Positive End-expiratory Pressure Improves Respiratory Function in Obese but not in Normal Subjects during Anesthesia and Paralysis

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Background: Morbidly obese patients, during anesthesia and paralysis, experience more severe impairment of respiratory mechanics and gas exchange than normal subjects. The authors hypothesized that positive end-expiratory pressure (PEEP) induces different responses in normal subjects (n = 9; body mass index < 25 kg/m²) versus obese patients (n = 9; body mass index > 40 kg/m²).

Methods: The authors measured lung volumes (helium technique), the elastances of the respiratory system, lung, and chest wall, the pressure-volume curves (occlusion technique and esophageal balloon), and the intraabdominal pressure (intrabladder catheter) at PEEP 0 and 10 cm H₂O in paralyzed, anesthetized postoperative patients in the intensive care unit or operating room after abdominal surgery.

Results: At PEEP 0 cm H₂O, obese patients had lower lung volume (0.59 ± 0.17 vs. 2.15 ± 0.58 l [mean ± SD], P < 0.01); higher elastances of the respiratory system (26.8 ± 4.2 vs. 16.4 ± 3.6 cm H₂O/l, P < 0.01), lung (17.4 ± 4.5 vs. 10.3 ± 3.2 cm H₂O/l, P < 0.01), and chest wall (9.4 ± 3.0 vs. 6.1 ± 1.4 cm H₂O/l, P < 0.01); and higher intraabdominal pressure (18.8 ± 7.8 vs. 9.0 ± 2.4 cm H₂O, P < 0.01) than normal subjects. The arterial oxygen tension was significantly lower (110 ± 30 vs. 218 ± 47 mmHg, P < 0.01; inspired oxygen fraction = 50%).

and the arterial carbon dioxide tension significantly higher (37.8 ± 6.8 vs. 28.4 ± 3.1, P < 0.01) in obese patients compared with normal subjects. Increasing PEEP to 10 cm H₂O significantly reduced elastances of the respiratory system, lung, and chest wall in obese patients but not in normal subjects. The pressure-volume curves were shifted upward and to the left in obese patients but were unchanged in normal subjects. The tension changes were significantly correlated with alveolar recruitment (r = 0.81, P < 0.01).

Conclusions: During anesthesia and paralysis, PEEP improves respiratory function in morbidly obese patients but not in normal subjects. (Key words: Mechanical ventilation, obesity; postoperative period.)

RESPIRATORY dysfunction is an important cause of postoperative injury and death after abdominal surgery in morbidly obese patients. These patients are characterized by a reduced lung volume compared with nonobese subjects, and it has been suggested that such reductions in lung volume are associated with a larger amount of atelectasis or airway closure. This results in arterial hypoxemia and marked alterations in respiratory mechanics, including increases in total respiratory system, lung and chest wall elastance, and lung resistance.

In mechanically ventilated normal subjects, the application of positive end-expiratory pressure (PEEP) increases lung volume and reopens atelectatic lung regions. Some authors have found that in normal anesthetized and paralyzed subjects before surgery PEEP only slightly improves respiratory mechanics; others have not. In any case, PEEP generally does not improve oxygenation both before and during surgery and is not currently recommended during anesthesia and paralysis in normal subjects. Thus, there is general agreement that the indiscriminate application of PEEP has no place in routine anesthesia in normal subjects.

We hypothesized that the lung collapse and alterations in respiratory mechanics are functions of increased body...
Table 1. Study Population

<table>
<thead>
<tr>
<th>Patient Number</th>
<th>Sex</th>
<th>Surgical Procedure</th>
<th>Age (yr)</th>
<th>Weight (kg)</th>
<th>Height (m)</th>
<th>BMI (kg/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>F</td>
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<td>24</td>
<td>60</td>
<td>1.65</td>
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<tr>
<td>2</td>
<td>M</td>
<td>Pancreatic pseudocystis</td>
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<td>70</td>
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<td>F</td>
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<td>5</td>
<td>M</td>
<td>Gastroresection</td>
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<td>1.81</td>
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<td>8</td>
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<td>Colon resection</td>
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<td>50</td>
<td>1.50</td>
<td>22.2</td>
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<tr>
<td>9</td>
<td>M</td>
<td>Colon resection</td>
<td>43</td>
<td>72</td>
<td>1.75</td>
<td>23.5</td>
</tr>
</tbody>
</table>

Mean ± SD 5M/4F 43.3 ± 15.2 66.4 ± 10.5 1.69 ± 0.10 23.1 ± 1.2

<table>
<thead>
<tr>
<th>Obese patients</th>
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<tr>
<td>10</td>
<td>F</td>
<td>Gastric binding</td>
<td>39</td>
<td>160</td>
<td>1.72</td>
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<tr>
<td>11</td>
<td>M</td>
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<td>34</td>
<td>150</td>
<td>1.79</td>
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<td>12</td>
<td>F</td>
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<td>43</td>
<td>135</td>
<td>1.62</td>
<td>51.4</td>
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<tr>
<td>13</td>
<td>M</td>
<td>Gastric binding</td>
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<td>225</td>
<td>1.92</td>
<td>61.0</td>
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<td>14</td>
<td>F</td>
<td>Gastric binding</td>
<td>52</td>
<td>105</td>
<td>1.58</td>
<td>42.1</td>
</tr>
<tr>
<td>15</td>
<td>F</td>
<td>Gastric binding</td>
<td>35</td>
<td>144</td>
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<td>47.2</td>
</tr>
<tr>
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<td>F</td>
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<td>1.60</td>
<td>46.9</td>
</tr>
<tr>
<td>17</td>
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<td>Gastric binding</td>
<td>68</td>
<td>160</td>
<td>1.55</td>
<td>66.6</td>
</tr>
<tr>
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<td>M</td>
<td>Ileojunal bypass</td>
<td>43</td>
<td>132.5</td>
<td>1.75</td>
<td>43.3</td>
</tr>
</tbody>
</table>

Mean ± SD 3M/6F 43.4 ± 14.4 147.9 ± 34.1 1.70 ± 0.12 51.0 ± 8.2

BMI = body mass index.

mass index and intraabdominal pressure. Thus, morbidly obese patients should have a greater potential for alveolar collapse. In the present investigation, we tested the hypothesis that PEEP is more effective in preventing atelectasis, improving respiratory mechanics and oxygenation in morbidly obese patients compared to normal subjects.

Materials and Methods

Study Population

The investigation was approved by the ethics committee of our institution, and informed consent was obtained from each subject preoperatively.

Normal Subjects. Nine normal subjects (five males) scheduled for abdominal surgery were included in the study. Their anthropometric and clinical characteristics are shown in table 1. Mean age and body mass index were 43.3 ± 15.2 yr (range, 24–66 yr) and 23.1 ± 1.2 kg/m² (range, 21.1–24.8 kg/m²), respectively. None had a history of smoking or clinical evidence of cardiopulmonary disease.

Obese Patients. Nine morbidly obese patients (three males) admitted to the intensive care unit of our institution after abdominal surgery for ileojejunal bypass or gastric binding were included in the study (see table 1). Mean age and body mass index were 43.4 ± 14.4 yr (range, 19–68 yr) and 51.0 ± 8.2 kg/m² (range, 42.1–66.6 kg/m²), respectively. None of the patients had a history of smoking or clinical evidence of cardiopulmonary disease. Their preoperative pulmonary function tests, done in seated position, were as follows: Average forced vital capacity was 93.5 ± 8.8% of predicted, the forced expiratory volume in 1 s was 92.4 ± 8.6% of predicted, and the ratio of the latter to the former was 96.6 ± 8.8% of predicted. The average arterial blood-gas measurements during spontaneous ventilation in room air, before surgical intervention, included arterial oxygen tension (PaO₂) of 88 ± 9 mmHg, arterial carbon dioxide tension (PaCO₂) of 39±2 mmHg, and pH of 7.41 ± 0.02.

Anesthesia Procedure during the Surgery. In normal subjects and in obese patients anesthesia was induced with intravenous thiopental sodium (5–7 mg/kg). Muscle relaxation to facilitate endotracheal intubation was provided with succinylcholine (1 mg/kg), and maintenance of paralysis with pancuronium bromide. They were intubated with auffed endotracheal tube (Portex Ltd., Hythe, Kent, United Kingdom) and mechanically ventilated (tidal volume 8–12 ml/kg ideal body weight, and respiratory rate to maintain PaCO₂, between 35 and 45 mmHg) during the surgical procedure. Anesthesia was maintained with isoflurane 0.5–1.0% in 50/50% O₂/N₂O and boluses of fentanyl, if appropriate.

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Protocol Procedure. Normal subjects were studied in the recovery room about 20 min after the end of the surgical procedure; obese patients were immediately transported to the intensive care unit, still anesthetized and paralyzed. In obese patients, the entire protocol was performed in the intensive care unit after they reached respiratory and hemodynamic stability as judged by the physician in charge (137 ± 50 min after the end of the surgical procedure).

During the protocol, both normal subjects and obese patients were anesthetized with diazepam (0.1–0.2 mg/kg), paralyzed with pancuronium bromide (0.1–0.2 mg/kg), and mechanically ventilated with a ventilator (Siemens Servo 900C, Siemens-Elema, Solna, Sweden) in volume control mode (I:E ratio equal to 3:3) with constant inspiratory flow (average tidal volume 0.683 ± 0.045 I [0.010 ± 0.001 I/kg ideal body weight] and 0.681 ± 0.040 I [0.010 ± 0.002 I/kg ideal body weight], inspiratory flow 0.488 ± 0.031 l/s and 0.480 ± 0.120 l/s, and respiratory rate 13.8 ± 0.7 breaths/min and 13.9±0.3 breaths/min in normal subjects and in obese patients, respectively). Inspiratory oxygen fraction was maintained equal to 50% during the entire protocol.

In all patients, we measured gas exchange; elastic and flow-resistant properties of the respiratory system, lung, and chest wall; and end-expiratory lung volume at two different PEEP levels (0 and 10 cm H2O) in normal subjects and in obese patients, applied in random order and maintained for at least 25–30 min. All measurements were made during the last 5 to 10 min of each level of PEEP. No previous volume history maneuver had been used in either group before starting the protocol. Other than changing PEEP level, baseline ventilatory settings were kept constant in each patient throughout the experiment. The entire protocol lasted about 1 h.

Physiologic Measurements
All the measurements were performed in supine position, without any abdominal bandage.

Intraabdominal Pressure. Intraabdominal pressure was measured using a transurethral bladder catheter. The technique has been previously reported and validated. Using a sterile technique, 100 ml normal saline was infused through the urinary catheter into the bladder. The catheter was then clamped and intraabdominal pressure recorded by a pressure transducer as mean pressure at end-expiration. The zero was set at the level of the pubis. The intraabdominal pressure was measured in only six out of nine normal subjects, those who had the bladder catheter already inserted for clinical purposes.

End-expiratory Lung Volume. The end-expiratory lung volume was measured at end-expiration, at 0 cm H2O of PEEP, and at 10 cm H2O of PEEP using a closed-circuit helium dilution method. The expected end-expiratory lung volume was computed according to the formula derived from normal awake supine subjects.

Respiratory Mechanics. Airway pressure (Paw) was measured proximal to the endotracheal tube by using polyethylene tubing (2 mm inner diameter, 120 cm long), connected to a Bentley Trantec pressure transducer (Irvine, CA). Gas flow was recorded by using a heated pneumotachograph (Hans Rudolph, Kansas City, MO) connected to an MP 45-1 differential pressure transducer (Validyne, Northridge, CA). Volume was obtained by digital integration of the flow signal.

Esophageal pressure (Pes) was measured from an esophageal balloon (Bicore CP-100, Irvine, CA) inflated with 0.5–1.0 ml of air, positioned at the lower third of the esophagus. The validity of Pes was verified, according to Baydur et al. Because the patients were paralyzed, the airway and esophageal pressure were altered by compressing the thorax with the airways occluded at end-expiration. One could question the accuracy of Pes in obese patients while supine. Mediastinal organs may compress the esophagus and invalidate the translation into a pleural pressure. However, no alternative methods are available in humans, and this method has been previously adopted to partition respiratory mechanics in both awake and paralyzed obese patients in supine and prone positions.

Both flow and pressure signals were recorded on a personal computer and processed via an analog-to-digital converter (Colligo; Elekton, Milan, Italy) at a sample rate of 200 Hz and stored for subsequent computer analysis.

To determine the static elastance of total respiratory system, lung and chest wall, Paw and Pes were recorded during a 4 to 5 s airway occlusion at end-expiration and at end-inspiration. The pressure-volume (P-V) curves of the total respiratory system, lung, and chest wall were measured by inflating the respiratory system at different volumes (from 0.1 to 1.0 l, in 100-ml steps) and recording the corresponding Paw and Pes during airways occlusion at end-inspiration. End-expiratory volume corresponded to the elastic equilibrium volume in each patient, as evidenced by zero flow during an expiratory pause and absence of changes in Paw after airway occlusion.

Quantitative Analysis of Respiratory Mechanics
Static elastance of the total respiratory system was computed as ∆Paaw/VT, where ∆Paaw is the difference be-
between end-inspiratory and end-expiratory airway pressures and \( V_T \) is the tidal volume. Static elastance of the chest wall was computed as \( \Delta P_{es}/V_T \), where \( \Delta P_{es} \) is the difference between end-inspiratory and end-expiratory esophageal pressures. Static lung elastance was calculated as respiratory system elastance minus chest wall elastance.

From the P-V curve we derived the following parameters:

1. **Starting elastance:** This was computed as the ratio between the pressure at 100 ml inflation and the corresponding volume. The starting elastance at PEEP 0 cm H\(_2\)O likely reflects the mechanical characteristics of the respiratory system at end-expiration. In fact, during the measurement of the starting elastance it is unlikely that any significant alveolar recruitment or small airway reopening occur, because of the low pressures used.

2. **Inflation elastance:** This was computed as the slope of the P-V curve during inflation in its most linear segment; to do so we excluded by visual inspection the points included in the inflection region. Throughout the remaining points of the inflation limb we performed a linear regression. The reciprocal of the slope of the linear regression was defined as the value after occlusion corrected for the tube resistance (which was determined experimentally), \( P_t \) is the pressure recorded after the immediate drop from \( P_{max} \), \( P_{e} \) is the plateau pressure, and \( V'_t \) is the flow immediately preceding the occlusion. The minimum resistance represents the "ohmic" resistive component of the respiratory system, and the maximum resistance includes the minimum plus the "additional" respiratory resistance caused by stress relaxation or time constant inequalities within the respiratory system tissues. There was no appreciable decrease in \( P_{es} \) immediately after the occlusion (i.e., \( P_t \) in the esophageal tracings was not identifiable); the minimum resistance of the respiratory system reflects essentially airway resistance; and minimum chest wall resistance can be considered negligible. As a consequence, maximum chest wall resistance results entirely from to the viscoelastic properties of the chest wall tissues. Additional resistance of the lung was obtained as additional respiratory resistance minus additional chest wall resistance; the sum of minimum lung resistance and additional lung resistance gives the maximum lung resistance. Additional lung and chest wall resistances result from stress relaxation or time constant inequalities within the lung and chest wall, respectively.

3. **Lower inflection point:** This was computed as the pressure corresponding to the intersection between the starting and inflation elastance obtained by a computerized system.

4. **Inflation to starting elastance:** This was computed as a quantitative estimate of the curvilinearity of the P-V curve.

At PEEP these computations were performed as a change from the end-expiratory pressure.

**Estimation of "Recruited" Alveolar Volume**

We first computed the difference of gas volume measured with helium at 10 cm H\(_2\)O and 0 cm H\(_2\)O pressure (actual \( \Delta \) gas volume). We then computed on the P-V curve, starting at PEEP 0 cm H\(_2\)O, the gas volume expected at 10 cm H\(_2\)O. We defined as recruitment the difference between the actual \( \Delta \) gas volume and the expected \( \Delta \) gas volume.

**Resistances of the Total Respiratory System, Lung, and Chest Wall**

Maximum and minimum resistances of the respiratory system were computed from \( P_{aw} \) as \( (P_{max}' - P_t)/V'_t \) and \( (P_{max}' - P_t)/V'_t \), where \( P_{max}' \) is the maximal pressure value after occlusion corrected for the tube resistance (which was determined experimentally), \( P_t \) is the pressure recorded after the immediate drop from \( P_{max} \), \( P_{e} \) is the plateau pressure, and \( V'_t \) is the flow immediately preceding the occlusion. The minimum resistance represents the "ohmic" resistive component of the respiratory system, and the maximum resistance includes the minimum plus the "additional" respiratory resistance caused by stress relaxation or time constant inequalities within the respiratory system tissues. There was no appreciable decrease in \( P_{es} \) immediately after the occlusion (i.e., \( P_t \) in the esophageal tracings was not identifiable); the minimum resistance of the respiratory system reflects essentially airway resistance; and minimum chest wall resistance can be considered negligible. As a consequence, maximum chest wall resistance results entirely from to the viscoelastic properties of the chest wall tissues. Additional resistance of the lung was obtained as additional respiratory resistance minus additional chest wall resistance; the sum of minimum lung resistance and additional lung resistance gives the maximum lung resistance. Additional lung and chest wall resistances result from stress relaxation or time constant inequalities within the lung and chest wall, respectively.

**Gas-exchange Parameters**

Arterial blood samples from the radial artery were analyzed for \( pH, P_{aO_2}, \) and \( P_{aCO_2} \) by a blood-gas analyzer (IL 1312 BGM; Instrumentation Laboratory Company, Lexington, MA). Expired gases were collected over a 3-min period in a Douglas bag at the same time as blood-gas samples. Expired gas was analyzed for mixed expired carbon dioxide concentration (Normocap, Datex, Finland). The physiologic dead-space fraction (\( V_d/V_T \)) was computed according to the following formula:

\[
V_d/V_T = (P_{aCO_2} - P_{eCO_2})/P_{aCO_2}
\]

where \( P_{eCO_2} \) is the mixed expired carbon dioxide partial pressure.

**Statistical Analysis**

Values are expressed as mean ± SD. The mean value of three breaths was used for each variable and for each experimental condition. Comparisons between normal subjects and obese patients were performed using the unpaired Student \( t \) test at both PEEP 0 and 10 cm H\(_2\)O. Values obtained at PEEP 10 cm H\(_2\)O were compared with PEEP 0 cm H\(_2\)O using the two-way analysis of variance. Regression analysis was performed with the least-squares method.
Table 2. Intraabdominal Pressure, Lung Volume, and Elastances of the Total Respiratory System and Lung and Chest Wall at Different PEEP Levels

<table>
<thead>
<tr>
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<th>0 cm H₂O</th>
<th>10 cm H₂O</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Normal</td>
<td>Obese</td>
</tr>
<tr>
<td>IAP (cm H₂O)</td>
<td>9.0 ± 2.4</td>
<td>18.8 ± 7.8**</td>
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<tr>
<td>EELV (l)</td>
<td>2.154 ± 0.584</td>
<td>0.587 ± 0.175**</td>
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<tr>
<td>Ers (cm H₂O/l)</td>
<td>16.39 ± 3.65</td>
<td>26.80 ± 4.20**</td>
</tr>
<tr>
<td>E,L (cm H₂O/l)</td>
<td>10.28 ± 3.24</td>
<td>17.38 ± 4.50**</td>
</tr>
<tr>
<td>E,cw (cm H₂O/l)</td>
<td>6.07 ± 1.43</td>
<td>9.41 ± 3.02**</td>
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</table>

Values are mean ± SD.

PEEP = positive end-expiratory pressure; IAP = intraabdominal pressure; EELV = end-expiratory lung volume; E = static elastance; rs = total respiratory system; L = lung; cw = chest wall.

Unpaired t test: *P < 0.05, **P < 0.01 versus normal.

Paired t test: †P < 0.05, ‡P < 0.01 versus 0 cm H₂O PEEP.

Results

Lung Volume; Elastances of the Total Respiratory System, Lung, and Chest Wall; and Intraabdominal Pressure at Different PEEP Levels

Table 2 summarizes some of the most relevant mechanical variables of the normal subjects and obese patients after surgery and their changes with PEEP. It is noteworthy that although in normal subjects the measured end-expiratory lung volume at PEEP 0 cm H₂O was similar to the end-expiratory lung volume expected (2.154 ± 0.584 vs. 2.271 ± 0.454 l, P not significant), in obese patients it was only 28% of expected (0.587 ± 0.175 vs. 2.209 ± 0.596 l, respectively; P < 0.01).

At PEEP 0 cm H₂O the elastances of the respiratory system, lung, and chest wall were significantly higher in obese patients compared with normal subjects. In obese patients the elastance of the total respiratory system significantly decreased with PEEP, because of a similar reduction in lung and chest wall elastance. In normal subjects, however, PEEP produced a slight reduction in lung elastance, without affecting total respiratory system and chest wall elastance.

Finally, it is worth noting that, on average, the intraabdominal pressure was almost twofold greater in obese patients compared with normal subjects (18.8 ± 7.8 vs. 9.0 ± 2.4 cm H₂O, P < 0.01). However, unexpectedly, the two most severe obese patients had intraabdominal pressures in the range observed in normal subjects, (patients 13 and 17, intraabdominal pressure = 9 and 8 cm H₂O, respectively).

Pressure–Volume Curve of the Total Respiratory System, Lung, and Chest Wall

In figure 1, the P–V curves of the total respiratory system, lung, and chest wall are reported for both normal and obese patients. In normal subjects the P–V curves at PEEP 0 and 10 cm H₂O roughly follow the same pattern. In the obese patients, however, the P–V curves at 10 cm H₂O of PEEP are shifted upward and to the left, suggesting alveolar recruitment.

The quantitative analysis of P–V curves is reported in table 3. As shown, the inflation and starting elastances derived from the P–V curve behave as the “cord elastances” (i.e., the elastances measured as Δpressure/Δvolume between end-inspiration and end-expiration and reported in table 2). Two additional pieces of information, however, may be derived from the P–V curve. First, the ratio of inflation elastance to starting elastances of the total respiratory system, lung, and chest wall, which estimates the curvilinearity of the P–V curve, is similar in obese patients and normal subjects at PEEP 0 cm H₂O, and in both populations, with increasing PEEP, the ratio tends to increase, indicating a more linear P–V curve at 10 cm H₂O of PEEP. Finally, the lower inflection point (Pinflex) of the total respiratory system was significantly higher at PEEP 0 cm H₂O in the obese patients and decreased with PEEP. However, at 10 cm H₂O PEEP, the obese patients and normal subjects showed similar Pinflex values.

Resistances

The resistances of the total respiratory system, lung, and chest wall in both normal and obese patients at PEEP 0 and 10 cm H₂O are shown in table 4. At PEEP 0 cm H₂O, maximum and additional resistance of the total respiratory system were significantly higher in obese patients compared with normal subjects. This increase resulted mainly from maximum and additional lung resistance. On the other hand, airway and chest wall resistances were similar in normal subjects and in obese

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patients. PEEP significantly decreased maximum resistance of the total respiratory system mainly by reducing the lung component, but the effect was more evident in obese patients than in normal subjects. The decrease in maximum lung resistance with PEEP was prevalent in the airway resistance component both in normal subjects and in obese patients.

**Gas Exchange and Recruitment**

As shown in table 5, despite similar minute ventilation and identical inspired oxygen fraction, the obese patients had significantly lower Pao2 values, higher alveolar-arterial oxygen difference, higher PaCO2 values, and higher physiologic dead-space fraction compared with normal subjects. The normal subjects did not show any significant change in gas exchange on increase of PEEP; the obese patients had significantly increased Pao2 values and decreased alveolar-arterial oxygen differences. However, the differences in Pao2, alveolar-arterial oxygen difference, PaCO2, and dead space remained significant between obese and normal subjects also at 10 cm H2O of PEEP. It is noteworthy that, although the average changes of Pao2 in normal subjects were not significant with increasing PEEP, in seven of nine normal patients the Pao2 actually decreased; Pao2 decreased in only one of nine obese patients.

The recruitment was significantly higher in obese patients compared with normal subjects (0.153 ± 0.168 and −0.060 ± 0.246 l, respectively; \( P < 0.05 \)). In the whole study population (normal and obese) the increase of Pao2 with PEEP was significantly correlated with recruitment (\( r = 0.81, P < 0.01 \); fig. 2) as the alveolar-arterial oxygen difference (\( r = 0.74, P < 0.01 \)). As shown, the normal subjects are mostly located in the nonrecruitment area (and did not have increases in Pao2), except for one normal subject (patient 8) who had
Table 3. Parameters of the Pressure-Volume Curves at Different PEEP Levels

<table>
<thead>
<tr>
<th></th>
<th>Normal 0 cm H2O</th>
<th>Obese 0 cm H2O</th>
<th>Normal 10 cm H2O</th>
<th>Obese 10 cm H2O</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Respiratory system (rs)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>$E_{elast}$ (cm H2O/l)</td>
<td>25.00 ± 5.50</td>
<td>43.76 ± 12.74**</td>
<td>12.33 ± 5.50‡</td>
<td>16.06 ± 4.32‡</td>
</tr>
<tr>
<td>$E_{es}$ (cm H2O/l)</td>
<td>15.00 ± 4.38</td>
<td>25.24 ± 6.98**</td>
<td>15.86 ± 4.37‡</td>
<td>17.44 ± 2.07‡</td>
</tr>
<tr>
<td>$E_{es}/E_{es}$</td>
<td>0.62 ± 0.23</td>
<td>0.60 ± 0.15</td>
<td>1.46 ± 0.65‡</td>
<td>1.13 ± 0.20‡</td>
</tr>
<tr>
<td>$P_{es}$ (cm H2O)</td>
<td>2.32 ± 1.71</td>
<td>8.39 ± 3.01**</td>
<td>1.58 ± 1.66‡</td>
<td>2.51 ± 0.67‡</td>
</tr>
<tr>
<td><strong>Lung (L)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$E_{max}$ (cm H2O/l)</td>
<td>17.00 ± 5.63</td>
<td>28.89 ± 9.12**</td>
<td>7.44 ± 5.96‡</td>
<td>10.32 ± 2.81‡</td>
</tr>
<tr>
<td>$E_{es}$ (cm H2O/l)</td>
<td>9.20 ± 3.45</td>
<td>16.64 ± 7.37*</td>
<td>9.21 ± 4.75‡</td>
<td>11.00 ± 1.52</td>
</tr>
<tr>
<td>$E_{es}/E_{max}$</td>
<td>0.59 ± 0.33</td>
<td>0.59 ± 0.21</td>
<td>2.52 ± 2.83‡</td>
<td>1.14 ± 0.32‡</td>
</tr>
<tr>
<td>$P_{max}$ (cm H2O)</td>
<td>1.94 ± 1.00</td>
<td>5.71 ± 3.18**</td>
<td>0.28 ± 0.55‡</td>
<td>1.61 ± 0.66‡</td>
</tr>
<tr>
<td><strong>Chest wall (cw)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$E_{max}$ (cm H2O/l)</td>
<td>8.00 ± 3.04</td>
<td>14.89 ± 5.49**</td>
<td>6.00 ± 2.69‡</td>
<td>5.73 ± 2.45‡</td>
</tr>
<tr>
<td>$E_{es}$ (cm H2O/l)</td>
<td>5.96 ± 1.32</td>
<td>8.72 ± 4.00</td>
<td>6.69 ± 2.14‡</td>
<td>6.44 ± 2.39‡</td>
</tr>
<tr>
<td>$E_{es}/E_{max}$</td>
<td>0.84 ± 0.40</td>
<td>0.63 ± 0.23</td>
<td>1.37 ± 0.94‡</td>
<td>1.18 ± 0.25‡</td>
</tr>
<tr>
<td>$P_{max}$ (cm H2O)</td>
<td>0.60 ± 0.54</td>
<td>2.60 ± 1.72**</td>
<td>0.41 ± 0.50‡</td>
<td>1.00 ± 0.49**‡</td>
</tr>
</tbody>
</table>

Data are mean ± SD.
PEEP = positive end-expiratory pressure; $E$ = static elastance; $E_{es}$ = starting; $E_{es}/E_{es}$ = inflation; $P_{es}$ = lower inflection point. 
Unpaired $t$ test: *$P < 0.05$, **$P < 0.01$ versus normal.
Paired $t$ test: †$P < 0.05$, ‡$P < 0.01$ versus 0 cm H2O PEEP.

a consistent recruitment and $P_{aO_2}$ increased and experienced the same effects as the obese patients. It is noteworthy that the statistical significance of figure 2 results entirely from the obese patients (for this population alone, $r = 0.95$, $P < 0.01$); the marginal recruitment, or even derecruitment, observed in the normal population considered alone was not correlated significantly with the $P_{aO_2}$ changes.

**Relationships among Body Weight, Intraabdominal Pressure, Lung Volumes, Respiratory Mechanics, and Gas Exchange**

In the whole population, at PEEP 0 cm H2O, we found a significant correlation between the body mass index and decreased end-expiratory lung volume ($r = 0.83$, $P < 0.01$), increased elastance of the respiratory system ($r = 0.86$, $P < 0.01$), decreased $P_{aO_2}$ ($r = 0.72$, $P < 0.01$), and increased $P_{aCO_2}$ ($r = 0.62$, $P < 0.01$). The chest wall elastance was significantly correlated with decreased end-expiratory lung volume ($r = 0.68$, $P < 0.01$), decreased $P_{aO_2}$ ($r = 0.62$, $P < 0.01$), and increased $P_{aCO_2}$ ($r = 0.77$, $P < 0.01$).

As the chest wall elastance appears to be a function of intraabdominal pressure ($r = 0.94$, $P < 0.01$; fig. 3), it is tempting to hypothesize the following sequence of events: Increasing body mass leads to increased intraabdominal pressure, which in turn, by decreasing the chest wall elastance, causes lung volume reduction and gas-

Table 4. Resistances of the Total Respiratory System and Lung and Chest Wall at Different PEEP Levels

<table>
<thead>
<tr>
<th></th>
<th>Normal 0 cm H2O</th>
<th>Obese 0 cm H2O</th>
<th>Normal 10 cm H2O</th>
<th>Obese 10 cm H2O</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_{rs}$ (cm H2O·l⁻¹·s)</td>
<td>7.7 ± 2.9</td>
<td>13.4 ± 4.7**</td>
<td>5.9 ± 3.3</td>
<td>8.9 ± 3.7‡</td>
</tr>
<tr>
<td>$\Delta R_{rs}$ (cm H2O·l⁻¹·s)</td>
<td>2.1 ± 0.8</td>
<td>5.1 ± 2.7**</td>
<td>2.8 ± 0.9</td>
<td>3.6 ± 1.1‡</td>
</tr>
<tr>
<td>$R_{L}$ (cm H2O·l⁻¹·s)</td>
<td>6.9 ± 2.9</td>
<td>11.9 ± 5.3*</td>
<td>4.5 ± 3.0‡</td>
<td>7.9 ± 4.2‡†</td>
</tr>
<tr>
<td>$R_{min,L}$ (cm H2O·l⁻¹·s)</td>
<td>5.6 ± 2.8</td>
<td>8.3 ± 5.1</td>
<td>3.1 ± 0.3‡</td>
<td>5.3 ± 3.5‡†</td>
</tr>
<tr>
<td>$\Delta R_{L}$ (cm H2O·l⁻¹·s)</td>
<td>1.3 ± 0.5</td>
<td>3.7 ± 1.9**</td>
<td>1.4 ± 0.7</td>
<td>2.4 ± 1.2*‡</td>
</tr>
<tr>
<td>$\Delta R_{cw}$ (cm H2O·l⁻¹·s)</td>
<td>0.8 ± 0.4</td>
<td>1.5 ± 1.1</td>
<td>1.4 ± 0.7‡</td>
<td>1.0 ± 1.0</td>
</tr>
</tbody>
</table>

Values are mean ± SD.
PEEP = positive end-expiratory pressure; $R_{rs}$ = maximum resistance of the respiratory system; $\Delta R_{rs}$ = "additional" resistance of the respiratory system; $R_{L}$ = maximum resistance of the lung; $R_{min,L}$ = alveolar resistance; $\Delta R_{L}$ = "additional" resistance of the lung; $\Delta R_{cw}$ = resistance of the chest wall.
Unpaired $t$ test: *$P < 0.05$, **$P < 0.01$ versus normal.
Paired $t$ test: †$P < 0.05$, ‡$P < 0.01$ versus 0 cm H2O PEEP.
Table 5. Gas Exchange at Different PEEP Levels

<table>
<thead>
<tr>
<th></th>
<th>Normal</th>
<th>Obese</th>
<th>Normal</th>
<th>Obese</th>
</tr>
</thead>
<tbody>
<tr>
<td>( V_t ) (l/min)</td>
<td>9.41 ± 0.77</td>
<td>9.54 ± 0.53</td>
<td>9.41 ± 0.56</td>
<td>9.16 ± 0.68</td>
</tr>
<tr>
<td>( F_{I_{2}} ) (%)</td>
<td>50 ± 0</td>
<td>50 ± 0</td>
<td>50 ± 0</td>
<td>50 ± 0</td>
</tr>
<tr>
<td>( P_{A}O_{2} ) (mmHg)</td>
<td>218.1 ± 47.0</td>
<td>110.2 ± 29.6**</td>
<td>215.3 ± 47.3</td>
<td>130.0 ± 28.0**×</td>
</tr>
<tr>
<td>( \Delta P_{A}O_{2} ) (mmHg)</td>
<td>110.0 ± 45.6</td>
<td>208.5 ± 30.5**</td>
<td>113.3 ± 86.8</td>
<td>187.3 ± 30.2**×</td>
</tr>
<tr>
<td>( P_{ECO_{2}} ) (mmHg)</td>
<td>28.4 ± 3.1</td>
<td>37.8 ± 6.8**</td>
<td>27.8 ± 5.7</td>
<td>39.4 ± 4.9**</td>
</tr>
<tr>
<td>( pH_{a} )</td>
<td>7.45 ± 0.07</td>
<td>7.38 ± 0.06</td>
<td>7.46 ± 0.09</td>
<td>7.38 ± 0.05*</td>
</tr>
<tr>
<td>( V_{D}/V_{T} ) (%)</td>
<td>28.7 ± 6.6</td>
<td>47.7 ± 22.2*</td>
<td>27.4 ± 4.5</td>
<td>49.0 ± 15.0**</td>
</tr>
</tbody>
</table>

Values are mean ± SD.

PEEP = positive end-expiratory pressure; \( V_t \) = total minute ventilation; \( F_{I_{2}} \) = oxygen inspiratory fraction; \( \Delta P_{A}O_{2} \) = alveolar-arterial oxygen difference; \( V_{D}/V_{T} \) = physiologic dead space.

Unpaired t test: \( *P < 0.05, **P < 0.01 \) versus normal.

Paired t test: \( tP < 0.01 \) versus 0 cm H\(_{2}O\) PEEP.

Discussion

In this study, we found remarkable differences at PEEP 0 cm H\(_{2}O\) in lung volumes, respiratory mechanics, and gas exchange in the early postoperative period, during anesthesia and paralysis, between normal and morbidly obese patients.

Moreover, we found that increasing PEEP to 10 cm H\(_{2}O\) led to a significant improvement of respiratory mechanics and gas exchange in the obese patients but not in normal subjects. We discuss the possible mechanisms underlying the differences we found between normal subjects and obese patients at PEEP 0 cm H\(_{2}O\), and their different responses to PEEP 10 cm H\(_{2}O\).

Lung Volumes, Respiratory Mechanics, and Gas Exchange at PEEP 0 cm H\(_{2}O\)

Reportedly, the end-expiratory lung volumes of obese patients before anesthesia and paralysis, as well as lung and chest wall elastances, are similar to normal.\(^\text{15}\) Damia \textit{et al.},\(^\text{16}\) using the same method of measurement we used, found normal values of end-expiratory lung volume in a population of morbidly obese patients before anesthesia. Indeed, despite the fact that preanesthetic end-expiratory lung volume values of our obese patients

Fig. 2. Relationship between arterial oxygen tension changes and alveolar recruitment with positive end-expiratory pressure in normal subjects (black circles) and obese patients (white circles).

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were likely similar to normal, as also suggested by the preoperative pulmonary function tests, the end-expiratory lung volume decrease during anesthesia and paralysis was dramatically different in obese patients compared with normal subjects. It is tempting to speculate that the cause of the end-expiratory lung volume decrease is the increased abdominal pressure unopposed by the diaphragm tone during anesthesia and paralysis.\textsuperscript{20,27} In fact, we found that, on average, the obese patients were characterized by an increased intraabdominal pressure. Moreover, increased abdominal pressure was associated with a reduction in end-expiratory lung volume and increased chest wall and respiratory system elastances. It is possible that the increased chest wall elastance led to a decrease of transpulmonary pressure, with consequent lung-size reduction or collapse. The importance of intraabdominal pressure is underlined by the findings of Damia et al.,\textsuperscript{10} who observed that, after opening of the abdominal wall, the lung volume in obese patients almost returned to the preanesthesia values.

However, the increased intraabdominal pressure may not entirely explain the end-expiratory lung volume reduction. In fact, we were not able to find any significant relationship between intraabdominal pressure and the body mass index; in the two patients with the highest body mass indices the intraabdominal pressure and the chest wall elastance were near normal, and the lung volume was greatly decreased. Moreover, in a previous study,\textsuperscript{28} we found that increasing the intraabdominal pressure up to 20 cm H\textsubscript{2}O during laparoscopy in normal subjects during anesthesia and paralysis resulted only in a moderate decrease in end-expiratory lung volume (about 20\%). These findings suggest that intraabdominal pressure is not the unique cause of end-expiratory lung volume reduction, and other factors are likely involved, such as the blood shift from abdomen to thorax\textsuperscript{29} and the distortion of the rib cage, without diaphragm displacement.\textsuperscript{40,51} Indeed, the exact mechanism leading to end-expiratory lung volume decrease remains an open question.

Whatever the cause of end-expiratory lung volume reduction, the respiratory mechanics are more affected in obese patients than in normal subjects. In obese patients lung and chest wall elastances are twofold greater than in normal patients, and the P-V curves show a greater inflection point, resulting from both the lung and chest wall components. It is known that, during anesthesia and paralysis, even normal subjects increase elastance, and reportedly\textsuperscript{52} the major component of the changes in elastance is the lung rather than the chest wall. Several mechanisms have been proposed to explain the elastance changes: Besides the reduction of end-expiratory lung volume, other factors may be involved, such as the distortion of rib cage (and lung), the cephalad shift of the diaphragm, surfactant alteration, blood shift from abdomen to thorax, or a combination of these.\textsuperscript{53-55}

Reduced end-expiratory lung volume and increased elastance are associated with a more severe deterioration in gas exchange in obese patients compared with normal subjects, who show a milder abnormality in alveolar-arterial oxygen difference. Several mechanisms have been proposed to explain the gas-exchange deterioration during anesthesia in normal subjects, such as small-airspace collapse\textsuperscript{36} and altered ventilation distribution with consequent ventilation-perfusion (\(V_{A}/Q\)) mismatch,\textsuperscript{7} and compression atelectasis with alveolar collapse and true shunt.\textsuperscript{57} It is likely that the mechanisms leading to the deterioration of gas exchange in normal subjects are operating to a higher degree in the obese patients. In fact, in the obese patients, the lower lung volume should enhance the small-airways collapse, with higher degree of \(V_{A}/Q\) mismatch, as also suggested by the increased \(P_{a}CO_{2}\) and dead space compared with normal. Moreover, it has been shown that the compression atelectasis increases with body size,\textsuperscript{58} and although we lack direct evidence, it is likely that compression atelectasis and true shunt are higher in obese patients compared with normal subjects.

**PEEP Response**

Raising the PEEP in normal subjects to 10 cm H\textsubscript{2}O neither increased \(P_{a}O_{2}\) nor decreased the alveolar-arterial oxygen difference; in the obese patients, it did so. As we did not measure the hemodynamics or the \(V_{A}/Q\) distribution, any explanation of our findings is only speculative. The role of PEEP in anesthesia remains controversial, as some authors have found a variable response to oxygenation in different subsets of patients and clinical conditions.\textsuperscript{7,12,13,59} It is well known that increasing PEEP may both improve or deteriorate \(P_{a}O_{2}\). The resolution of atelectasis, if present, should increase \(P_{a}O_{2}\), and the prevention of small-airways closure should improve the \(V_{A}/Q\) matching. Furthermore, PEEP, increasing lung volume, should induce a more even distribution of ventilation, with possible improvement of \(V_{A}/Q\). On the other hand, increasing PEEP may induce overstretching of pulmonary units and cardiac output decrease or redistribution, with possible negative effects on \(V_{A}/Q\) and...
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The failure to improve oxygenation in normal subjects has been attributed to the contemporary decrease of cardiac output with PEEP. It is then likely that the positive effect of PEEP on the obese patients outweighs its negative effects, but in normal subjects the positive and negative effect of PEEP seem balanced, resulting in unchanged oxygenation.

Although we do not have the "gold standard" for the recruitment evaluation (i.e., computed tomographic scan), several indirect findings suggest that the collapse is greater in obese patients than in normal subjects. In fact, the obese patients have lower lung volume, greater elastance, and evident lower inflection point. Consequently, the PEEP in obese patients induces recruitment, as suggested by the upward shift of the P-V curve and the decrease of inflection point, and the higher the recruitment, the higher the increase in oxygenation, as shown in figure 2. We thus believe that obesity leads to conditions under which the positive effects of PEEP outweigh its potential negative effects.

Possible Clinical Consequences

From the body of these data it is tempting to present an overall interpretation of the effects on the obese patients during anesthesia and paralysis. It appears that anesthesia and paralysis cause the reduction of the lung volume through a continuum related to the body mass index. The reduction of lung volume is associated to an increase of the elastance of the respiratory system, equally divided between its chest wall and lung components. From our data it seems that increased intrathoracic pressure may play an important (although not unique) role in increasing the chest wall elastance and decreasing the end-expiratory lung volume. The decrease of oxygenation is associated with the increase of body mass index and lung volume reduction, suggesting that a relevant lung collapse is likely present in the obese patients.

Applying 10 cm H2O of PEEP increases oxygenation in obese patients but not in normal subjects, and the oxygenation improvement is related to the amount of alveolar recruitment. The "opening" of collapsed units is a function of transmural pressure, which is mainly related to plateau pressure, that is, tidal volume. In this study we used relatively low tidal volume, and the plateau pressure we reached starting from 10 cm H2O of PEEP averaged 22.1 ± 1.9 and 20.7 ± 2.5 cm H2O in obese patients and in normal subjects, respectively. It is possible that we did not fully open the lung at end-inspiration, because the transmural pressure we reached could be lower than necessary.

We did not investigate the effects of different tidal volumes on respiratory mechanics and oxygenation, but considering the underlying pathophysiology, it is possible that higher tidal volumes may be beneficial in obese patients. Indeed, further studies are warranted to define the optimal levels of tidal volume and PEEP to open up and keep open the lung of obese patients, as well as to define at which level of body mass index PEEP or larger tidal volume is effective to maintain normal respiratory mechanics and oxygenation.

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