Use of manual alveolar recruitment maneuvers to eliminate atelectasis artifacts identified during thoracic computed tomography of healthy neonatal foals

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OBJECTIVE  
To evaluate use of single manual alveolar recruitment maneuvers (ARMs) to eliminate atelectasis during CT of anesthetized foals.

ANIMALS  
6 neonatal Standardbred foals.

PROCEDURES  
Thoracic CT was performed on spontaneously breathing anesthetized foals positioned in sternal (n = 3) or dorsal (3) recumbency when foals were 24 to 36 hours old (time 1), 4 days old (time 2), 7 days old (time 3), and 10 days old (time 4). The CT images were collected without ARMs (all times) and during ARMs with an internal airway pressure of 10, 20, and 30 cm H₂O (times 2 and 3). Quantitative analysis of CT images measured whole lung and regional changes in attenuation or volume with ARMs.

RESULTS  
Increased attenuation and an alveolar pattern were most prominent in the dependent portion of the lungs. Subjectively, ARMs did not eliminate atelectasis; however, they did incrementally reduce attenuation, particularly in the nondependent portion of the lungs. Quantitative differences in lung attenuation attributable to position of foal were not identified. Lung attenuation decreased significantly (times 2 and 3) and lung volume increased significantly (times 2 and 3) after ARMs. Changes in attenuation and volume were most pronounced in the nondependent portion of the lungs and at ARMs of 20 and 30 cm H₂O.

CONCLUSIONS AND CLINICAL RELEVANCE  
Manual ARMs did not eliminate atelectasis but reduced attenuation in nondependent portions of the lungs. Positioning of foals in dorsal recumbency for CT may be appropriate when pathological changes in the ventral portion of the lungs are suspected. (Am J Vet Res 2016;77:1276–1287)

Lung imaging plays a critical role in the evaluation of patients with respiratory disease. In human patients, CT has become the preferred modality for lung imaging, and its use has led to improvements in the characterization of various pulmonary diseases.1–5 The CT characteristics of the lungs are also well described in dogs and cats,6–8 and CT is considered superior to standard radiography for the detection of pathological changes within the lungs.9–12 In equine neonates, for which pulmonary disease is a major contributor to patient morbidity and mortality rates,13–16 the diagnosis and characterization of respiratory disease has largely relied on radiographic analysis.15 Computed tomography of the lungs has been described for healthy, sedated neonatal foals.17,18 In foals in both of those studies,17,18 CT revealed increased lung densities that were described as patchy alveolar patterns (consolidation) in the dependent portions of the lungs, relative to the nondependent portions of the lungs. These findings were considered most consistent with atelectasis and were most pronounced in foals < 7 days old.17

Atelectasis is readily detected by use of CT and represents one of the most common patient-related artifacts that can interfere with accurate evaluation of CT images.17–25 A primary reason for the develop-
ment of atelectasis involves sedation or anesthesia in spontaneously breathing and mechanically ventilated patients. In comparison to adults, anesthetized pediatric patients, including neonatal foals, are more susceptible to atelectasis. Alveolar recruitment maneuvers are used to minimize or reverse atelectasis. Examples include a single manual inflation (ie, breath holding) at PIPs ranging from 10 to 40 cm H2O and delivery of a series of inflations at various PIPs with or without a peak end expiratory pressure. A single inflation ARM is advantageous for CT because that ARM does not require mechanical ventilation, can be rapidly performed, and allows for control over pressure or volume (or both) delivered to the animal. Quantitative analysis of CT images through measurement of lung attenuation (density) and distribution of aeration is used to evaluate recruitment of atelectatic portions of the lungs.

To our knowledge, recruitment of atelectatic portions of the lungs for CT has not been evaluated in neonatal foals. In populations of sick equine neonates, such as those with respiratory tract disease, identification of clinically applicable CT protocols that minimize the development of atelectasis is essential. The objectives of the study reported here were to evaluate the use of manual single inflation ARMs with a PIP of 10, 20, and 30 cm H2O to reduce atelectasis detected on CT images of the lungs of spontaneously breathing anesthetized foals positioned in dorsal or sternal recumbency, to determine whether the amount of atelectasis decreases with increasing age of a foal, and to quantify the response to recruitment through CT-derived measurements of lung attenuation and volume. The specific hypotheses tested were that atelectasis would be more pronounced in the dependent portions of the lungs in foals at a younger age and in foals positioned in sternal recumbency, that delivery of manual ARMs would correspond to both subjective and quantifiable reductions in atelectasis, and that the magnitude of improvement after recruitment would be greater in older foals.

Materials and Methods

Animals

Six healthy neonatal Standardbred foals from the University of Illinois Equine Breeding Farm were obtained for use in the study. Mares were housed and monitored at the University of Illinois Veterinary Teaching Hospital for a minimum of 3 days prior to parturition, and all foalings were observed. Day of foaling was designated as day 0. Newborn foals were monitored to ensure they had typical neonatal behavior, and physical examinations were performed after the foals were able to stand to suckle and when foals were 12 and 24 hours old. In accordance with the University of Illinois Equine Breeding Farm protocol, hyperimmune plasma was administered IV to each foal when it was 12 hours old, and a blood sample was obtained when foals were 24 hours old and used for an IgG enzyme immunoassay to evaluate adequate transfer of passive immunity. Serial physical examinations and CBCs were performed on days 5 and 8 to confirm health status of the foals. Physical examinations were performed once daily, except on days 1, 4, 7, and 10, when foals were anesthetized and CT was performed. On those days, physical examinations were performed before and 2 and 8 hours after recovery from anesthesia. Inclusion criteria included absence of peripartum or postpartum abnormalities of the mare (ie, dystocia or retained fetal membranes) or foal (ie, dysmaturity, abnormal postfoaling behavior, failure of passive transfer of immunity, and abnormalities detected during physical examination). Criteria for removal of a foal from the study included abnormalities detected during physical examination or a CBC or pathological changes detected during CT. Each foal was housed with its dam throughout the study, and mares and foals were returned to the University of Illinois Equine Breeding Farm at the conclusion of the study. The study was approved by the University of Illinois Institutional Animal Care and Use Committee.

Anesthesia and anesthetic monitoring

For each foal, a 16-gauge over-the-wire long-term antimicrobial-coated catheter was placed aseptically in the left jugular vein when the foals were 12 hours old. Catheters were used for administration of hyperimmune plasma and then maintained for the duration of the study (10 days) for administration of all anesthetic medications. Care of catheters was performed in accordance with standard flushing and monitoring practices of the University of Illinois Veterinary Teaching Hospital. Catheters were flushed with a heparinized saline (0.9% NaCl solution (100 U of heparin/mL) every 8 hours and immediately after administration of medications. Catheters were also evaluated every 8 hours to ensure they had appropriate flow, and the catheter insertion site and area over the jugular vein were monitored for evidence of heat, swelling, or discharge or signs of pain during manipulation of the area.

Immediately before the procedures were performed on each study day, foals were walked from their stall to the CT suite and sedated by administration of butorphanol tartrate (0.05 mg/kg, IV) and midazolam (0.1 mg/kg, IV). Sedated foals were positioned in sternal recumbency, anesthesia was induced with propofol (4 to 6 mg/kg, IV, to effect), and a cuffed endotracheal tube (internal diameter, 12 to 14 mm) was inserted. Foals were then immediately transferred to the CT table and assigned by use of a random-number generator to be positioned in sternal (n = 3) or dorsal (3) recumbency, which was followed by attachment to a rebreathing circle system of an anesthesia machine equipped with a spirometer and pressure gauge. Anesthesia was maintained with sevoflurane in oxygen. Foals were allowed to have spontaneous respiration throughout all procedures, except during manual ARMs. Acquisition of CT images was initiated once foals had a regular pattern of respiration (approx 5 to 10 minutes after positioning...
on the CT table), which was determined visually on the basis of respiratory rate, symmetry in chest wall and abdominal movement, and a subjectively normal effort during the inspiratory and expiratory phases of respiration.

Physiologic monitoring of anesthetized foals was performed at 5-minute intervals by use of a multi-parameter patient monitor. Variables monitored included a continuous base-apex ECG, respiratory rate, \( \text{SpO}_2 \), PET\( \text{CO}_2 \), end-tidal sevoflurane concentration, and indirect (measured at tail base) SAP, MAP, and DAP. Minute volume was measured with the spirometer placed between the exhalation limb of the rebreathing circuit and the exhalation 1-way valve of the anesthesia machine. Measurements of respiratory rate and minute volume in anesthetized foals were obtained prior to the delivery of manual ARMs (baseline) and when the foals had resumed a regular pattern of spontaneous respiration after each successive manual ARM. Determination of a representative tidal volume was performed by measuring minute volume and dividing that value by the number of breaths per minute. After CT images were acquired, recumbent foals were transported to their respective stalls and assisted with recovery from anesthesia.

**Experimental design and manual ARMs**

Computed tomography was performed on each foal at 4 time points: 24 to 36 hours after birth (time 1), day 4 (time 2), day 7 (time 3), and day 10 (time 4). Anesthetized foals were allowed to breathe spontaneously throughout CT. Four ventilation protocols were included in the study; these comprised before (baseline) and after application of manual ARMs at a PIP of 10, 20, and 30 cm \( \text{H}_2\text{O} \).

At time 1, a baseline CT (ie, no application of a manual ARM) was performed on each anesthetized foal. At times 2 and 3, a baseline CT was obtained, and CT images were also obtained after application of a manual ARM at 10, 20, and 30 cm \( \text{H}_2\text{O} \), respectively. At time 4, only a baseline CT was performed. Timing of image acquisition at baseline was random with respect to the phase of respiration of the foal. The ARMs were performed by delivering a breath via manual compression of the anesthesia reservoir bag at the desired PIP (ie, 10, 20, and 30 cm \( \text{H}_2\text{O} \)) as measured on the pressure manometer of the anesthesia machine. The delivered breath was maintained during the entire CT acquisition period (breath hold; approx 23 seconds). Foals breathed spontaneously before and after each ARM and were required to establish a regular ventilatory pattern for a minimum of 5 minutes and a maximum of 10 minutes between successive ARMs.

**Acquisition of CT images**

Each foal was positioned on the CT table in sternal or dorsal recumbency with its head facing the CT gantry and the forelimbs and hind limbs extended cranially and caudally, respectively. Standard positioning was confirmed on an initial CT image by alignment of the caudal border of the scapulae with the vertebrae. Images were acquired with a 16-slice CT scanner and a detail algorithm with the following settings: 140 kVp, 300 mA, 0.5-second rotation, 0.9 pitch, 0.9-second table speed, 512 X 512 matrix, 30-cm display field of view, 50-cm scan field of view, and 5-mm contiguous slice thickness reconstructed to 0.625 mm for the sagittal and dorsal reformations. This technique has been validated for healthy foals. The CT images were stored as DICOM files for analysis. Images, including the entire lung field, were obtained for all times and ARMs. At times 2 and 3, abbreviated CT scans (ie, check-breath scans) consisting of 15 slices were performed immediately before application of each of the 3 ARMs to evaluate the potential impact of successive recruitment maneuvers. The region of the lungs where the caudal vena cava first appeared between the heart and diaphragm was chosen as the cranial landmark for these abbreviated scans and, on the basis of results of previous studies of healthy foals, represented the region where atelectasis, when identified, appeared most pronounced.

**Descriptive and quantitative analysis of CT images**

All CT images were reviewed separately by 3 investigators, including board-certified veterinary radiologists (RTO and SK) and a veterinarian board certified in veterinary internal medicine (KML). Investigators were not aware of foal age, study time point, or ARM. A consensus opinion was developed regarding presence or absence of soft tissue attenuation or other remarkable changes. Regions of attenuation were described by location (dorsal, middle, or ventral lung region; cranial to the heart, at the level of the heart, or caudal to the heart), and severity was subjectively described as mild, moderate, or marked. Attenuation of mild severity corresponded to minimal or focal areas of an interstitial pattern, whereas those of moderate severity included localized or patchy interstitial and alveolar patterns, and those of marked severity included extensive and coalescing regions of alveolar consolidation.

Quantitative image analysis was performed with the aid of DICOM viewing software and specialized semiautomated segmentation software. Thresholds of –860 HU and –120 HU were used for initial 3-D semiautomated segmentation of lung from nonlung structures, as previously described for foals. Initial segmentation threshold interval algorithms were applied to exclude large vessels and other air-filled structures (eg, trachea, large airways, gas-filled stomach, or gas-filled small intestine) and to include areas of a lung measuring greater than –120 HU (including presumed atelectatic regions).

Attenuation measurements obtained from a segmented whole lung were averaged and reported as mean whole lung attenuation. Attenuation measurements from ROIs within the dependent, middle, and...
nondependent portions of the lungs were used to characterize changes in attenuation in these specific regions in full CT scans at baseline and at each subsequent ARM (Figure 1). Similar ROIs were identified for the abbreviated check-breath scans to determine whether previous recruitment had an additive influence on attenuation. To maintain consistency in location for all ROIs, subjective guidelines were made in a consensus agreement by 3 investigators (KML, SKJ, and RTO) and were as follows: ROIs were placed in the dorsal third, middle third, and ventral third of the lungs on a CT image; ROIs included only lung parenchyma with no large pulmonary vessels or airways; and ROIs were placed in subjectively matched locations across all scans for each foal.

Because attenuation corresponds with lung aeration, attenuation measurements from the whole lung field were used to evaluate the degree of lung aeration. Lung aeration was further characterized on the basis of a standard attenuation scale as belonging to 1 of 4 categories: hyperinflated = regions between –1,000 and –901 HUs, well aerated = regions between –900 and –501 HUs, poorly aerated = regions between –500 and –101 HUs, and nonaerated = regions ≥ –100 HUs. Total lung volume and relative proportion of lung volume in each of these categories of aeration were derived as described elsewhere.

Statistical analysis

Distribution of the continuous data was evaluated for normality by use of the Shapiro-Wilk test, skewness, kurtosis, and Q-Q plots. Normally distributed data were reported as mean ± SD values, and nonnormally distributed data were reported as median and range values. A repeated-measures ANOVA and the Friedman test for repeated measures were used to evaluate changes in measured variables over time for normally and nonnormally distributed data, respectively. Linear mixed models were used to evaluate quantitative CT data. Mean lung attenuation was the outcome variable, and treatment, time, and position were predictor variables included in the model. Interaction terms developed from the predictor variables were also included. A stepwise procedure was used in model building to determine the best fit. Values of P < 0.05 were considered significant. Commercial software was used to analyze the data.

Results

Four female and 2 male Standardbred foals were included in the study. Two additional foals did not meet inclusion criteria because of complications at birth. At time 1, median age was 31 hours (range, 28 to 36 hours) and mean ± SD body weight was 68 ± 10 kg. Body weight of all foals increased significantly (P = 0.002) over the course of the study. Complications associated with anesthesia or CT procedures were not observed, and results of physical examinations and CBCs remained within anticipated limits for the duration of the study.

Mean ± SD interval between induction of anesthesia and initiation of CT for all 4 study times was 8.22 ± 2.6 minutes. This interval did not differ significantly (P = 0.371) among the 4 study times. For study times 1 and 4 (baseline scan only), mean time for acquisition of CT images was 5.4 ± 2.3 minutes and 5.3 ± 3.4 minutes, respectively, and the mean durations of anesthesia and recovery were 55.5 ± 4.1 minutes and 39.4 ± 7.8 minutes, respectively. There were no significant differences in CT imaging time among the 4 study times, but the duration of anesthesia was significantly (P = 0.03) greater for time 1 than for time 4. For study times 2 and 3, mean ± SD CT imaging time was 24.67 ± 3.6 minutes and 25.33 ± 3.2 minutes, respectively, and the mean durations of anesthesia and recovery were 58.33 ± 6.9 minutes and 56.67 ± 4.9 minutes, respectively. There were no significant differences in CT imaging time (P = 0.796) or duration of anesthesia (P = 0.683) between study times 2 and 3. Mean ± SD breath-hold duration for ARMs was 23.3 ± 0.53 seconds for time 2 and 23.78 ± 1.5 seconds for time 3; breath-hold durations did not differ significantly (P = 0.476) between study times 2 and 3.

There were no significant differences in respiratory rate during anesthesia during any ARM for time 2 (P = 0.350) or time 3 (P = 0.242). Median respiratory rate for time 2 was 11.5 breaths/min (range, 4 to 20 breaths/min) and for time 3 was 11.5 breaths/min (range, 5 to 39 breaths/min). Although representative calculated tidal volume increased over the course of the ARMs, these increases were not significant for time 2 (P = 0.168) or time 3 (P = 0.341; Figure 2). There were no significant differences in indirect SAP, MAP, or DAP during anes-

![Figure 1](image1.png)
The P<sub>e</sub>T<sub>CO</sub> did not differ significantly during anesthesia for any ARM for time 2 (P = 0.281) or time 3 (P = 0.198; Figure 3). Median P<sub>e</sub>T<sub>CO</sub> during anesthesia for time 2 was 62.2 mm Hg (range, 52 to 69 mm Hg) and during anesthesia for time 3 was 60.5 mm Hg (range, 55 to 69 mm Hg).

The Sp<sub>O</sub> did not differ significantly during anesthesia for any ARM for time 2 (P = 0.664) or time 3 (P = 0.712; Figure 3). Median Sp<sub>O</sub> during anesthesia for time 2 was 99% (range, 93% to 100%) and during anesthesia for time 3 was 98.5% (range, 93% to 100%).

Descriptive analysis of baseline CT images obtained at times 1 through 4 revealed moderate-to-severe increases in attenuation and patchy-to-coalescing consolidation consistent with presumed atelectasis. This pattern was most prominent in the ventral portion of the lung field caudal to the heart in foals positioned in sternal recumbency (Figure 3) and in the caudal dorsalmost portion of the lung field in foals positioned in dorsal recumbency (Figure 4). Subjectively, the area of increased attenuation and consolidation did not differ when results for each foal were compared across study times 1 through 4, but it did appear to occupy a larger volume of the lung field in foals positioned in sternal recumbency, compared with the volume for foals positioned in dorsal recumbency.

Manual ARMs of 10, 20, and 30 cm H<sub>2</sub>O did not eliminate atelectasis. Subjectively, ARMS reduced atelectasis and provided a more homogenous distribution of lung attenuation in the nondependent portion of the lung field, with these regions also appearing to increase in volume (Figure 5). These changes were incremental, with the most prominent changes identified at 30 cm H<sub>2</sub>O for foals positioned in dorsal recumbency and with minimal changes identified at 10 cm H<sub>2</sub>O for all foals (Figures 3 and 4). Subjective evaluation of the abbreviated check-breath scans did not identify changes in attenuation or radiographic patterns.

Significant differences attributable to position (sternal vs dorsal) were not identified for any quantitative CT variable evaluated (Table 1). Thus, for purposes of statistical analysis, results were reported for all foals as 1 group, irrespective of position. Mean total lung volume measurements for baseline CT images increased significantly (P = 0.034) over the course of the study. When baseline CT images were compared across times 1 through 4, no significant differences were identified in mean total lung attenuation (P = 0.502) or the proportion of the lung field categorized as hyperaerated (P = 0.231), well aerated (P = 0.642), poorly aerated (P = 0.511), or nonaerated (P = 0.305). Quantitative evaluation of identified ROIs in check-breath scans acquired immediately before each ARM did not identify significant changes in measurements of lung attenuation.

The mean total lung volume measurements for baseline CT images increased significantly (P < 0.001) with ARMs of increasing pressure at times 2 and 3 (Figure 6).
When selected ROIs in the dependent, middle, and nondependent lung fields were evaluated during ARMs (Figure 7), significant decreases in attenuation were detected in the middle ($P = 0.019$) and nondependent ($P = 0.026$) lung fields but not in the dependent lung fields ($P = 0.442$). Quantitative measurements of total lung volume increased significantly with ARMs of increasing pressure at times 2 ($P = 0.001$) and 3 ($P = 0.004$). Changes in attenuation and volume were most pronounced at 20 and 30 cm H$_2$O (Figure 8). There were no significant differences between times 2 and 3 with respect to changes in attenuation ($P = 0.805$) or volume ($P = 0.684$) in response to ARMs. When selected ROIs in the dependent, middle, and nondependent lung fields were evaluated immediately before the ARMs (ie, check-breath scans), changes in attenuation were not identified (Figure 9).

Changes in the amount of the lung field categorized as hyperaerated, well aerated, poorly aerated, or nonaerated in response to ARMs were determined (Table 2). Compared with baseline values, ARMs caused significant ($P = 0.042$) increases in the proportion of the lung field categorized as hyperaerated at both times 2 and 3. These increases were not significant for ARMs of 10 cm H$_2$O ($P = 0.261$) but were significant for both 20 cm H$_2$O ($P = 0.034$) and 30 cm H$_2$O ($P = 0.007$). Application of ARMs also resulted in significant ($P = 0.002$) increases in the proportion of the lung field categorized as well aerated at both times 2 and 3. These increases were not significant at ARMs of 10 cm H$_2$O ($P = 0.316$) but were significant ($P < 0.001$) at both 20 and 30 cm H$_2$O. Increased amounts of hyperaerated and well aerated lung field corresponded to significant reductions in the proportion of the lung field categorized as poorly aerated ($P < 0.001$) or nonaerated ($P = 0.004$). Significant reductions in poorly aerated lung field were detected for ARMs of 10 cm H$_2$O ($P = 0.017$), 20 cm H$_2$O ($P < 0.001$), and 30 cm H$_2$O ($P < 0.001$). Significant ($P = 0.002$) reductions in the amount of nonaerated lung field were only found for ARMs of 30 cm H$_2$O.

**Discussion**

In the present study, CT of anesthetized neonatal foals with and without the
use of ARMs was tolerated well. Atelectasis was identified in all foals and was most prominent in the dependent portion of the lungs. Subjectively, atelectasis appeared more pronounced when foals were positioned in sternal recumbency for CT, compared with results for foals positioned in dorsal recumbency; however, quantifiable differences in attenuation attributable to positioning were not recognized. Application of ARMs did not eliminate atelectasis but did result in subjective and quantifiable improvements in lung attenuation, particularly in the nondependent lung regions. Contrary to our original hypotheses, age-related differences were not evident for severity of atelectatic changes or the response of foals to application of ARMs.

Anesthesia-associated atelectasis develops within minutes after anesthetic induction and appears on CT images as areas of increased attenuation (ie, density), particularly in dependent lung fields. Although morphological analysis in healthy sheep has confirmed these densities represent atelectatic portions of the lungs, the radiographic appearance is not unique to atelectasis and thus may complicate image interpretation in animals with concurrent pulmonary disease. In the study reported here, radiographic findings attributable to atelectasis were identified on CT at all time points. Images were acquired within 10 minutes after anesthetic induction for foals positioned in sternal recumbency, which indicated the relatively rapid formation of atelectasis in anesthetized, spontaneously breathing healthy foals.

In CT, atelectasis is defined quantitatively as regions of a lung with attenuation values between -100 and -100 HU, which corresponds to nonaerated portions of a lung. On the basis of this definition, the mean proportion of atelectatic lungs in the present study was between 19% and 27% without application of ARMs and was reduced to between 13% and 16% (reduction of 31% to 40.7%) after application of an ARM at 30 cm H₂O (Table 2). These proportions are much greater than those reported for anesthetized and mechanically ventilated sheep (7%) and adult (10%) and pediatric (6.7%) humans as well as for similarly aged sedated foals (0.15%). The absence of mechanical ventilation and

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**Figure 5**—Digital subtraction thoracic CT images for the cranial portion of the lungs (A), level of the heart caudal to the carina (B), and caudodorsal portion of the lungs (C) of a neonatal foal positioned in sternal recumbency. The images represent CT images obtained before application of a manual ARM superimposed on CT images obtained after application of an ARM at a PIP of 30 cm H₂O. Areas of the lungs in gray (asterisks) represent the matched recruited and nonrecruited portions of the lungs, whereas areas of the lungs in white (arrows) represent recruited lung field alone and correspond to an increase in lung volume. The ventral region of the lungs in dark gray (arrowhead) represents lung field with persistent atelectasis. Notice that the greatest differences in lung volume between recruited and nonrecruited portions of the lungs are primarily in the caudodorsal portion of the lungs.

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**Table 1**—Median (range) quantitative measurements of mean whole lung attenuation and mean total lung volume derived from CT images of anesthetized neonatal foals positioned in sternal (n = 3) or dorsal (3) recumbency before (baseline) and after sequential application of ARMs at a PIP of 10, 20, and 30 cm H₂O at each of 4 time points.*

<table>
<thead>
<tr>
<th>Position</th>
<th>Time</th>
<th>ARM</th>
<th>Attenuation (HU)</th>
<th>Lung volume (L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sternal</td>
<td>1</td>
<td>Baseline</td>
<td>–361.65 (–257 to –430)</td>
<td>2.3 (1.9 to 2.7)</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>Baseline</td>
<td>–341.85 (–273 to –404)</td>
<td>2.9 (2.1 to 3.1)</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>10 cm H₂O</td>
<td>–393.78 (–298 to –434)</td>
<td>3.0 (2.0 to 3.2)</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>20 cm H₂O</td>
<td>–518.67 (–366 to –531)</td>
<td>3.3 (2.4 to 3.7)</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>30 cm H₂O</td>
<td>–572.84 (–491 to –583)</td>
<td>4.1 (2.7 to 4.2)</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>Baseline</td>
<td>–302.75 (–184 to –393)</td>
<td>2.6 (1.9 to 3.3)</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>10 cm H₂O</td>
<td>–330.81 (–251 to –384)</td>
<td>2.8 (2.0 to 3.2)</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>20 cm H₂O</td>
<td>–461.29 (–411 to –467)</td>
<td>3.6 (2.4 to 3.8)</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>30 cm H₂O</td>
<td>–536.46 (–526 to –547)</td>
<td>4.1 (3.6 to 4.6)</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>Baseline</td>
<td>–418.93 (–307 to –425)</td>
<td>3.0 (2.1 to 3.7)</td>
</tr>
</tbody>
</table>

| Dorsal   | 1    | Baseline | –406.40 (–388 to –425) | 2.6 (2.4 to 2.8) |
|          | 2    | Baseline | –369.76 (–355 to –429) | 3.3 (2.5 to 3.7) |
|          | 2    | 10 cm H₂O | –448.66 (–427 to –466) | 3.3 (2.7 to 3.9) |
|          | 2    | 20 cm H₂O | –533.08 (–498 to –561) | 3.6 (3.0 to 4.5) |
|          | 2    | 30 cm H₂O | –538.28 (–532 to –593) | 4.2 (3.3 to 5.0) |
|          | 3    | Baseline | –375.48 (–314 to –399) | 3.3 (2.5 to 3.6) |
|          | 3    | 10 cm H₂O | –398.39 (–328 to –429) | 3.3 (2.9 to 3.8) |
|          | 3    | 20 cm H₂O | –445.64 (–319 to –470) | 3.4 (2.5 to 3.7) |
|          | 3    | 30 cm H₂O | –536.46 (–526 to –547) | 4.1 (3.6 to 4.6) |
|          | 4    | Baseline | –383.21 (–343 to –423) | 3.2 (3.0 to 3.8) |

*Time points were defined as follows: time 1, 24 to 36 hours after birth; time 2, 4 days after birth; time 3, 7 days after birth; and time 4, 10 days after birth.
likely corresponding hypoventilation may explain the higher proportion of atelectasis in the foals of the study reported here. In contrast, the proportion of nonaerated lungs reported for the sedated foals of that other study more closely approximated proportions of 0.01% reported for human pediatric patients sedated for CT. Factors influencing the formation of atelectasis that may be clinically relevant to healthy and sick neonatal foals undergoing CT include immaturity, positioning, increased Fi\textsubscript{O\textsubscript{2}}, and duration of anesthesia (or sedation). Compared with adults, pediatric patients, including neonatal foals, are considered more prone to the formation of atelectasis because of the greater chest wall compliance and susceptibility to decreases in functional residual capacity, propensity for respiratory muscle fatigue, and increased sensitivity to respiratory depressant effects of anesthetic drugs, which in the absence of ventilatory support may increase hypoventilation.

The preferential development of atelectasis in the dependent portion of the lungs is widely recognized regardless of positioning and is attributable to reduced transmural distending pressures and impaired lung expansion. Although cranial displacement of the diaphragm and abdominal organs creates compressive forces on the dorsally dependent portion of the lungs, the caudoventral portion of the lungs is considered most prone to atelectasis formation because of its greater surface area-to-volume ratio, increased compliance, and compression by the adjacent heart and overlying lung tissue. In the present study, atelectasis in the caudoventral portion of the lungs of foals in sternal recumbency appeared more pronounced than in the dorsally dependent portion of the lungs of foals in dorsal recumbency. This observation did not correspond to quantitative differences in measurements of nonaerated portions of the lungs that were attributable to positioning. Visual assessment of atelectasis may underestimate quantitatively derived volumes. This could be particularly true when

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**Figure 6** — Mean ± SD lung attenuation in anesthetized spontaneously breathing foals (n = 6) during study times 2 and 3 before (baseline) and after manual application of ARMs at a PIP of 10, 20, and 30 cm H\textsubscript{2}O. Lung attenuation decreased significantly (P < 0.001) with increasing PIP at both times 2 and 3. See Figure 2 for key.

**Figure 7** — Mean ± SD lung attenuation for representative ROIs in the dependent (black squares and dotted line), middle (gray circles and solid line), and nondependent (black diamonds and solid line) portions of the lungs in foals (n = 6) obtained at time 2 before (baseline) and after manual application of ARMs at a PIP of 10, 20, and 30 cm H\textsubscript{2}O. There were significant decreases in attenuation with increasing PIPs for the nondependent (P = 0.026) and middle (P = 0.019) portions of the lungs but not for the dependent portion of the lungs (P = 0.442).

**Figure 8** — Mean ± SD lung volume in anesthetized spontaneously breathing foals (n = 6) obtained at times 2 and 3 before (baseline) and after application of ARMs at a PIP of 10, 20, and 30 cm H\textsubscript{2}O. Lung volume increased significantly with increasing PIPs at time 2 (P = 0.001) and time 3 (P = 0.004). See Figure 2 for key.

**Figure 9** — Mean ± SD lung attenuation for representative ROIs in the dependent (black squares and dotted line), middle (gray circles and solid line), and nondependent (black diamonds and solid line) portions of the lungs in foals (n = 6) obtained at time 2 immediately before manual application of ARMs at a PIP of 10, 20, and 30 cm H\textsubscript{2}O. There were no significant (P ≥ 0.05) changes in attenuation identified among PIPs for any ROI.
Table 2—Mean ± SD percentage of total lung tissue characterized on the basis of lung aeration for CT images of anesthetized foals (n = 6) before (baseline) and after sequential manual application of ARMs at a PIP of 10, 20, and 30 cm H₂O obtained at each of 2 time points.*

<table>
<thead>
<tr>
<th>Time</th>
<th>ARM</th>
<th>Hyperaerated</th>
<th>Well aerated</th>
<th>Poorly aerated</th>
<th>Nonaerated</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>Baseline</td>
<td>0.71</td>
<td>38</td>
<td>38</td>
<td>24</td>
</tr>
<tr>
<td></td>
<td>10 cm H₂O</td>
<td>1.12</td>
<td>46</td>
<td>32</td>
<td>21</td>
</tr>
<tr>
<td></td>
<td>20 cm H₂O</td>
<td>1.66</td>
<td>63</td>
<td>20</td>
<td>16</td>
</tr>
<tr>
<td></td>
<td>30 cm H₂O</td>
<td>1.78</td>
<td>69</td>
<td>16</td>
<td>13</td>
</tr>
<tr>
<td>3</td>
<td>Baseline</td>
<td>0.66</td>
<td>31</td>
<td>42</td>
<td>27</td>
</tr>
<tr>
<td></td>
<td>10 cm H₂O</td>
<td>0.95</td>
<td>36</td>
<td>37</td>
<td>26</td>
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<tr>
<td></td>
<td>20 cm H₂O</td>
<td>1.05</td>
<td>54</td>
<td>23</td>
<td>22</td>
</tr>
<tr>
<td></td>
<td>30 cm H₂O</td>
<td>1.57</td>
<td>66</td>
<td>17</td>
<td>16</td>
</tr>
</tbody>
</table>

*Lung aeration was categorized as follows: hyperinflated = regions between –1,000 and –901 HU, well aerated = regions between –900 and –501 HU, poorly aerated = regions between –500 and –101 HU, and nonaerated = regions ≥ –100 HU.

See Table 1 for remainder of key.

comparing lung regions with relative differences in surface-to-volume ratio, which thus may explain the discrepancy in the present study between visual and quantitative interpretation of atelectasis in the dorsal and caudoventral lung regions.

Use of an FiO₂ above that of ambient air for delivery of inhalation anesthetics is considered the standard of care for most anesthetized patients, but the contribution of FiO₂ to atelectasis formation is clearly recognized. Increased FiO₂ drives greater oxygen transport across the alveolar membrane, contributes to washout of the alveolar nitrogen skeleton, and is most pronounced in regions of low ventilation-perfusion matching, especially with concurrent hypoventilation. Decreasing FiO₂ to < 1.0% has resulted in reduced atelectasis formation and improved response to ARMs but may also negatively impact hypoxemia in certain patients. An FiO₂ of 1.0% was used in the present study because it was considered most clinically applicable and was the standard of care for our facility; however, use of reduced FiO₂ concentrations has not been investigated in neonatal foals to the authors’ knowledge. It is unknown whether delivery of inhalation anesthetics with a reduced FiO₂ in the foals of the study reported here would have resulted in reduced atelectasis formation or an improved response to ARMs.

The suspected increase in atelectasis development during anesthesia has been reported in patients with concurrent pulmonary disease, patients undergoing abdominal or thoracic surgery, or patients with progressive hypventilation. Although progression of atelectasis could have impaired the response of the healthy foals in the study reported here to successive ARMs, it was most likely not a relevant contributing factor. In healthy anesthetized humans and sheep, pulmonary atelectasis detected within minutes after induction of anesthesia did not progress during the course of anesthesia when anesthesia exceeded 1 hour. In the present study, the duration of anesthesia for CT was < 1 hour, and although PetCO₂ was consistent with hypoventilation, it did not increase over the course of anesthesia, which indicated that hypoventilation was not increasing. Furthermore, changes in CT-derived measurements of lung attenuation obtained before each successive ARM were not identified in the dependent or nondependent portions of the lungs (Figure 9).

Differences in improvement of atelectasis in response to ARMs have been reported in humans and other animals. In the present study, ARMs resulted in improved whole lung attenuation and increased lung volume (Figures 6 and 8) but did not eliminate atelectasis and did not result in improved attenuation in the dependent (atelectatic) portion of the lungs (Figure 7). Furthermore, although the amount of poorly aerated lungs was decreased for all ARMs, significant reductions in the proportion of nonaerated lungs were detected only at 30 cm H₂O (Table 2). The ideal pressure required to open atelectatic regions of healthy lungs in anesthetized foals is unknown. In mechanically ventilated anesthetized adult horses, recruitment pressures as high as 60 to 80 cm H₂O have been reported. In contrast, in mechanically ventilated anesthetized cats, single inflation pressures of 15 cm H₂O reduce but do not eliminate atelectasis, and in humans, inflation pressures of 30 to 40 cm H₂O are necessary for successful recruitment but may not achieve a sustained effect without the presence of a peak end expiratory pressure.

Because neonatal foals have a relatively compliant chest wall and small thoracic mass, recommended ventilator settings for inspiratory pressure in these animals are approximately half those used for adult horses. To avoid potential barotrauma, pressures chosen for the study reported here were more closely approximated those reported for humans and small animals. Given the partial resolution of atelectasis, it is possible that higher pressures for inflation or sequential inflations over a series of breaths would have been necessary to improve recruitment. It is also likely that pressure measured at the anesthesia machine in the present study underestimated the actual pressure delivered to the lungs because of the unavoidable loss of pressure associated with compliance of the anesthesia machine and tubing. Thus, further evaluation of recruitment by use of greater pressures or serial
inflations should be performed with consideration for the anatomic location at which pressure is measured.

Overdistention of noncollapsed or partially collapsed alveoli during recruitment may result in barotrauma and is evaluated on CT by measuring increases in lung volume and the proportion of hyperaerated lungs.21,22 In the present study, significant increases in the proportion of hyperinflated lungs were detected in response to recruitment at pressures of 20 and 30 cm H2O. Furthermore, increases in total lung volume identified on CT subsequent to recruitment appeared limited to nondependent (nonatelectatic) portions of the lungs (Figure 5), which corresponded to the area of the healthy lungs most likely to contain noncollapsed or partially collapsed alveoli. Although the maximum proportion of hyperaerated lungs remained < 2% of total lung volume in the healthy foals of the present study, the impact in foals with pulmonary disease, particularly those that may be more susceptible to barotrauma or volutrauma,22 is unknown.

In another study,27 subjective and quantitative identification of atelectasis on CT was more pronounced in healthy sedated foals < 7 days old than in foals 7 to 14 days old. Contrary to our hypotheses, age-related differences in attenuation, categorization of lung aeration, or response to ARMs were not identified at any time point in the present study. Age-related differences in sedated foals have been attributed to suspected differences in chest wall compliance and specific lung differences in younger foals.26,31,52 Although these differences may also have existed for the foals in the study reported here, it is possible that the respiratory depressant effects of sedative and anesthetic agents and the subsequently greater magnitude of the atelectasis masked age-related differences. It is also recognized that a greater age difference between successive ARMs may have been necessary to detect differences, assuming they existed.

The present study had several limitations. Measurements of direct blood pressure and arterial blood gas variables were not performed because of the short duration of anesthesia but would have allowed for more sensitive monitoring of hemodynamic changes, including evidence of cardiovascular depression, hypercapnia, and hypoxemia. A potential bias in the study was that the order of ARMs was not randomized. The decision to sequentially increase pressure was made to reduce the potential additive effect that an earlier ARM at a higher pressure might have had on a subsequent ARM at a lower pressure. Although it was still possible that a previous ARM may have influenced subsequent ARMs, all foals had regular respiratory patterns for a minimum of 5 minutes between successive ARMs, which should have provided sufficient time for the reformation of atelectasis given the rapidity of atelectasis formation.35 Furthermore, measurements of lung attenuation immediately before each successive ARM did not identify progressive decreases for the dependent or nondependent portions of the lungs. Finally, although anesthesia-associated atelectasis reportedly resolves within 24 hours in other species,23,24 this has not been specifically evaluated in neonatal foals. Thus, it is unknown whether repeated anesthetic events over the course of the present study influenced atelectasis formation.

Single inflation ARMs are considered to be rapidly useable, safe, and clinically applicable; thus, they were considered an appropriate approach for minimizing atelectasis in neonatal foals anesthetized for the purpose of CT. Results from the present study suggested that although the ARMs were tolerated well by all foals, atelectasis was not totally eliminated at the pressures used. Furthermore, comparison with previous studies27,28 in which CT images for healthy, sedated foals have been described would suggest that the use of inhalation anesthesia without ventilatory support may result in more profound development of atelectasis.

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**Footnotes**

- Pneumomune-Re, Lake Immunogenics Inc, Ontario, NY.
- IDEXX Snap foal IgG test kit, IDEXX Laboratories Inc, Westbrook, Me.
- Cell-dyn 3700 hematology analyzer, GMi Inc, Ramsey, Minn.
- MILA International Inc, Erlanger, Ky.
- Butorphic, 10 mg/mL, Lloyd Laboratories Inc, Shenandoah, Iowa.
- Midazolam, 5 mg/mL, Hospira Inc, Lake Forest, Ill.
- PropoFlo, 10 mg/mL, Abbott Laboratories, North Chicago, Ill.
- Randomness and integrity services Ltd, Dublin, Ireland.
- Millennium small animal machine, Eagle Eye Anesthesia Inc, Jacksonville, Fla.
- Mark 20 Wright respirometer, Ferraris Medical Inc, Louisville, Colo.
- SevoFlo, Abbott Laboratories, North Chicago, Ill.
- Datascope Passport, Datascope Corp, Paramus, NJ.
- GE Healthcare, Chalfont St Giles, Buckinghamshire, England.
- OsiriX, v6.5.2 64-bit Pixmeo, Geneva, Switzerland.
- SPSS, version 22.0, IBM Statistics, Armonk, NY.

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