3). Chest wall elastance increased from the supine to prone position (table 1; fig. 4). Lung elastance did not change with position (table 1). Driving pressure of the respiratory system increased from supine to prone position at both PEEP 0 and 7, with median increases of 3.60 cm H\(_2\)O (\( P = 0.001 \)) and 3.22 cm H\(_2\)O (\( P < 0.0001 \)), respectively. Transpulmonary driving pressure did not change significantly from supine to prone at PEEP 0 or PEEP 7.

**Discussion**

In our patient population, end-expiratory esophageal pressure decreased and end-expiratory transpulmonary pressure increased at any given airway pressure when subjects were moved from supine to prone. Consistent with these changes, expiratory reserve volume increased, indicating an increase in relaxation volume. These findings suggest that the prone position could recruit lung volume in patients with ARDS by increasing transpulmonary pressure at a given PEEP. Indeed, Guerin et al.\(^{16}\) reported that the prone position increased the end-expiratory lung volume at a given PEEP in 5 of 12 patients with ARDS, and suggested that alveolar recruitment may be a mechanism of improved oxygenation in some patients. Gattinoni et al.\(^5\) described the variation...
### Table 1. Results

<table>
<thead>
<tr>
<th></th>
<th>Positive End-expiratory Pressure 0</th>
<th>Positive End-expiratory Pressure 7</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Supine</td>
<td>Prone</td>
</tr>
<tr>
<td>Tidal ventilation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peak airway pressure (cm H₂O)</td>
<td>1.46 ± 0.47</td>
<td>1.40 ± 0.37</td>
</tr>
<tr>
<td>Esophageal pressure (cm H₂O)</td>
<td>8.95 ± 2.47</td>
<td>3.23 ± 3.87</td>
</tr>
<tr>
<td>Transpulmonary pressure (cm H₂O)</td>
<td>-7.36 ± 2.72</td>
<td>-1.77 ± 4.07</td>
</tr>
<tr>
<td>Chest wall elastance (cm H₂O/l)</td>
<td>5.78 ± 3.08</td>
<td>13.95 ± 6.22</td>
</tr>
<tr>
<td>Lung elastance (cm H₂O/l)</td>
<td>17.72 ± 7.11</td>
<td>17.63 ± 7.60</td>
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<tr>
<td>At relaxation volume</td>
<td></td>
<td></td>
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<tr>
<td>Esophageal pressure (cm H₂O)</td>
<td>7.30 [5.85, 9.51]</td>
<td>1.87 [0.80, 5.67]</td>
</tr>
<tr>
<td>Expiratory reserve volume (l)</td>
<td>0.20 [0.41, 0.15]</td>
<td>0.37 [0.66, 0.29]</td>
</tr>
</tbody>
</table>

Data are presented as mean ± SD, mean (95% CI), or median [quartile 1, quartile 3], depending on distribution. Pressure measurements during tidal ventilation were performed at end expiration.

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Fig. 2. Esophageal pressure measured at relaxation volume decreased from the supine to prone position. Each line corresponds to an individual patient.

Fig. 3. Expiratory reserve volume (ERV) measured at relaxation volume increased from the supine to prone position. Each line corresponds to an individual patient.

Fig. 4. Chest wall elastance measured at positive end-expiratory pressure (PEEP) 0 increased from supine to prone. Each line corresponds to an individual patient.
in recruitability of lung tissue in ARDS due to patient-to-patient differences in severity of lung disease. Use of esophageal manometry in prone patients may allow titration of ventilator settings specific to a patient’s physiology, and could elucidate the mechanisms of improved lung recruitment.

The concordance of the increases in transpulmonary pressure and those in lung volume suggest that esophageal manometry provides a useful estimate of an effective average pleural pressure during the transition between positions. Transpulmonary pressure increased on average by 5.54 cm H₂O at PEEP 0 and 4.96 cm H₂O at PEEP 7. Although esophageal pressure is known to be artefactually increased in the supine position because of the weight of mediastinal structures, the observed increase could not be simply due to artifact because lung volume also increased. Given the average elastance of the lung in our patients, this increase in transpulmonary pressure should have resulted in a 300-ml average increase in lung volume. However, we found that the volume of the lungs at relaxation volume increased by an average of 190 ml, which is somewhat less. This discrepancy may be due to the known artifact, which would cause the increase in lung volume associated with assumption of the prone position to be less than that predicted by the increase in transpulmonary pressure.

Driving pressure of the respiratory system (plateau pressure – PEEP) increased from the supine to prone position, while transpulmonary driving pressure did not change significantly. The increase in respiratory system driving pressure was due to increased chest wall elastance. Respiratory system driving pressure was reported to be superior to several other metrics in predicting mortality in patients with ARDS, and it was suggested that limiting driving pressure during mechanical ventilation might improve survival. The practice of limiting driving pressure has not been tested prospectively, but it would be important to keep the effects of the chest wall in mind in determining the best ventilator strategies for these patients. Transpulmonary driving pressure may be a more appropriate measure of pulmonary risk of injury when patients are undergoing positional change. In addition, transpulmonary driving pressures may be a better marker for individual mechanical ventilator parameters in the setting of elevated intraabdominal pressure due to various causes.

There are several limitations of our study. In this study we did perform a formal power calculation a priori. However, using our estimates from our data, we observe more than 99% power to detect a difference in transpulmonary pressure between the supine and prone positions. Furthermore, our esophageal pressure measurements cannot reveal potentially important changes in the cephalocaudal and dorsoventral gradients in pleural pressure caused by change in position. The changes in relaxation lung volume on assuming the prone position may be affected by both disease process and the structure of the operating bed. Both Jackson and Wilson (Mizuho OSI., USA) frames may allow the abdominal contents to fall away from the diaphragm, which could contribute significantly to these mechanisms.

Conclusions

Esophageal pressure decreases, and transpulmonary pressure and expiratory reserve volume increase, when patients are moved from the supine to prone position. This suggests that abdominal contents shifting caudally under the influence of gravity increase transpulmonary pressure and lung volume at a given PEEP. This may be one of the mechanisms for the observed clinical benefit with prone positioning.

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Competing Interests

The authors declare no competing interests.

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ANESTHESIOLOGY REFLECTIONS FROM THE WOOD LIBRARY-MUSEUM

The McKesson Oxygen Tent: The Role of the Rubber Sheet

By the early 1930s, physician-anesthetist Elmer Isaac “Ira” McKesson, M.D. (1881 to 1935), was developing the concepts behind his McKesson Oxygen Tent (above). To “prevent oxygen from passing through the mattress and escaping from the tent,” a rubber sheet was placed underneath the patient’s sheets and mattress cover. Through a large door in the cabinet, an ice box was completely filled “with cracked ice, the size of one’s fist.” Then, through a smaller door in some hospital-model cabinets, the carbon-dioxide absorber was filled with soda lime and returned to the cabinet. In 1935 as he lay dying from cancer, Dr. McKesson helped decide which of his many namesake oxygenating inventions would be used to ease his labored breathing. After McKesson’s death, his namesake oxygen tents were rented to hospitals by his onetime competitor, the Ohio Chemical and Manufacturing Company. A few years after Ohio’s advertisement above, instructions for using McKesson Oxygen Tents would be included in 1943 U.S. Army manuals. (Copyright © the American Society of Anesthesiologists’ Wood Library-Museum of Anesthesiology.)

George S. Bause, M.D., M.P.H., Honorary Curator and Laureate of the History of Anesthesia, Wood Library-Museum of Anesthesiology, Schaumburg, Illinois, and Clinical Associate Professor, Case Western Reserve University, Cleveland, Ohio. UJYC@aol.com.