Effects of an alveolar recruitment maneuver on cardiovascular and respiratory parameters during total intravenous anesthesia in ponies

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Objective—To evaluate pulmonary and cardiovascular effects of a recruitment maneuver (RM) combined with positive end-expiratory pressure (PEEP) during total intravenous anesthesia in ponies.

Animals—6 healthy adult Shetland ponies.

Procedure—After premedication with detomidine (10 µg/kg, IV), anesthesia was induced with clonidine (0.06 mg/kg, IV) and ketamine (2.2 mg/kg, IV) and maintained with a constant rate infusion of detomidine (0.024 mg/kg/h), clonidine (0.036 mg/kg/h), and ketamine (2.4 mg/kg/h). The RM was preceded by an incremental PEEP titration and followed by a decremental PEEP titration, both at a constant airway pressure difference (ΔP) of 20 cm H2O. The RM consisted of a stepwise increase in ΔP by 25, 30, and 35 cm H2O obtained by increasing peak inspiratory pressure (PIP) to 45, 50, and 55 cm H2O, while maintaining PEEP at 20 cm H2O. Hemodynamic and pulmonary variables were analyzed at every step of the PEEP titration–RM.

Results—During the PEEP titration–RM, there was a significant increase in PaO2 (+12%), dynamic compliance (+62%), and heart rate (+17%) and a decrease in shunt (−19%) and mean arterial blood pressure (−21%) was recorded. Cardiac output remained stable.

Conclusions and Clinical Relevance—Although baseline oxygenation was high, PaO2 and dynamic compliance further increased during the RM. Despite the use of high PIP and PEEP and a high tidal volume, limited cardiovascular compromise was detected. A PEEP titration–RM may be used to improve oxygenation in anesthetized ponies. During stable hemodynamic conditions, PEEP titration–RM can be performed with acceptable adverse cardiovascular effects. (Am J Vet Res 2006;67:152–159)

Horses develop pronounced disturbances of gas exchange during anesthesia and recumbency. These disturbances are characterized by an increase in PaCO2 attributable to hypoventilation and by an increase in (P[A–a]O2). The latter results in a low PaO2 despite high FIO2. The main causes of hypoxemia during anesthesia are pulmonary ventilation-perfusion mismatches attributable to atelectasis and zones of low ventilation at relative overperfusion caused by hydrostatic forces. A marked increase in venous admixture, which can represent up to 51% of CO, has been detected in horses. These changes are more pronounced in horses in dorsal recumbency than in lateral recumbency, are positively related to body mass, and are dependent on the shape of the thoracoabdominal contour. This disturbance of gas exchange also exists in ponies. Computed tomography in ponies with a body weight of approximately 100 kg reveals early development of large densities in dependent lung regions. These densities have been identified as atelectasis, and a significant association between their area on CT images and

<table>
<thead>
<tr>
<th>P[A–a]O2</th>
<th>Alveolar-to-arterial partial pressure difference of oxygen</th>
</tr>
</thead>
<tbody>
<tr>
<td>FiO2</td>
<td>Inspired oxygen fraction</td>
</tr>
<tr>
<td>CO</td>
<td>Cardiac output</td>
</tr>
<tr>
<td>CT</td>
<td>Computed tomography</td>
</tr>
<tr>
<td>PIP</td>
<td>Peak inspiratory pressure</td>
</tr>
<tr>
<td>PEEP</td>
<td>Positive end-expiratory pressure</td>
</tr>
<tr>
<td>RM</td>
<td>Recruitment maneuver</td>
</tr>
<tr>
<td>ARDS</td>
<td>Acute respiratory distress syndrome</td>
</tr>
<tr>
<td>CI</td>
<td>Cardiac index</td>
</tr>
<tr>
<td>IPPV</td>
<td>Intermittent positive pressure ventilation</td>
</tr>
<tr>
<td>TIVA</td>
<td>Total intravenous anesthesia</td>
</tr>
<tr>
<td>Vt</td>
<td>Tidal volume</td>
</tr>
<tr>
<td>VM</td>
<td>Minute volume</td>
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<tr>
<td>Cdyn</td>
<td>Dynamic compliance</td>
</tr>
<tr>
<td>HR</td>
<td>Heart rate</td>
</tr>
<tr>
<td>CCO</td>
<td>Continuous cardiac output</td>
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<tr>
<td>PVo2</td>
<td>Partial pressure of O2 in mixed venous blood</td>
</tr>
<tr>
<td>SvO2</td>
<td>Mixed venous oxygen saturation of hemoglobin</td>
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<tr>
<td>Hb</td>
<td>Hemoglobin</td>
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<tr>
<td>∆P</td>
<td>Constant airway pressure difference</td>
</tr>
<tr>
<td>MAP</td>
<td>Mean arterial pressure</td>
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<tr>
<td>HPV</td>
<td>Hypoxic pulmonary vasoconstriction</td>
</tr>
</tbody>
</table>

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the degree of venous admixture can be detected.\(^9\) Similar findings were detected in sheep.\(^{10}\)

In humans, general anesthesia may also be associated with arterial hypoxemia. Intraoperative atelectasis was suggested to be the major cause of alterations in gas exchange.\(^{11,12}\) and atelectatic lung areas were detected in 87% of anesthetized adults.\(^{12}\) Results of clinical studies\(^{11,13}\) in humans indicate that for a complete reopening of all collapsed lung tissue, an inflation pressure of 40 cm H\(_2\)O held for 15 seconds was required.\(^{11,14}\) Lachmann\(^{15}\) suggested that atelectatic human lungs could be opened by sufficient PIP and can be prevented from collapsing again by immediate application of PEEP. In this way, more lung tissue becomes available for gas exchange with beneficial effects on lung compliance and oxygenation. The basic principles of the open lung concept were used to develop an alveolar recruitment strategy for patients with healthy but partially collapsed lungs.\(^{15,35}\) The effects of this strategy and variations thereof on arterial oxygenation and lung compliance have since been detected in clinical settings.\(^{15,30}\) Furthermore, recruiting the lung while preventing derecruitment decreases the potential for ventilator-induced lung injury by avoiding the shear stresses associated with a repetitive opening and closing of unstable lung alveoli.\(^{26-28}\) Consequently, alveolar RM's have become accepted as an important part of a lung protective ventilation strategy in humans with ARDS, with significantly improved survival rates.\(^{15}\)

The application of high peak inspiratory pressure for an RM and high sustained airway pressure attributable to PEEP carries the risk of barotrauma, alveolo-capillary injury,\(^{26-29}\) and hemodynamic compromise. In humans, a PEEP > 10 cm H\(_2\)O significantly decreases the CI,\(^{29}\) CO, and hepatic plasma flow.\(^{30}\) In pigs, a marked transient impairment of hemodynamics has been detected during administration of a sustained PIP of 40 cm H\(_2\)O. This was associated with decreased blood flow in the celiac artery, cranial mesenteric artery, renal arteries, and portal vein.\(^{30}\) Positive end-expiratory pressure is therefore adjusted to the lowest pressure that prevents alveolar derecruitment. In humans, this corresponds usually to 10 to 20 cm H\(_2\)O.\(^{30,31,32}\) Determination of the minimal open lung PEEP is determined on the basis of careful monitoring for decreases in arterial oxygenation\(^{33}\) and lung compliance during decremental PEEP titration.\(^{34,35}\)

Hypoxemia has long been recognized as a common and potentially hazardous adverse effect of anesthesia in horses, and many attempts have been made for its prevention. Intermittent positive pressure ventilation can correct hypoventilation and normalize Pa\(_{\text{CO}}_2.\(^{36,38}\) However, in practice, IPPV is often not effective in improving Pa\(_{\text{O}}_2.\(^{2,32}\)\) Because atelectasis is thought to play an important role in the genesis of hypoxemia during general anesthesia in horses, the combination of IPPV and PEEP has been advocated to prevent atelectasis formation or to reopen atelectatic lung regions. Positive end-expiratory pressure in combination with IPPV has been studied in anesthetized horses\(^{2,32,36}\) and ponies\(^{3,36}\) and has variable and limited effects on oxygenation. In horses, as in other species, IPPV strongly interferes with cardiovascular function.\(^{36,37,41}\) There are marked additional depressing effects on cardiovascular parameters when IPPV is combined with PEEP,\(^{37,38,42}\) decreasing CO by as much as 50%.\(^{30}\) The purpose of the study reported here was to evaluate pulmonary and cardiovascular effects of an RM combined with PEEP during TIVA in ponies.

### Materials and Methods

**Ponies**—The study was approved by the local Ethics Committee for Animal Experiments. Six male Shetland ponies from 3 to 5 years old were used in the study. Mean ± SD body weight of ponies was 133 ± 18.3 kg. Ponies were chosen from a convenience sample and were considered healthy as determined by results of clinical examination, CBC, and serum biochemical analyses. Food was withheld for 12 hours prior to anesthesia; access to water was not restricted. All ponies had the left carotid artery surgically relocated to a subcutaneous position 6 months before the study.

#### Anesthesia technique

Ponies were premedicated with detomidine\(^{1}\) (10 µg/kg, IV) to permit insertion of a Swan-Ganz-type catheter.\(^4\) Anesthesia was induced via this catheter (central venous port) by use of climazolam\(^1\) (0.06 mg/kg, IV) and ketamine\(^1\) (2.2 mg/kg, IV). After tracheal intubation with a 16-mm-diameter endotracheal tube, ponies were connected to a circle system\(^3\) operating in semiclosed mode, with an O\(_2\) flow of 4 L/min. The anesthesia circuit had been checked for leaks at 60 cm H\(_2\)O before each experiment. The cuff was inflated until a leak-proof seal was obtained. Anesthesia was maintained by continuous IV infusion of detomidine, ketamine, and climazolam delivered by a volumetric pump\(^1\) (1 g of ketamine, 15 mg of climazolam, and 10 mg of detomidine were dissolved in 500 mL of sterile isotonic saline [0.9% NaCl] solution). The TIVA infusion rate was maintained at 0.02 mL/kg/min and corresponded to infusions of detomi- dine at a rate of 0.024 mg/kg/h, ketamine at a rate of 2.4 mg/kg/h, and climazolam at a rate of 0.036 mg/kg/h. Lactated Ringer's solution\(^1\) was administered at a rate of 10 mL/kg/h during induction of anesthesia and was maintained throughout the study.

Ponies were placed on a padded table and positioned in dorsal recumbency. The F\(_{\text{I}}\)\(_{\text{O}}\)\(_2\) was set at 1.0 throughout the study. Mechanical ventilation was performed by use of a modified human ventilator\(^1\) functioning in the pressure-controlled mode. At the end of the study, 20 minutes after TIVA was discontinued, the effects of climazolam were antagonized with sarmazenil\(^3\) (0.04 mg/kg, IV).

#### Instrumentation

In standing sedated ponies, pulmonary artery catheterization was performed with a special transducer via the right jugular vein during local anesthesia (lidocaine\(^3\)). The tip of the continuous thermodilution Swan-Ganz catheter\(^2\) (flow-directed balloon-tipped pulmonary artery catheter) was placed in the pulmonary artery by use of pressure waveform analysis. The pulmonary artery catheter is modified to locate a 10-cm thermal filament in the right ventricle during use. The thermal filament continually transfers a safe level of heat directly into the blood. The resulting temperature changes are detected at the distal thermistor located in the catheter. These data are collected and calculated by computer; CO is computed from the area under the curve by use of an equation similar to that used for standard bolus thermodilution. After induction of anesthesia, the transverse facial artery or the left carotid artery was cannulated with a 20-gauge over-the-needle polypropylene catheter\(^3\) for invasive blood pressure monitoring and arterial blood sampling. The arterial and the pulmonary artery catheters were connected to calibrated pressure transducers via fluid-filled...
extension lines. Pressure transducers were positioned at the level of the sternal manubrium after ponies were positioned in dorsal recumbency.

Measured and calculated parameters—Respiratory gas flows, volumes, and pressures were measured by use of an electronic spirometric system. The sensor, located between the endotracheal tube and the Y-piece, was connected to dedicated software for data display and post hoc data analysis (breath-by-breath analysis, body temperature and pressure, saturated [BTPS]). The PIP, PEEP, VT, and expired V̇E were measured. The Cdyn was automatically calculated as (V̇E)/(PIP – PEEP). The Pao2, end-tidal O2, and end-tidal CO2 in the respiratory gas were continuously measured via sampling from the distal part of the endotracheal tube. Cardiovascular monitoring consisted of measurement of the HR derived from the ECG in a base-apex configuration, arterial blood pressure. The CI was calculated by dividing the CO (mL/min) by the body weight (kg) of each pony. By use of 3-way taps, arterial and mixed-venous blood samples for measurements of PaO2, Pvo2, Paco2, (P[A–a]O2), SaO2, and SvO2 and for determination of the Hb concentration were anaerobically collected in 2-mL syringes containing heparin. Samples were collected during at least 2 breathing cycles from the transverse facial or carotid artery and the pulmonary artery, respectively; stored on ice; and analyzed with electronically saturated [BTPS]). The PIP, PEEP, VT, and expired V̇E were measured. The Cdyn was automatically calculated as (V̇E)/(PIP – PEEP). The Pao2, end-tidal O2, and end-tidal CO2 in the respiratory gas were continuously measured via sampling from the distal part of the endotracheal tube. Cardiovascular monitoring consisted of measurement of the HR derived from the ECG in a base-apex configuration, arterial blood pressure. The CI was calculated by dividing the CO (mL/min) by the body weight (kg) of each pony. By use of 3-way taps, arterial and mixed-venous blood samples for measurements of PaO2, Pvo2, Paco2, (P[A–a]O2), SaO2, and SvO2 and for determination of the Hb concentration were anaerobically collected in 2-mL syringes containing heparin. Samples were collected during at least 2 breathing cycles from the transverse facial or carotid artery and the pulmonary artery, respectively; stored on ice; and analyzed within 30 minutes. These variables were measured by use of conventional electrode techniques and corrected to the blood temperature and hemoglobin concentration of each pony, and (P[A–a]O2) was calculated. Alveolar oxygen tension (Pao2) and shunt fraction were calculated by use of the standard oxygen equation:

\[
\text{Shunt fraction} = \left( \frac{Qs}{Qt} \right) = \frac{(Cc'O2 - CaO2)}{(Cc'O2 - CvO2)}
\]

where \(Cc'O2\) is the pulmonary end capillary oxygen content, \(CaO2\) is the arterial oxygen content, \(CvO2\) is the mixed venous oxygen content, \(P_s\) is the barometric pressure, and \(Pc'O2\) is the pulmonary end capillary partial pressure of oxygen.

RM—After spontaneous breathing, mechanical ventilation began at a PIP of 20 cm H2O and a PEEP of 0 cm H2O (P 20/0), baseline IPPV). The RM was preceded by an incremental PEEP titration phase and followed by a decremental PEEP titration phase, both at a ∆P of 20 cm H2O (Figure 1). The proper RM consisted of a stepwise increase in ∆P by 25, 30, and 35 cm H2O obtained by increasing PIP to 45, 50, and finally 55 cm H2O, while maintaining PEEP at 20 cm H2O. The subsequent decremental PEEP titration phase was initiated with an abrupt decline in PIP to 40 cm H2O (P 40/20). Thereafter, PIP and PEEP were uniformly decreased in steps of 5 cm H2O (P 35/15, P 30/10, and P 25/5) and ended with IPPV (final IPPV). Each pressure was maintained for 3 minutes. When starting the RM, respiratory frequency was decreased to 6 breaths/min with an inspiration-to-expiration ratio of 1:1 to avoid an excessive decrease in Paco2 that accompanies increased alveolar ventilation.

Study protocol—Between premedication and induction of anesthesia, the Swan-Ganz catheter was introduced and the first standing CCO was measured. After induction of anesthesia, ponies were breathing spontaneously for 60 minutes before IPPV began. Measurements obtained after 20

<table>
<thead>
<tr>
<th>PIP/PEEP (cm H2O)</th>
<th>V̇E (mL/kg)</th>
<th>Pao2 (mm Hg)</th>
<th>(P[A–a]O2) (mm Hg)</th>
<th>Cdyn (mL/cm H2O)</th>
<th>Paco2 (mm Hg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SB</td>
<td>7</td>
<td>5–15</td>
<td>368.9</td>
<td>207.6–469.1</td>
<td>265.0</td>
</tr>
<tr>
<td>P 20/0 BL</td>
<td>14</td>
<td>10–17</td>
<td>441.3</td>
<td>390.4–460.4</td>
<td>210.6</td>
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<tr>
<td>P 25/5</td>
<td>14</td>
<td>10–16</td>
<td>425.2</td>
<td>387.4–464.9</td>
<td>211.6</td>
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<tr>
<td>P 30/10</td>
<td>14</td>
<td>10–16</td>
<td>423.0</td>
<td>359.5–438.7</td>
<td>212.2</td>
</tr>
<tr>
<td>P 35/15</td>
<td>13</td>
<td>9–15</td>
<td>406.9</td>
<td>371.5–505.2</td>
<td>214.3</td>
</tr>
<tr>
<td>P 40/20</td>
<td>13</td>
<td>9–15</td>
<td>450.4</td>
<td>378.2–459.9</td>
<td>176.9</td>
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<tr>
<td>P 45/20</td>
<td>17</td>
<td>12–15</td>
<td>472.0</td>
<td>420.7–489.3</td>
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<tr>
<td>P 50/20</td>
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<td>12–15</td>
<td>472.0</td>
<td>420.7–489.3</td>
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<tr>
<td>P 55/20</td>
<td>17</td>
<td>12–15</td>
<td>472.0</td>
<td>420.7–489.3</td>
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<tr>
<td>P 60/20</td>
<td>17</td>
<td>12–15</td>
<td>472.0</td>
<td>420.7–489.3</td>
<td>165.6</td>
</tr>
</tbody>
</table>

*Significantly (P < 0.05) different from baseline value. †Significantly (P < 0.05) different from the value recorded at the same airway pressure during the incremental PEEP titration phase.

Figure 1—Alveolar RM during total IV anesthesia in 6 ponies. The figure depicts the setting of airway pressures throughout the study. Baseline (BL) was established during IPPV and was followed by the incremental PEEP titration (IP), by the RM, and by the decremental PEEP titration (DP). The decremental PEEP titration ended with the final IPPV. The upper solid line represents IP, and the lower solid line represents the PEEP.
minutes of IPPV were considered as baseline values to study the effects of the subsequent PEEP titration–RM and included ventilation and cardiovascular parameters with blood gas values. During the PEEP titration–RM sequence, respiratory and cardiovascular measurements were obtained at the end of each 3-minute step of the procedure and once after the end of the sequence during IPPV.

**Statistical analysis**—Hemodynamic and pulmonary variables are given as median values and ranges. They were analyzed by use of descriptive statistics and the Wilcoxon signed rank test. For analysis of PaO₂, (P[A–a]O₂), Cdyn, and shunt, the Wilcoxon signed rank test was used to determine differences between baseline and observed maximal values of the sampling point median. For other cardiovascular and respiratory data, the same test was used to analyze differences between median baseline and median values at maximal airway pressure of the RM and between median values at maximal airway pressure and at the final IPPV. The Wilcoxon signed rank test was also used for comparison of data obtained at baseline IPPV and at final IPPV as well as for identical PEEP levels before and after the RM. For all tests, a value of P < 0.05 was considered significant.

**Results**

Duration from sedation to induction of anesthesia ranged from 10 to 25 minutes. During this time, the Swan-Ganz catheter was inserted and the first standing CO measurement was performed. Anesthesia was induced in all ponies without complications, and a stable plane of anesthesia was maintained, which was characterized by minor variations in HR, MAP, and respiratory rate and clinical signs such as palpebral reflex, globe position, tear production, and muscular jaw tone. Throughout the study, no inotropes were administered. Mean total duration of anesthesia was 173 minutes (range, 160 to 180 minutes) and included the period from induction of anesthesia to extubation. In each pony, the RM was completed without major hemodynamic complications. No abnormalities were detected during clinical examination of ponies performed the next day. The PEEP titration–RM sequence lasted a mean of 33 minutes and began with the airway setting of P 25/5 in the incremental PEEP titration phase and ended with the final IPPV period.

The Vₜ and V_M were maximal during highest airway pressures. At baseline, Vₜ was 14 mL/kg and was increased to 23 mL/kg at maximal airway pressure (P 55/20) when the lungs were actively recruited (Table 1). At final IPPV, a Vₜ of 16 mL/kg was measured. There was a concomitant significant (P = 0.03) increase in V_M recorded at baseline (8.6 L) and at P 55/20 (16.3 L). Compared with baseline, V_M (8.6 L) was significantly (P = 0.03) increased after completion of the RM (12.4 L at the final IPPV period). The maximal values of Cdyn and PaO₂ and minimal values of shunt and (P[A–a]O₂) were recorded during the decremental phase of the PEEP titration (Figure 2). The Cdyn increased significantly (P = 0.03) from baseline 90.5 mL/cm H₂O to a maximal value of 147 mL/cm H₂O measured at P 30/10 in the decremental PEEP titration phase and ended with the final IPPV period. Each pressure was maintained for 3 minutes. See Figure 1 for remainder of key.

### Table 2—Median and range values of hemodynamic variables measured during SB, at IPPV (P 20/0) during which BL was established, at the incremental phase of the PEEP titration (P 25/5 to P 40/20), at the decremental phase of the PEEP titration (P 40/20 to P 25/5), and at the final IPPV period (P 20/0) during total IV anesthesia in 6 ponies.

<table>
<thead>
<tr>
<th>PIP/PEEP (cm H₂O)</th>
<th>MAP (mm Hg)</th>
<th>HR (bpm)</th>
<th>CO (L/min)</th>
<th>CI (mL/kg/min)</th>
<th>Shunt (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Median</td>
<td>Range</td>
<td>Median</td>
<td>Range</td>
<td>Median</td>
</tr>
<tr>
<td>SB</td>
<td>104.0</td>
<td>96.0–148.0</td>
<td>34 30–42</td>
<td>5.8 5.0–6.9</td>
<td>49.8</td>
</tr>
<tr>
<td>P 20/0 (BL)</td>
<td>115.5</td>
<td>97.0–147.0</td>
<td>35 32–37</td>
<td>5.2 3.6–5.9</td>
<td>41.0</td>
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<tr>
<td>P 25/5</td>
<td>113.5</td>
<td>98.0–150.0</td>
<td>34 30–39</td>
<td>4.5 3.8–5.8</td>
<td>35.4</td>
</tr>
<tr>
<td>P 30/10</td>
<td>113.0</td>
<td>95.0–143.0</td>
<td>35 30–41</td>
<td>4.3 3.6–5.4</td>
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<tr>
<td>P 35/15</td>
<td>112.0</td>
<td>106.0–125.0</td>
<td>35 30–45</td>
<td>3.9 3.3–5.9</td>
<td>32.4</td>
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<tr>
<td>P 40/20</td>
<td>103.5</td>
<td>92.0–142.0</td>
<td>38 30–49</td>
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<tr>
<td>P 45/20</td>
<td>96.5</td>
<td>89.0–134.0</td>
<td>41 34–50</td>
<td>4.2 3.0–6.1</td>
<td>31.6</td>
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<tr>
<td>P 50/20</td>
<td>95.5</td>
<td>81.0–130.0</td>
<td>41 35–48</td>
<td>4.2 2.8–5.6</td>
<td>32.3</td>
</tr>
<tr>
<td>P 55/20</td>
<td>90.5*</td>
<td>84.0–130.0</td>
<td>41 33–48</td>
<td>4.3 2.9–5.3</td>
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<td>34 30–44</td>
<td>4.0 3.5–7.0</td>
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<tr>
<td>P 20/0</td>
<td>109.0</td>
<td>84.0–133.0</td>
<td>37 30–40</td>
<td>4.0 3.6–4.5</td>
<td>30.9</td>
</tr>
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</table>

bpm = Beats per minute.

See Table 1 for remainder of key.
phase. After the RM at final IPPV, $C_{dy}$ continued to be significantly ($P = 0.03$) higher than at baseline (120.4 vs 90.5 mL/cm H$_2$O). At all pressure steps during the decremental PEEP titration after the RM, $C_{dy}$ was significantly (all $P = 0.03$) higher than during the respective pressure steps of the incremental phase. The PaO$_2$ increased from a baseline value of 441.3 mm Hg to a maximal value of 495.1 mm Hg measured at P 35/15 during the decremental PEEP titration phase; the increase from baseline was significant ($P = 0.03$) at the next lower step of the decremental PEEP titration (479.1 mm Hg at P 30/10). The PaO$_2$ decreased to 445.2 mm Hg at final IPPV. When compared with the incremental PEEP titration phase, PaO$_2$ at P 30/10 was significantly ($P = 0.03$) higher during the decremental phase. Concomitantly, ($P[A–a]O_2$) decreased by 28% from a baseline of 210.6 mm Hg to a minimal value of 151.6 mm Hg at P 35/15 during the decremental PEEP titration phase. The decrease from baseline was significant ($P = 0.03$) at P 30/10 (167.2 mm Hg). When compared with the incremental PEEP titration phase at P 30/10, ($P[A–a]O_2$) was significantly ($P = 0.03$) lower during the decremental phase. The calculated shunt fraction at baseline was 6.2% and decreased by 19% to a value of 5% during the decremental PEEP titration phase (P 30/10; $P = 0.03$). The shunt fraction was significantly ($P = 0.03$) lower during the decremental phase of the PEEP titration at P 30/10, compared with the respective airway setting during the incremental phase. The PaCO$_2$ decreased from 40.2 mm Hg at baseline to 27.6 mm Hg at P 55/20. This represented a decrease of 38% ($P = 0.03$). The PaCO$_2$ was 30.9 mm Hg at final IPPV ($P = 0.04$), a value significantly ($P = 0.04$) lower than that at baseline.

When IPPV began after spontaneous breathing, MAP decreased by 12% and CO decreased by 15% (Table 2). Mean arterial blood pressure decreased further during the incremental PEEP titration and the RM by 21% from a baseline value of 115.5 mm Hg to 90.5 mm Hg at P 55/20 ($P = 0.03$). During the decremental PEEP titration phase, MAP returned to a value of 109 mm Hg at final IPPV ($P = 0.03$; Figure 3). In 1 individual pony, high MAP values were recorded, which explains the great variations in MAP. The HR increased from a baseline value of 35 beats/min to 41 beats/min at P 55/20 ($P = 0.03$) and decreased to baseline values at final IPPV ($P = 0.03$; Figure 3). In 1 pony, measurement of CO was not possible because of technical reasons, and data from this pony were excluded from statistical analyses. In the remaining 5 ponies, CO decreased slightly during RM (5.2 L/min at baseline to 4.3 L/min at P 55/20). Cardiac index at baseline was 41 mL/kg/min and decreased to 33.3 mL/kg/min at P 55/20.

Except for 1 pony, recovery from anesthesia after IV administration of medetomidine was quick and no complications were detected. Because of persistent excitatory behavior after administration of the antagonist, 1 pony required resedation with an IV bolus of detomidine.

**Discussion**

The main finding of our study was that an alveolar RM caused only minor cardiovascular effects and, clinically, no adverse pulmonary effects in healthy ponies undergoing TIVA anesthesia. Furthermore, significant changes in $C_{dy}$ and PaO$_2$ during PEEP titration were detected, thus providing the possibility of systematic identification of an optimal PEEP. This open lung PEEP should prevent closure of alveoli that are opened by a preceding RM.

As expected, some alterations in cardiovascular parameters were recorded: first, when IPPV was substituted for spontaneous breathing, and second, when an RM was superimposed on IPPV. During the RM, MAP and CO decreased further, compared with baseline; the maximal decrease occurred at maximal airway pressures. The reduction in MAP was significant and is thought to have been caused by increased intrathoracic pressure, which increases impedance to blood flow through the lungs, thus causing a diminished end-diastolic left ventricular volume.44 To our knowledge, there are no studies in equids documenting the hemodynamic effects of PEEP when combined with such high peak airway pressures as performed in the study reported here. The recorded decrease in CO was small, compared with results of other studies38,39 with sustained increases in airway pressures. It is likely that the concomitant increase in HR during the RM partially compensated for decreased venous return and hence CO. In horses anesthetized with halothane, MAP and CO decreased by 27% and 16%, respectively, when a PEEP of 10 cm H$_2$O was added to IPPV.38 In ponies in which anesthesia was administered IV, CO decreased by 24% and 51% and MAP decreased by 7% and 12% after PEEP of 20 and 30 cm H$_2$O, respectively.39 In humans, IV administration of fluids has been advocated during an RM when signs of hemodynamic instability appear, and it has been found that the hemodynamic effects of PEEP may be minimized by normovolemia or hypervolemia.45,46 In the study reported here, lactated Ringer’s solution was infused at 10 mL/kg/h starting at induction of anesthesia.
and was maintained at this rate until the end of the procedure. No attempt was made to precondition ponies with increased fluid load before starting the RM.

Intermittent bolus thermodilution is well documented as a method for measurement of CO in equids. In humans, there is clinically acceptable agreement between the CCO measurement method and the classical intermittent thermodilution method. In calves with a body weight of 70 kg, CCO had higher accuracy and greater resistance to thermal noise than standard bolus measurements. The method of CCO measurement has not been validated in ponies. However, size and weight of ponies in our study were on the same order of magnitude and in the range encountered in adult humans. This allowed correct positioning of the pulmonary artery catheter in the study reported here and suggests that a similar precision of CO measurement can be expected. In our study, we emphasized trends of CO during the influence of changing airway pressures, rather than absolute values.

During a PEEP titration–RM sequence in humans, an increase in Cdyn and an increase in PaO2 suggest recruitment of previously collapsed lung areas. In our study, the marked and sustained increase in Cdyn (maximal > 62% at P 30/10 in the decremental PEEP titration phase), and the fact that Cdyn remained high after the RM at final IPPV, suggested successful recruitment of lung tissue because the formation of atelectasis is associated with a decrease in Cdyn. However, this marked increase in Cdyn caused a significant, but only small, improvement in oxygenation. This finding may be associated with the high baseline PaO2 (411.3 mm Hg) in ponies in our study, compared with values generally detected in anesthetized adult horses breathing 100% oxygen. In the study reported here, the maximal median PaO2 was recorded at P 35/15 (495.1 mm Hg), but compared with baseline, the increase from baseline at this sampling point did not reach significance because of 1 comparatively low PaO2 value (326.1 mm Hg) recorded in 1 individual pony that caused great variations in our data. At the next step of the decremental PEEP titration phase (P 30/10), the increase in PaO2 was significant at an absolute PaO2 value that was lower that at the previous step. The fact that the ponies had a high baseline PaO2 and little venous admixture may be associated with the anesthetic protocol used. It is recognized that isoflurane and halothane, pulmonary shunt was 20% to 25%, which decreased to 15% when horses were ventilated, and during IPPV (P 30/0), shunt fractions of 21% have been calculated. In our study, the shunt fraction was low, although ponies were breathing 100% oxygen. It has been found that a high FiO2 of 1.0 promotes the formation of atelectasis and shunt in humans as well as in horses.

To prevent recruited alveoli from collapsing, PEEP must be applied after alveolar recruitment. An optimal PEEP is the lowest value of PEEP necessary to keep the lung tissue open. To find optimal PEEP, the closing pressure has to be determined for each animal. In our study, changes in Cdyn and changes in arterial oxygenation were investigated. A decrease in PaO2 and Cdyn during the decremental steps of PEEP titration is considered a sign of alveolar closing: they mark the pressure at which collapse (derecruitment) of lung tissue occurs. The distinct decrease in PaO2 and in Cdyn occurred at slightly different airway pressures (PaO2 decreased at P 30/10 and Cdyn at P 25/5 of the decremental PEEP titration phase), and this finding is in agreement with results of studies in human patients. On 1 hand, PEEP prevents alveoli from collapsing while simultaneously distending other alveoli. High PEEP distends more lung tissue, thus causing decreased lung compliance. When PEEP is decreased from a state of distension, compliance initially increases to the point at which collapse of unstable lung alveoli occurs, which finally leads to decreased compliance again.

Despite the scheduled reduction in the respiratory rate during the RM, the PaCO2 decreased to a minimal value of 27.6 mm Hg at P 55/20 as a sequel of the increased alveolar ventilation. Even at final IPPV, PaCO2 was significantly lower than the baseline value. Hypocapnia (PaCO2 < 30 mm Hg) should be avoided because it carries the risk of decreased cerebral blood flow and diminished catecholamine release with debilitation of the cardiovascular system. Prevention of excessive hypocapnia during RM is facilitated by continuous monitoring of PaCO2 and includes a reduction of the respiratory rate; limiting AP by increasing PEEP; or, alternatively, the addition of CO2 to the inspiratory gas.
In the study reported here, no evidence of barotrauma during or after anesthesia was detected. This was not unexpected because it is in agreement with findings in animals and humans applying similar airway pressures. In a sheep model of ARDS, high-pressure (P 60/40) short-term and repetitive RMs were applied safely without sustained hemodynamic compromise and histologic injury to the lungs. Absence of barotrauma was also reported in the clinical setting for human patients by use of airway pressures of 50 to 65 cm H₂O (V_T of 18 mL/kg) during general anesthesia or even 80 cm H₂O in patients with ARDS and chest trauma. Results of 1 study indicate that it is not the high airway pressure but rather the large regional V_T that causes lung injury. In our study, a V_T of as much as 23 mL/kg was used. Healthy adult sheep ventilated with a V_T of 50 to 70 mL/kg (PIP; 50 cm H₂O) developed severe respiratory failure.

For the statistical analyses, a conservative approach was used. The Wilcoxon signed rank test was used because a small sample size (6 ponies) was used for statistical analyses, and therefore, normal distribution of the data was not ensured.

On the basis of the results of our study, further research on cardiorespiratory effects of RM, inhalation anesthetics, and hypovolemic states in equids is warranted. Tissue oxygen delivery and uptake measured during RM in equids during hypoxic states would be ideal measures of successful treatment of hypoxemia.

The PEEP titration and RM described in the study reported here resulted in only limited cardiovascular compromise despite use of high PEEP and peak airway pressures. Although baseline oxygenation was high, there was a significant increase in Pao₂ and decrease in shunt attributable to the RM. Evaluation of Pao₂ and C_{O₂} in the decremental phase of the PEEP titration permitted detection of an alveolar closing pressure.

References


