# Comparison of radiographic and computed tomographic images of the lungs in healthy neonatal foals

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Received May 14, 2014.
Accepted August 25, 2014.

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## OBJECTIVE
To compare CT and radiographic images of the lungs in sedated healthy foals positioned in sternal recumbency and to investigate whether a relationship exists between CT-derived measurements of lung attenuation and $Pa{CO_2}$ and $Pa{O_2}$.

## ANIMALS
6 healthy Standardbred foals < 14 days of age.

## PROCEDURES
Thoracic CT images were acquired followed by radiographic views with each foal sedated and positioned in sternal recumbency. For each foal, both CT and radiographic images were evaluated for severity and extent of changes by lung regions on the basis of a subjective scoring system by 3 investigators. Quantitative analysis of CT images was also performed. Assessments of $Pa{O_2}$ and $Pa{CO_2}$ were performed before sedation, following sedation prior to CT, and after CT prior to radiography.

## RESULTS
Interobserver agreement for CT and radiographic image scoring was strong (0.73) and fair (0.65), respectively; intraobserver agreement was near perfect for CT (0.97) and radiographic (0.94) image scoring. Increased CT attenuation and radiographic changes were identified for all foals and were preferentially distributed in the caudoventral portion of the lungs. Radiographic scores were significantly lower than CT image scores. A positive correlation ($r$ = 0.872) between lung attenuation and CT image score was identified. A significant increase in $Pa{CO_2}$ was not considered clinically relevant. Significant changes in $Pa{O_2}$ were not observed.

## CONCLUSIONS AND CLINICAL RELEVANCE
Results suggested that interpretation of CT images may be less subjective, compared with interpretation of radiographic images. These findings may aid in the evaluation of CT and radiographic images of neonatal foals with respiratory tract disease. (*Am J Vet Res* 2015;76:42–52)

Computed tomography is considered the gold standard for lung imaging in human medicine.[1-5] Multidetector CT along with quantitative 3-D CT image analysis of lung attenuation and the distribution of whole lung and regional gas and tissue volumes has led to improvements in the CT characterization of various pulmonary diseases[1-5] as well as nonpathological changes such as atelectasis.[2-6] In veterinary medicine, particularly for dogs and cats, CT characteristics of the lungs are well described,[7,8] and CT is also considered superior to standard radiography for the detection of pathological changes within the lungs.[9-13] In hospitalized neonatal foals, for which respiratory tract disease significantly impacts patient morbidity and mortality rates,[14-17] radiography remains the standard imaging technique for reasons of availability, cost, and practicality. The increasing availability of multidetector CT units in veterinary hospitals and the ability to perform CT examination of foals without the use of general anesthesia[18] may allow increased use of CT in this population of veterinary patients.

## ABBREVIATION
HU Hounsfield units

Computed tomographic imaging of the lungs has been described for healthy sedated neonatal foals.[18] In all foals in that study,[18] increased CT lung attenuation and patchy alveolar patterns were observed in the dependent lung fields, relative to findings in the nondependent lung fields. These changes were considered most consistent with atelectasis and were most pronounced in foals < 7 days of age.[18] Radiographic evaluation of the lungs of healthy and sick neonatal foals has also been undertaken.[17,19-21] In healthy newborn foals, radiographic opacities related to ongoing fetal fluid absorption, which may interfere with accurate diagnosis of respiratory tract disease, are no longer present by 6 to 12 hours after birth.[20,21] In hospitalized foals with respiratory tract disease, the most commonly reported radiographic change is an alveolar-interstitial pattern within the caudoventral and caudodorsal lung regions,[17,20] with greater caudodorsal lung pathological changes associated with poorer clinical outcomes. Observation of an interstitial pattern on radiographic views of foals in lateral recumbency is associated with mild or early positional atelectasis, but may also be seen in cases of pneumonia. With more pronounced atelectasis, an alveolar pattern may also be observed.[20] To date, there are no reports comparing radiographic with CT lung imaging for foals, to our knowledge.

Atelectasis of the lungs is readily detected with CT as regions of increased soft tissue attenuation (compared with findings for normal, unaffected tissue) and has the potential to interfere with the accurate evaluation of CT images. In humans, a primary reason for the development of atelectasis involves the use of sedation or IV or inhalation anesthesia in spontaneously breathing or ventilated patients undergoing CT imaging.[22] Investigations examining anesthesia- or sedation-associated atelectasis routinely use CT as the preferred imaging method for identifying and quantifying the volume and distribution of atelectatic lung tissue.[6,18,23–26] Under these conditions, the mechanisms thought to contribute to the development of atelectasis include compression of the dependent lung regions, increased absorption of alveolar gas, and reduction in pulmonary surfactant.[6,22–26] In neonatal foals sedated for CT examinations, the mechanisms contributing to atelectasis most likely include compression of the ventral lung regions by overlying lung tissue and possible effects of sedative medications on ventilation.[18]

In addition to the potential impact on accurate CT image interpretation, atelectasis may impair gas exchange and hypoxemia, as has been described for awake and anesthetized ponies and horses positioned in lateral recumbency[23,27] and anesthetized horses and humans positioned in dorsal or sternal recumbency.[23,28–30] Atelectasis may be affected by positioning of the patient, with prone or ventral position resulting in better oxygenation in both humans and other animals, respectively.[31] Studies of anesthetized adult ponies in dorsal recumbency[23] and humans in supine position[29,32] have identified a relationship between the amount of atelectatic lung tissue determined with CT and the degree of impairment in gas exchange. Recumbent foals are commonly positioned in sternal recumbency to minimize atelectasis and improve gas exchange as indicated by findings of Stewart et al.[33] The relationship between the volume of atelectatic lung as detected by CT and measurements of $Pa{O_2}$ and $Pa{CO_2}$ has not been reported in sedated foals in sternal recumbency, to our knowledge.

The objectives of the study reported here were to compare CT and radiographic images of the lungs in sedated healthy foals positioned in sternal recumbency and to investigate whether a relationship exists between CT-derived measurements of lung attenuation and $Pa{O_2}$ and $Pa{CO_2}$. The intent was to compare CT and radiographic images on the basis of descriptive findings and a subjective scoring system of the severity and extent of pathological changes and to investigate whether quantitative measurements of lung attenuation on CT images correspond to subjective scores for findings. We hypothesized that positional atelectasis would be identified primarily in the caudoventral portion of the lungs on CT images. We also hypothesized that if identified on radiographic views, atelectasis would be identified in the same region as determined by CT, but would be scored as more severe by use of CT images. Finally, we hypothesized that greater whole lung attenuation and a greater amount of lung categorized as poorly aerated would correspond to higher scores (ie, greater severity and extent of pathological changes) assigned to images and lower arterial $Pa{O_2}$ and higher $Pa{CO_2}$ measurements in the foals.

## Materials and Methods

### ANIMALS

Seven healthy university-owned Standardbred foals (≤ 14 days of age) were used in the study. Prior to study inclusion, all foals underwent complete physical examination, hematologic analysis including CBC[a] and arterial blood gas analysis,[b] ultrasonographic examination[c] of the lungs and heart, and standing bilateral thoracic radiography[d] to ensure that they were in good health and to rule out any underlying cardiopulmonary disorders. Three additional foals were excluded from study participation. One foal had rib fractures visible on standing thoracic radiographs, and 2 foals had fever and an inflammatory leukogram. Study foals were housed with their dams from birth at the University of Illinois Horse Farm and transported 2 km to the Veterinary Teaching Hospital the morning of the experiment. Experimental procedures and full recovery from sedation were completed within 7 hours for all foals. The foals were monitored continuously throughout the experimental period until full recovery from sedation and normal nursing behavior was observed. Computed tomographic image data, but not radiographic data, from 2 foals in this study were included in a previous study.[18] This study was approved by the University of Illinois Institutional Animal Care and Use Committee (protocol No. 10064).

### SEDATION

For each foal, a 16-gauge over-the-wire jugular catheter[e] was placed aseptically in the upper third of the right or left jugular vein for administration of medications. Foals were administered butorphanol tartrate[f] (0.05 mg/kg) and midazolam[g] (0.1 mg/kg) for sedation immediately prior to CT. If additional sedation was necessary to complete image acquisition, second doses of butorphanol (0.05 mg/kg) and midazolam (0.1 mg/kg) with or without propofol[h] (maximum dose, 4 mg/kg [administered to effect]) were administered. Foals breathed spontaneously throughout the entire procedure without provision of supplemental oxygen. Following image acquisition, recumbent foals were transported back to the stall and allowed to recover under supervision.

### CT IMAGE ACQUISITION

Each foal was positioned on the CT table in sternal recumbency with the head facing the CT gantry and the forelimbs and hind limbs extended cranially and caudally, respectively. Standard positioning was confirmed on the CT scout image by alignment of the caudal border of the scapulae with the vertebrae. Images were acquired with a 16-slice helical CT scanner[i] 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.[18] Computed tomographic images were stored as Digital Imaging and Communications in Medicine (DICOM) files for analysis.

## RADIOGRAPHIC IMAGE ACQUISITION

Immediately following CT image acquisition, while each foal remained in sternal recumbency, bilateral horizontal beam thoracic radiographic views were obtained with a portable computed radiography system.[j] Limb positioning was identical to that used for the CT examination. The following settings were used: 90 kV, 5 to 10 mA. Radiographic images were stored as DICOM files for analysis.

## ARTERIAL BLOOD GAS ANALYSIS

For each foal, a 1- to 2-mL blood sample for arterial blood gas analysis[b] was collected aseptically from a dorsal metatarsal artery at each of 3 time points: prior to sedation, after sedation immediately prior to CT image acquisition, and after CT immediately prior to radiographic image acquisition. The blood sample collected prior to sedation was obtained with each foal in lateral recumbency; the other blood samples were collected when the foal was positioned in sternal recumbency. A sampling kit with dry lithium heparin[k] was used for collection of arterial blood, and samples were analyzed immediately following collection. Sample exposure to oxygen was minimized by expulsion of air from the syringe, thorough mixing of the sample, and immediate processing after removal of the stopper.

## DESCRIPTIVE IMAGE ANALYSIS AND SCORING OF RADIOGRAPHIC AND CT IMAGES

All CT and radiographic images were independently reviewed by 3 investigators, including a board-certified radiologist (RTO), a board-certified internist (KML), and a resident in equine internal medicine (ECS). Investigators were blinded to which CT and radiographic images were from the same foal as well blinded to foal age, amount of propofol administered, and blood gas analysis results. Images were assessed for quality and subjectively described according to the presence or absence of soft tissue attenuation or any other remarkable changes.

Radiographic images were objectively scored on the basis of a system modified from a previous report.[17] Briefly, the thorax was divided into 4 anatomic regions: craniodorsal, cranioventral, caudodorsal, and caudoventral **(Figure 1)**. The carina and caudal vena cava were used as landmarks to separate cranial from caudal portions and dorsal from ventral portions, respectively. The presence or absence of bronchial, interstitial, and alveolar patterns was assessed for each region. Bronchial and interstitial lung patterns were categorized as absent, mild, moderate, or severe and assigned a score of 0, 1, 2, or 3, respectively. Alveolar patterns were categorized as absent, minimal, focal, localized, or extensive and assigned a score of 0, 1, 3, 4, or 6, respectively. Because an extensive alveolar pattern may interfere with the assessment of bronchial or interstitial patterns, scores for alveolar, bronchial, and interstitial patterns were added to obtain a summarized regional score, with the maximum regional score being 6. Regional scores were then combined for a maximum total score of 24. The total score was divided by the number of regions assessed (4), resulting in a corrected total score with a maximum corrected score of 6. From scores assigned by each of the 3 reviewers, mean values were calculated.

Computed tomographic images were subjectively evaluated on the basis of a similar scoring system with the thorax divided into 4 anatomic regions: craniodorsal, cranioventral, caudodorsal, and caudoventral. Similar landmarks were used divide the lungs into cranial, caudal, dorsal, and ventral regions. Once the regions were identified, they were further subdivided to account for potential slice-to-slice variability in radiographic patterns

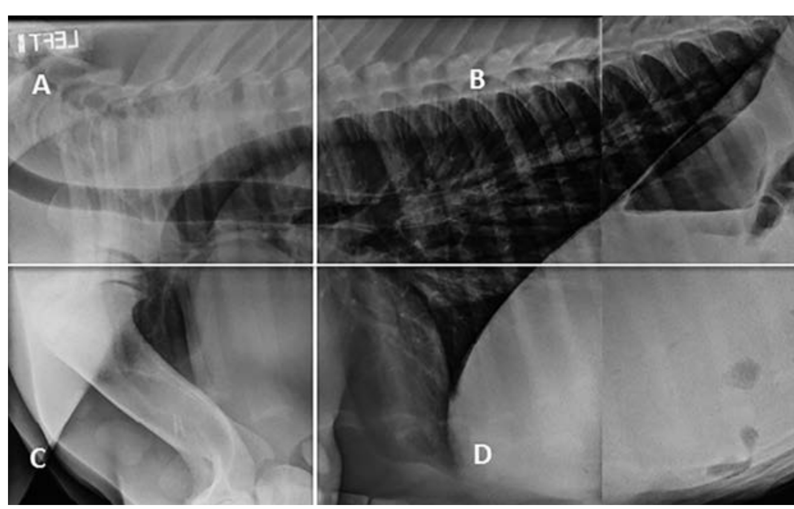


**Figure 1**—Composite of lateral thoracic radiographs of a sedated neonatal Standardbred foal positioned in sternal recumbency illustrating division of the lung fields into craniodorsal (A), caudodorsal (B), cranioventral (C), and caudoventral (D) regions for assessment and assignment of subjective scores for soft tissue attenuation and characterization of bronchial, interstitial, and alveolar patterns. A horizontal white line overlies the ventral margin of the cranial vena cava to separate the craniodorsal region from the cranioventral region, a horizontal white line overlies the dorsal margin of the caudal vena cava to separate the caudodorsal region from the caudoventral region, and a vertical white line through the carina separates the cranial regions (craniodorsal and cranioventral) from the caudal regions (caudodorsal and caudoventral).

within a particular region. Each region was partitioned into 5 equal segments based on the total number of transverse CT slices per region. The CT slices bordering each segment were evaluated and scored. Thus, for each of the craniodorsal, cranioventral, caudodorsal, and caudoventral regions, 4 representative slices were evaluated in each foal **(Figure 2)**. The maximum score for any of these 4 transverse slices was used as total regional score. The same scoring system used for radiographic interpretation was applied to CT images with a maximum regional score of 6, a maximum total lung score of 24, and a maximum corrected total score of 6. From scores assigned by each of the 3 reviewers, mean values were calculated. Randomized repeated readings of both CT and radiographic images at monthly intervals were performed 3 times by 1 investigator (ECS) to test repeatability of scoring.

## QUANTITATIVE ANALYSIS OF CT IMAGES

Quantitative image analysis was performed with the aid of semiautomated software[l] as previously described.[18] Initial 3-D segmentation of lung tissue from nonlung structures was performed by selecting structures with attenuation between −860 and −120 HU. Additional slice-by-slice manual segmentation was performed to exclude large vessels or other air-filled structures (eg, trachea, large airways, gas-filled stomach, or gas-filled small intestine) and to include areas of lung measuring > −120 HU, including presumed atelectatic regions. Attenuation measurements obtained from segmented lung areas were averaged and reported as mean whole lung attenuation. Because attenuation corresponds with lung aeration,[2,3] attenuation measurements were used to evaluate the degree of whole lung aeration. Lung aeration was further characterized as belonging to 1 of 4 categories based on a standard attenuation (HU) scale, with 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.[2,3] Total lung volume and relative proportion of lung volume belonging to these categories of aeration were derived as previously described.[18] Whole lung attenuation and the relative volume of lung characterized as hyperinflated, well aerated, poorly aerated, and nonaerated were correlated to CT and radiographic scores as well as to measurements of $Pa{O_2}$ and $Pa{CO_2}$ before and after CT image acquisition.

## STATISTICAL ANALYSIS

Sample size for this study was determined on the basis of the following criteria: $\alpha = 0.05$, power = 0.80, expected difference of 80 (± 50) HU for CT attenuation, and expected difference of 10 (± 3) mm Hg for arterial blood gas variables. For comparisons of CT attenuation and arterial blood gas variables, sample sizes of 4 and 6 foals, respectively, were required. Distribution of the data was evaluated by means of the Shapiro-Wilk test. Results are reported as mean ± SD.

Interobserver agreement for CT and radiographic interpretation was determined on the basis of intraclass correlation coefficients. Intraobserver agreement for repeated readings by 1 reader was also determined on the basis of intraclass correlation coefficients. Comparison between CT image scores and radiographic image scores for each foal was performed with a Wilcoxon matched pairs test. Correlation between arterial blood gas variables and lung volume or categories of aeration of the lung tissue was determined by means of a Pearson correlation test. Correlation between lung volume and categories of lung tissue aeration, weight, total dose of propofol administered, or age was also determined by means of a Pearson correlation test. Changes in $Pa{O_2}$ and $Pa{CO_2}$ over time (within subject) and by age (between subjects) were evaluated via a general linear model for repeated measures. Significance was set at a value of $P < 0.05$. A commercial statistical software program[m] was used to analyze the data.

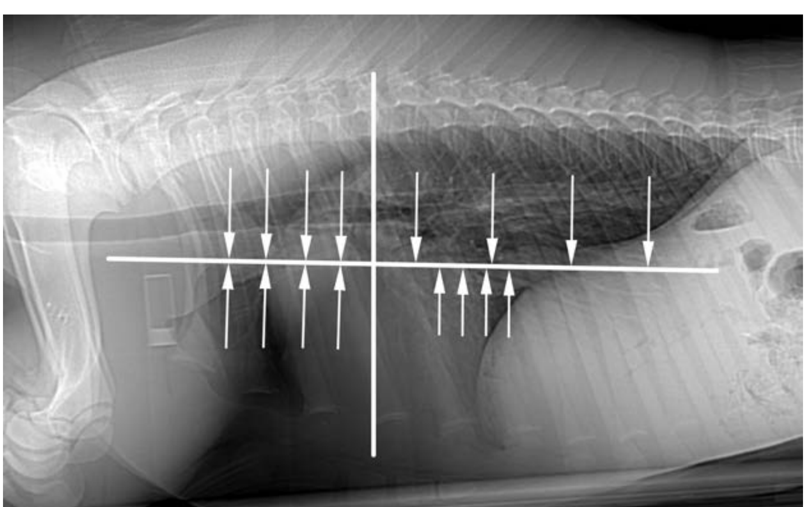

**Figure 2**—Lateral CT scout image of a sedated neonatal Standardbred foal positioned in sternal recumbency. Cranial is to the left of the image. The thorax is divided into craniodorsal, cranioventral, caudodorsal, and caudoventral regions with a horizontal line overlying the ventral margin of the cranial vena cava (to separate the craniodorsal region from the cranioventral region), a horizontal line overlying the dorsal margin of the caudal vena cava (to separate the caudodorsal region from the caudoventral region), and a vertical line through the carina (to separate the craniodorsal region from the caudodorsal region and the cranioventral region from the caudoventral region). Each region is further subdivided into 5 equal segments based on CT slice number. The arrows represent the slices bordering these segments that were evaluated for image scoring. ***See*** Figure 1 for remainder of key.

# Results

Seven foals (5 fillies and 2 colts) were initially included in the study. Foals were 3 to 12 days old (mean ± SD, 6.9 ± 3.8 days) and weighed between 58 and 90.5 kg (mean, 74 ± 12.1 kg). One foal was excluded from both CT and radiographic image analysis owing to poor response to sedation

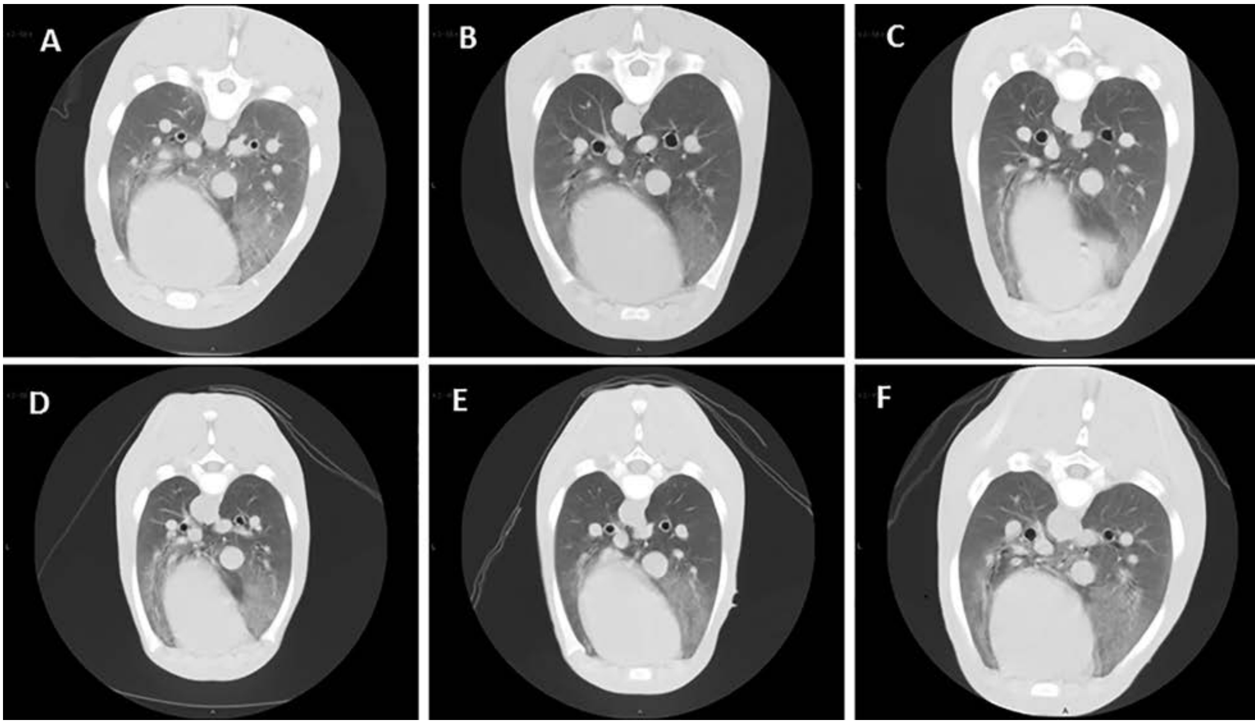


**Figure 3**—Transverse thoracic CT images obtained at the same anatomic location (the level of heart caudal to the carina) in 6 Standardbred foals (A through F) < 14 days of age. Variable degrees of increased attenuation (opacification) of the lung parenchyma with unstructured interstitial and patchy to coalescing alveolar (ground glass) patterns in the ventral portion of the lungs are evident.

and resultant excessive movement and poor quality of the CT and radiographic images. A second foal was excluded from radiographic image analysis because the digital file for the radiographic views was not properly saved. No additional complications were encountered in any foal during acquisition of the CT and radiographic images. Comparisons between CT and radiographic images were restricted to data from the 5 foals with both CT and radiographic images of good quality.

## IMAGING PROCEDURES

The depth of sedation with butorphanol and midazolam differed among foals but was sufficient for completion of CT image acquisition in 6 of the 7 foals. Six foals required administration of propofol for additional sedation during subsequent acquisition of the radiographic images. The mean ± SD total propofol dose administered was 0.54 ± 0.43 mg/kg (range, 0 to 1.32 mg/kg). Recovery from sedation was unremarkable for all foals.

## RADIOGRAPHIC AND CT DESCRIPTIVE ANALYSIS

Five foals were included for radiographic image analysis, and 6 foals were included for CT image analysis. On the radiographic views, occasional artifacts (restraint bands and hair) were identified, but none interfered with interpretation because they did not overlap lung regions. Minor motion artifacts attributed to breathing were identified in 5 foals on several CT slices and appeared as black or white bands, dark spots, loss of resolution, or distortion of anatomic features. When motion artifacts interfered with accurate interpretation of the lung tissue, the next caudal slice without evidence of motion was interpreted.

Radiographically, an alveolar pattern consistent with atelectasis was identified in 4 of 5 foals, with the caudal lung regions being more affected than the cranial lung regions and the caudoventral region being slightly more affected than the caudodorsal region. Moderate interstitial changes were noted primarily in the caudodorsal lung region. Within CT images, soft tissue attenuation (opacification) and interstitial and patchy to coalescing alveolar (ground glass) patterns with occasional air bronchograms consistent with atelectasis were identified ventrally and caudal to the heart in the caudoventral region in all foals **(Figure 3)**. Subjectively, there was no difference in CT image interpretation between the right and left lungs. Also, there were no subjective differences between either radiographic or CT images that could be attributed to age or weight of the foals.

## CT AND RADIOGRAPHIC IMAGE SCORES

Mean ± SD total image scores (maximum possible score, 24) for CT (n = 6) and radiographic (5) images were 10.0 ± 2.1 (range, 5 to 15) and 7.8 ± 2.1 (range, 3 to 13), respectively. Mean corrected total image scores (maximum possible score, 6) for CT and radiographic images were 2.5 ± 0.62 and 1.95 ± 0.59 (range, 0.92 to 2.33), respectively. Total CT image scores (n = 5) were significantly ($P$ = 0.042) higher than total radiographic image scores. Corrected

CT image scores (n = 5) were also significantly ($P$ = 0.042) higher than corrected radiographic image scores. There was a significant ($P$ = 0.011) correlation between corrected CT and radiographic scores (n = 5; **Figure 4**). The mean scores were highest in the caudoventral region for both CT (5.4 ± 0.94) and radiographic (3.3 ± 0.56) images **(Table 1)**. These findings corresponded to the distribution of changes identified in the descriptive interpretation of the images. Interobserver class coefficient was fair (0.65) for radiographic image scores and strong (0.73) for CT image scores. Intraobserver agreement showed near perfect agreement for CT (0.97) and radiographic (0.94) image scores.

## LUNG ATTENUATION AND VOLUME

Mean CT whole lung attenuation was –463 ± 57 HU (range, –536 to –390 HU) for all foals (n = 6). Whole lung attenuation was consistent with well-aerated lung tissue (–900 to –500 HU) in 2 of 6 foals and consistent with poorly aerated lung tissue (–500 to –100 HU) in 4 of 6 foals.

Mean whole lung volume was 3.25 ± 0.34 L (range, 2.5 to 3.72 L) for all 6 foals. Mean percentage of lung volume characterized as hyperinflated was 0.12 ± 0.08% (range, 0.05% to 0.27%), as well aerated was 45.5 ± 18.32% (range, 25% to 71%), as poorly aerated was 52.5 ± 17.72% (range 27% to 71%), and as nonaerated was 2.1 ± 0.93% (range, 0.21% to 3.2%).

There was no correlation between attenuation and either foal age ($P$ = 0.130) or the amount of propofol administered ($P$ = 0.199). However, there was a significant ($P$ = 0.018) positive correlation ($r$ = 0.838) between foal weight and extent of CT lung attenuation **(Figure 5)**. There was also a significant negative correlation between body weight and percentage of well-aerated lung tissue as measured by CT ($r$ = –0.867; $P$ = 0.012) and a positive correlation between weight and poorly aerated lung tissue ($r$ = 0.875; $P$ = 0.010).

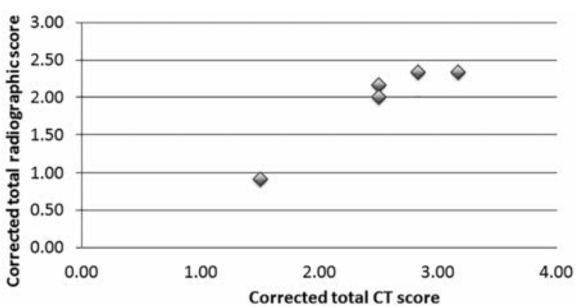


**Figure 4**—Correlation ($P$ = 0.011) between total corrected radiographic and corrected total CT image scores for 5 sedated healthy Standardbred foals < 14 days of age positioned in sternal recumbency during image acquisition. Sedated foals underwent CT examination followed by radiography. The CT and radiographic images were divided into craniodorsal, cranioventral, caudodorsal, and caudoventral regions, and each region was scored for bronchial, interstitial, and alveolar patterns (radiographic images). Bronchial and interstitial lung patterns were categorized as absent, mild, moderate, or severe and assigned a score of 0, 1, 2, or 3, respectively. Alveolar patterns were categorized as absent, minimal, focal, localized, or extensive and assigned a score of 0, 1, 3, 4, or 6, respectively. Because an extensive alveolar pattern may interfere with the assessment of bronchial or interstitial patterns, scores for alveolar, bronchial, and interstitial patterns were added to obtain a summarized regional score, with a maximum regional score of 6. Regional scores were then combined for a maximum total score of 24. The total score was divided by the number of regions assessed (4), resulting in a corrected total score (maximum corrected score, 6). Computed tomographic images were subjectively evaluated on the basis of a similar scoring system. Once the regions were identified, they were further subdivided to account for potential slice-to-slice variability in radiographic patterns within a particular region. Each region was partitioned into 5 equal segments based on the total number of transverse CT slices per region. The CT slices bordering each segment were evaluated and scored. Thus, for each of the craniodorsal, cranioventral, caudodorsal, and caudoventral regions, 4 representative slices were evaluated for each foal. The maximum score for any of these 4 transverse slices was used as the total regional score. The same scoring system used for radiographic interpretation was applied to CT images with a maximum regional score of 6, a maximum total lung score of 24, and a maximum corrected total score of 6. Mean values of scores assigned by 3 reviewers were calculated.

## CORRELATION OF CT LUNG ATTENUATION WITH IMAGE SCORES

Significant ($P$ = 0.023) positive correlation ($r$ = 0.872) was detected between mean lung attenuation and CT image scores for both total and corrected total scores **(Figure 6)**. There were also significant negative and positive correlations between percentage of normally aerated ($r$ = –0.841; $P$ = 0.036) and poorly aerated lung tissue ($r$ = 0.827; $P$ = 0.042) for both total and corrected total CT scores, respectively. There was no significant ($P$ = 0.084) correlation between mean CT lung attenuation and radiographic image scores.

## CHANGES IN $Pa_{O_2}$ AND $Pa_{CO_2}$

Among the 6 foals, mean $Pa_{O_2}$ was 76.8 ± 5.77 mm Hg (range, 65.9 to 81.7 mm Hg) prior to sedation, 67.2 ± 5.5 mm Hg (range, 66.4 to 79.6 mm Hg) prior to CT, and 71.2 ± 8.87 mm Hg (range, 63.3 to 75.5 mm Hg) prior to radiography **(Figure 7)**. There was no significant ($P$ = 0.166) difference in $Pa_{O_2}$ detected among time points. There was also no correlation between $Pa_{O_2}$ and age ($P$ = 0.339).

Among the 6 foals, mean $Pa_{CO_2}$ was 41.2 ± 2.58 mm Hg (range, 37.6 to 45.1 mm Hg) prior to sedation, 42.7 ± 1.99 mm Hg (range, 41.2 to 45.9 mm Hg) prior to CT, and 42.1 ± 5.52 mm Hg (range, 40.5 to 54.7 mm Hg) prior to radiography. The $Pa_{CO_2}$ increased significantly ($F$ = 3.69; $P$ = 0.05), compared with the presedation value **(Figure 8)**. Age and $Pa_{CO_2}$ were not correlated ($P$ = 0.137).

## CORRELATION OF CT IMAGE SCORES, LUNG VOLUME, AND LUNG ATTENUATION WITH $Pa_{O_2}$ AND $Pa_{CO_2}$

A significant negative correlation was detected between CT image score and $Pa_{O_2}$ prior to CT ($r$ = 0.872; $P$ = 0.023) but not between radiographic image score and $Pa_{O_2}$ prior to radiography ($r$ = 0.827; $P$ = 0.084). No significant correlations between CT or radiographic image scores and $Pa_{O_2}$ were observed for any other time

**Table 1**—Scores for lung changes (maximum score, 6) identified in CT and radiographic images obtained from 5* sedated healthy Standardbred foals < 14 days of age positioned in sternal recumbency.

| | Thoracic region | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Craniodorsal | | Cranioventral | | Caudodorsal | | Caudoventral | |
| Foal | Radiographic image score | CT image score | Radiographic image score | CT image score | Radiographic image score | CT image score | Radiographic image score | CT image score |
| 1 | 0.7 | 1 | 1.3 | 2.3 | 3 | 1.3 | 3.6 | 6 |
| 2 | 0.7 | 0.3 | 2.3 | 1.6 | 3 | 1.3 | 3.6 | 5.6 |
| 3 | 1 | 0.3 | 2 | 1 | 2.3 | 3 | 3.3 | 5.3 |
| 4 | 0.3 | 0 | 1 | 1.6 | 1 | 0.6 | 2.3 | 3.6 |
| 5 | 1 | 1.6 | 1.6 | 2 | 3.3 | 3.6 | 3.6 | 6 |
| Mean | 0.7 | 0.7 | 1.5 | 1.7 | 2.5 | 1.6 | 3.3 | 5.4 |

*Six foals were included in the study, but 1 foal for which CT images but no radiographic images were available was excluded from this analysis.

Sedated foals underwent CT examination followed by radiography. The CT and radiographic images were divided into craniodorsal, cranioventral, caudodorsal, and caudoventral regions, and each region was scored for bronchial, interstitial, and alveolar patterns. Bronchial and interstitial lung patterns were categorized as absent, mild, moderate, or severe and assigned a score of 0, 1, 2, or 3, respectively. Alveolar patterns were categorized as absent, minimal, focal, localized, or extensive and assigned a score of 0, 1, 3, 4, or 6, respectively. Because an extensive alveolar pattern may interfere with the assessment of bronchial or interstitial patterns, scores for alveolar, bronchial, and interstitial patterns were added to obtain a summarized regional score, with a maximum regional score of 6. Computed tomographic images were subjectively evaluated on the basis of a similar scoring system. Once the regions were identified, they were further subdivided to account for potential slice-to-slice variability in radiographic patterns within a particular region. Each region was partitioned into 5 equal segments based on the total number of transverse CT slices per region. The CT slices bordering each segment were evaluated and scored. Thus, for each of the craniodorsal, cranioventral, caudodorsal, and caudoventral regions, 4 representative slices were evaluated for each foal. The maximum score for any of these 4 transverse slices was used as the total regional score. The same scoring system used for radiographic interpretation was applied to CT images with a maximum regional score of 6. Data represent the mean value of scores assigned by each of 3 reviewers.

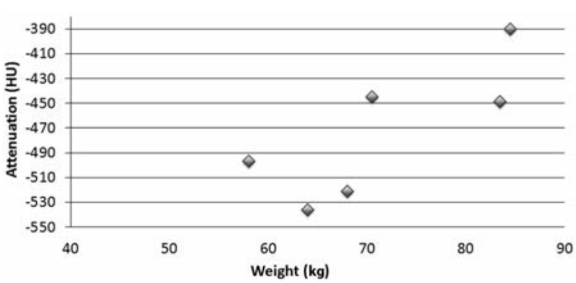


**Figure 5**—Correlation (*P* = 0.018) between weight and mean CT lung attenuation (HU) for 6 sedated healthy Standardbred foals < 14 days of age positioned in sternal recumbency during image acquisition. Initial 3-D segmentation of lung from nonlung structures was performed by selecting structures with attenuation between –860 and –120 HU. Additional slice-by-slice manual segmentation was performed to exclude large vessels or other air-filled structures (eg, trachea, large airways, gas-filled stomach, or gas-filled small intestine) and to include areas of lung measuring > –120 HU, including presumed atelectatic regions. Attenuation measurements obtained from segmented lung areas were averaged and reported as mean whole lung attenuation. Because attenuation corresponds with lung aeration, attenuation measurements were used to further characterize lung aeration as hyperinflated regions (–1,000 to –901 HU), well-aerated regions (–900 to –501 HU), poorly aerated regions (–500 to –101 HU), and nonaerated regions (> –100 HU).

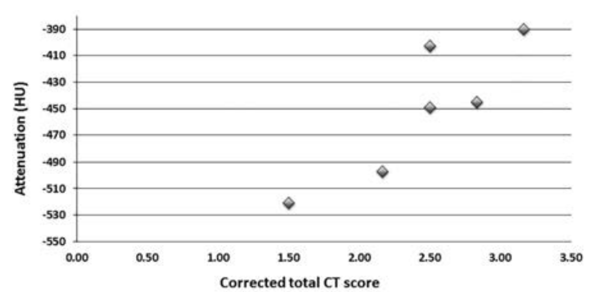


**Figure 6**—Correlation (*P* = 0.026) between mean CT lung attenuation (HU) and corrected total CT image scores for 6 sedated healthy Standardbred foals < 14 days of age positioned in sternal recumbency during image acquisition. ***See*** Figures 4 and 5 for key.

point. There was a significant (*P* = 0.036) positive correlation (*r* = 0.787) between $Pa_{O_2}$ and lung volume prior to sedation. No significant correlation between lung volume and $Pa_{O_2}$ or $Pa_{CO_2}$ was identified for any other time point. There was no significant correlation between mean whole lung attenuation and $Pa_{O_2}$ prior to sedation (*P* = 0.63) or prior to CT (*P* = 0.48). There was no significant correlation between mean whole lung attenuation and $Pa_{CO_2}$ prior to sedation (*P* = 0.58) or prior to CT (*P* = 0.52). No significant correlation between category of lung aeration and either $Pa_{O_2}$ or $Pa_{CO_2}$ at any time point was identified.

## Discussion

In the present study, CT and radiographic imaging changes consistent with positional atelectasis were identified in all foals (by radiography in 5 foals and by CT in 6 foals) and most prominent in the caudoventral portion of the lungs. Scores of the severity and extent of pathological changes assigned to the CT images were greater than those assigned to radiographic images for both the whole lung and the caudoventral region, which suggests that changes consistent with positional atelectasis appeared more pronounced or extensive in CT images, compared with findings in radiographic images. This may be partly due to lack of superimposition of structures on CT images, compared with radiographic images, which improves detection of pulmonary changes. As hypothesized, greater whole lung attenuation and a greater proportion of

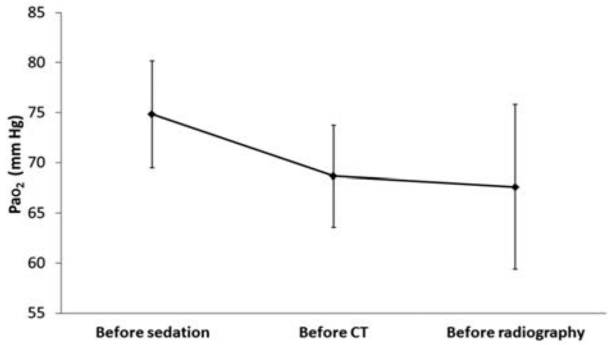


**Figure 7**—Mean ± SD $Pa_{O_2}$ (mm Hg) in 6 Standardbred foals < 14 days of age prior to sedation, after sedation immediately prior to CT image acquisition, and after CT immediately prior to radiographic image acquisition. The blood sample collected prior to sedation was obtained with each foal in lateral recumbency; the other blood samples were collected when the foal was positioned in sternal recumbency. The difference in $Pa_{O_2}$ among time points was not significant (*P* = 0.166).

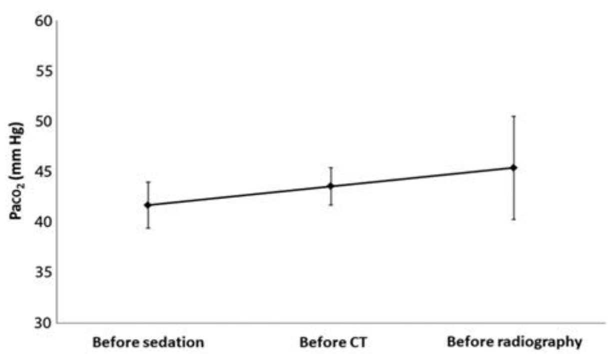


**Figure 8**—Mean ± SD $Pa_{CO_2}$ (mm Hg) in the 6 foals in Figure 7 prior to sedation, after sedation immediately prior to CT image acquisition, and after CT immediately prior to radiographic image acquisition. Compared with the value before sedation, $Pa_{CO_2}$ was significantly (*P* = 0.05) increased after CT immediately prior to radiographic image acquisition.

lung tissue characterized as poorly aerated both corresponded to a greater calculated CT image score. A relationship between radiographic image scores and whole lung attenuation derived from CT images was not observed. No relationship was identified between mean whole lung attenuation or the proportion of lung volume characterized as nonaerated or poorly aerated and $Pa_{O_2}$ or $Pa_{CO_2}$ at any time point. However, a greater CT score was associated with a lower $Pa_{O_2}$ in the blood sample obtained immediately prior to CT.

Positional atelectasis typically develops in the dependent lung[22,28,31,34] and is characterized on both CT and radiographic images as regions of attenuation or opacity, respectively.[31] The amount and distribution of atelectatic changes identified by means of CT in the present study were similar to those previously identified by means of CT in a population of foals with similar age and weight distributions.[18] Similar to the previous study,[18] the contribution of residual fetal pulmonary fluid to increased lung attenuation cannot be entirely ruled out but is expected to be minimal in foals several days after parturition because detection of pulmonary fluid in foals by means of standard radiography is limited to 6 to 12 hours after birth.[20,21] Factors that may have contributed to atelectasis in the foals in the present study included high thoracic wall compliance (reported for very young foals[33,35]), compression of the dependent (ventral) lung by overlying lung tissue or adjacent structures such as the heart or diaphragm,[10,36] and drugs administered for sedation. Computed tomographic imaging of the thorax is not possible in healthy or sick foals without sedation. The sedative medications administered (midazolam, butorphanol, and propofol) may cause variable degrees of dose- and rate-dependent respiratory depression and skeletal muscle relaxation,[37–42] which may cause a further increase in thoracic wall compliance and a corresponding reduction in functional residual capacity.[43]

Previous studies[17,20] evaluating thoracic radiographs of neonatal foals describe atelectatic changes in both the caudoventral and caudodorsal lung regions. In the present study, most changes were identified in the caudoventral portion of the lungs. The differences in the distribution of changes on radiographic views between the present study and the previous studies were most likely due to differences in positioning of the foals for image acquisition. In the present study, foals underwent radiography in sternal recumbency, whereas in earlier studies, those foals underwent radiography in lateral recumbency; in lateral recumbency, both the caudoventral and caudodorsal regions of the lungs would be dependent. Dorsoventral radiographic views were not obtained in the present study. The addition of this view would have contributed to the characterization of radiographic findings.

All investigators who assessed images gave higher scores to CT images, compared with scores for radiographic images (*P* = 0.03), but the difference between the mean CT image score (9.78 ± 2.1) and mean radiographic image score (7.8 ± 2.12) was not large. Computed tomographic image scores, but not radiographic image scores, were correlated with whole lung attenuation derived from the CT images. Computed tomography provides greater image resolution and is considered more sensitive and less subjective than radiography for detecting atelectasis[31] as well as other pulmonary parenchymal lesions.[9,11] The small difference in the scores assigned to radiographic images versus CT images may be related to study design. Radiographic images were acquired after CT and the administration of propofol, and it is possible the duration of recumbency and sedation may have led to progressive worsening of atelectasis for a given foal during the experimental period. Ideally, randomization of the order of procedures may have eliminated this potential bias.

The scoring system used in the present study was based on that used in a previous study[18] evaluating respiratory tract disease in hospitalized foals < 4 weeks of age. In that study,[18] foals were considered radiographically normal if they were assigned a corrected total lung score < 1 of 6. On the basis of that definition, only 1 of the 6 foals that underwent radiography in the present study would be considered radiographically normal. Differences in radiographic technique (digital vs analog radiography) and positioning (sternal vs lateral recumbency), potential differences in duration of recumbency, and the use of sedation and a younger population of foals all may have influenced the characterization and distribution of atelectasis in the present study and thus limit direct comparison of scores for normal foals between this study and the previous study.[18] In the present study, higher scores were primarily assigned to the caudoventral region where focal or localized alveolar patterns (and presumed positional atelectasis) were identified. In the previous study,[18] foals classified as radiographically normal did not include identification of alveolar patterns. On the basis of this scoring system, small changes in the extent of alveolar pattern have a pronounced impact on the total score.

Interobserver agreement for scores assigned to images of foals in the present study was moderate (0.65) for radiographic images and strong (0.73) for CT images. Intraobserver agreement was almost perfect for radiographic (0.941) and CT (0.97) images. These findings may suggest greater objectivity when interpreting CT images, compared with radiographic images, for neonatal foals. Previous research has shown that there may be significant variation between individual readers in the interpretation of radiographic images.[44] All investigators agreed on the prevalent radiographic patterns and their regional distributions but differed in the assessment of extent of changes primarily with regard to the scoring of alveolar patterns as focal, localized, or extensive. Because the alveolar pattern is accorded higher scores than any other pattern, minor differences in alveolar pattern interpretation had a strong impact on total scores. The subjective categorization of patterns may be an inherent flaw in the scoring system used. Other factors that possibly contributed to the differences in scoring of the images were the small number of foals for which images were evaluated and the differences in field of expertise of the investigators (radiologist vs internist vs resident).[45]

Mean whole lung CT attenuation for foals in the present study (–463 ± 57 HU) closely approximated values previously reported[18] for neonatal foals of similar body weight (–472 ± 45 HU), and both were just greater than the lower limit of –500 HU for normally aerated lung tissue. The proportion of lung volume characterized as nonaerated (2.1%) was larger than that in the previous study (0.15%), but still quite small, compared with the proportion of lung volume characterized as poorly (52.5%) or well aerated (45.5%) in the present study. Computed tomographic scores were correlated with whole lung attenuation, and there was a strong correlation between greater attenuation and the relative volume of lung characterized as poorly aerated.

The impact of atelectasis on systemic oxygenation in anesthetized patients, including horses, is well recognized.[22,23,28–31,46] The relationship between hypoxemia and the amount of atelectatic lung tissue identified by means of CT has also been described, but results are conflicting for horses.[23,24,28,29,32] In the present study, a correlation between higher CT scores and lower $Pa_{O_2}$ in the blood sample obtained from sedated foals immediately prior to CT was identified. There was no correlation between radiographic image score and $Pa_{O_2}$ at any time point. The study results did not support a correlation between CT-derived lung attenuation and $Pa_{O_2}$ or $Pa_{CO_2}$ at any time point, nor did any $Pa_{O_2}$ correlate to the amount of lung tissue categorized as nonaerated, poorly aerated, or well aerated. Despite the administration of sedative drugs and imaging findings of presumed positional atelectasis, changes in $Pa_{O_2}$ were not observed in any foal over the course of the experimental period. The significant increase in $Pa_{CO_2}$ observed was not clinically important and was most likely attributable to the effect of sedative drugs.

In the present study, several factors may explain the lack of change in measured $Pa_{O_2}$ or the lack of correlation between $Pa_{O_2}$ and CT-derived measurements of attenuation or aeration. As assessed by CT, attenuation for most of the lungs was consistent with normal to poorly aerated lung tissue; the actual proportion of lung tissue characterized as atelectatic (on the basis of CT-derived attenuation of –100 to 100 HU[31,47]) was quite small and thus potentially insufficient to cause detectable alterations in $Pa_{O_2}$ or $Pa_{CO_2}$ in this group of healthy foals. The study was also likely underpowered as a result of the small sample size and the observed variability in $Pa_{O_2}$. This variability probably reflects temporal differences among blood sample collections as well as age-related differences with regard to expected reference values for $Pa_{O_2}$ in very young foals. Four foals included in the present study were < 7 days old. In neonatal foals, normal $Pa_{O_2}$ values change over the first several days after birth and do not approach adult values until the end of the first week after birth.[33] Post hoc sample size calculation revealed that assessment of 8 foals would have been necessary to reach significance given the observed variation in $Pa_{O_2}$ among foals. Power analysis performed prior to study onset had supported a sample size of 6 foals.

Results of the present study indicated that CT is a more objective and more sensitive method for detection of presumed positional atelectasis in neonatal foals, compared with radiography. Comparison between CT and radiographic images of foals with pulmonary disease is necessary to determine the clinical relevance of the findings of this study and the prognostic capability of CT. Although the observed decrease in $Pa_{O_2}$ was not significant and increases in $Pa_{CO_2}$ were relatively minor in the healthy foals used in the present study, efforts should be made to minimize time of the procedure and the amount of sedation used because changes in $Pa_{O_2}$ and $Pa_{CO_2}$ may be more pronounced in compromised foals.

## Acknowledgments

Supported in part by the Morris Animal Foundation.

Presented as a poster at the 31st Annual American College of Veterinary Internal Medicine Forum, Seattle, June 2013.


## Footnotes

a. Cell-dyn 3700 hematology analyzer, GMI Inc, Ramsey, Minn.
b. Critical Care Express, Nova Biomedical Inc, Waltham, Mass.
c. MyLab70VETXV, Easote North America Inc, Indianapolis, Ind.
d. Advantax, GE Healthcare, Chalfont St Giles, Buckinghamshire, England.
e. MILA International Inc, Erlanger, Ky.
f. Butorphic (10 mg/mL), Lloyd Laboratories Inc, Shenandoah, Iowa.
g. Midazolam (5 mg/mL), Hospira Inc, Lake Forest, Ill.
h. PropoFlo (10 mg/mL), Abbott Laboratories, North Chicago, Ill.
i. GE Healthcare, Chalfont St Giles, Buckinghamshire, England.
j. Elkin EDR-5 Clinical Digital Radiography System, Eklin Medical Systems Inc, Santa Clara, Calif.
k. Pro-Vent, Smiths Medical, Keene, NH.
l. Amira, Visage Imaging Inc, San Diego, Calif.
m. SPSS Inc, version 19.0, SPSS Inc, Chicago, Ill.

## References


1. Grenier PA, Beigelman-Aubry C, Fétita C. New frontiers in CT imaging of airway disease. *Eur Radiol* 2002;12:1022–1044.
2. Gattinoni L, Caironi P, Valenza F, et al. The role of CT-scan studies for the diagnosis and therapy of acute respiratory distress syndrome. *Clin Chest Med* 2006;27:559–570.
3. Rouby JJ, Puybasset L, Nieszkowska A, et al. Acute respiratory distress syndrome: lessons from computed tomography of the whole lung. *Crit Care Med* 2003;31(suppl 4):S285–S295.
4. Hoffman EA, Reinhardt JM, Sonka M, et al. Characterization of the interstitial lung diseases via density-based and texture-based analysis of computed tomography images of lung structure and function. *Acad Radiol* 2003;10:1104–1118.
5. Reske AW, Busse H, Amato MB, et al. Image reconstruction affects computer tomographic assessment of lung hyperinflation. *Intensive Care Med* 2008;34:2044–2053.
6. Staffieri F, Franchini D, Carella GL, et al. Computed tomographic analysis of the effects of two inspired oxygen concentrations on pulmonary aeration in anesthetized and mechanically ventilated dogs. *Am J Vet Res* 2007;68:925–931.
7. Oliveira CR, Mitchell MA, O'Brien RT. Thoracic computed tomography in feline patients without use of chemical restraint. *Vet Radiol Ultrasound* 2011;52:368–376.
8. Cipone M, Diana A, Gandini G, et al. Use of computed tomography in thoracic diseases of small animals. *Vet Res Commun* 2003;27:381–384.
9. Armbrust LJ, Biller DS, Bamford A, et al. Comparison of three-view thoracic radiography and computed tomography for detection of pulmonary nodules in dogs with neoplasia. *J Am Vet Med Assoc* 2012;240:1088–1094.
10. Alexander K, Joly H, Blond L, et al. A comparison of computed tomography, computed radiography, and film-screen radiography for the detection of canine pulmonary nodules. *Vet Radiol Ultrasound* 2012;53:258–265.
11. Eberle N, Fork M, von Babo V, et al. Comparison of examination of thoracic radiographs and thoracic computed tomography in dogs with appendicular osteosarcoma. *Vet Comp Oncol* 2011;9:131–140.
12. Wion L, Perkins G, Ainsworth SM, et al. Use of computed tomography to diagnose a *Rhodococcus equi* mediastinal abscess causing severe respiratory distress in a foal. *Equine Vet J* 2001;33:523–526.
13. Woodring JH. Determining the cause of pulmonary atelectasis: a comparison of plain radiography and CT. *AJR Am J Roentgenol* 1988;150:757–763.
14. Wilkins PA, Otto CM, Dunkel B, et al. Acute lung injury (ALI) and acute respiratory distress syndromes (ARDS) in veterinary medicine: consensus definitions. *J Vet Emerg Crit Care* 2007;17:333–339.
15. Beech J. Respiratory problems in foals. *Vet Clin North Am Equine Pract* 1985;1:131–149.
16. Freeman L, Paradis MR. Evaluation of the effectiveness of equine neonatal care. *Vet Med* 1992;87:921–926.
17. Bedenice D, Heuwieser W, Brawer R, et al. Clinical and prognostic significance of radiographic pattern, distribution, and severity of thoracic radiographic changes in neonatal foals. *J Vet Intern Med* 2003;17:876–886.
18. Lascola KM, O'Brien RT, Wilkins PA, et al. Qualitative and quantitative interpretation of computed tomography of the lungs in healthy neonatal foals. *Am J Vet Res* 2013;74:1239–1246.
19. Bedenice D, Heuwieser W, Solano M, et al. Risk factors and prognostic variables for survival of foals with radiographic evidence of pulmonary disease. *J Vet Intern Med* 2003;17:868–875.
20. Lester GD, Lester NV. Abdominal and thoracic radiography in the neonate. *Vet Clin North Am Equine Pract* 2001;17:19–46.
21. Kutasi O, Horvath A, Harnos A, et al. Radiographic assessment of pulmonary fluid clearance in healthy neonatal foals. *Vet Radiol Ultrasound* 2009;50:584–588.
22. Magnusson L, Spahn DR. New concepts of atelectasis during general anaesthesia. *Br J Anaesth* 2003;91:61–72.
23. Nyman G, Funkquist B, Kvart C. Atelectasis causes gas exchange impairment in the anaesthetised horse. *Equine Vet J* 1990;22:317–324.
24. Staffieri F, De Monte V, De Marzo C, et al. Effects of two fractions of inspired oxygen on lung aeration and gas exchange in cats under inhalant anesthesia. *Vet Anaesth Analg* 2010;37:483–490.
25. Staffieri F, Driessen B, De Monte V, et al. Effects of positive end-expiratory pressure on anesthesia-induced atelectasis and gas exchange in anesthetized and mechanically ventilated sheep. *Am J Vet Res* 2010;71:867–874.
26. Henao-Guerrero N, Ricco C, Jones JC, et al. Comparison of four ventilatory protocols for computed tomography of the thorax in healthy cats. *Am J Vet Res* 2012;73:646–653.
27. Hall LW. Cardiovascular and pulmonary effects of recumbency in two conscious ponies. *Equine Vet J* 1984;16:89–92.
28. McDonell WN, Hall LW, Jeffcott LB. Radiographic evidence of impaired pulmonary function in laterally recumbent anaesthetised horses. *Equine Vet J* 1979;11:24–32.
29. Hedenstierna G, Rothen HU. Atelectasis formation during anesthesia: causes and measures to prevent it. *J Clin Monit Comput* 2000;16:329–335.
30. Nyman G, Hedenstierna G. Ventilation-perfusion relationships in the anaesthetised horse. *Equine Vet J* 1989;21:274–281.
31. Duggan M, Kavanagh BP. Pulmonary atelectasis. *Anesthesiology* 2005;102:838–854.
32. Tokics L, Hedenstierna G, Strandberg A, et al. Lung collapse and gas exchange during general anesthesia: effects of spontaneous breathing, muscle paralysis, and positive end-expiratory pressure. *Anesthesiology* 1987;66:157–167.
33. Stewart JH, Rose RJ, Barko AM. Respiratory studies in foals from birth to seven days old. *Equine Vet J* 1984;16:323–328.
34. Brismar B, Hedenstierna G, Lundquist H, et al. Pulmonary densities during anesthesia with muscular relaxation—a proposal of atelectasis. *Anesthesiology* 1985;62:422–428.
35. Koterba AM, Kosch PC. Respiratory mechanics and breathing pattern in the neonatal foal. *J Reprod Fertil Suppl* 1987;35:575–585.
36. Ahlberg NE, Hoppe F, Kelter U, et al. A computed tomographic study of volume and X-ray attenuation of the lungs of Beagles in various body positions. *Vet Radiol Ultrasound* 1985;26:43–47.
37. Mama KR, Steffey EP, Pascoe PJ. Evaluation of propofol as a general anesthetic for horses. *Vet Surg* 1995;24:188–194.
38. Short CE, Bufalari A. Propofol anesthesia. *Vet Clin North Am Small Anim Pract* 1999;29:747–778.
39. Muir WW. Anxiolytics, nonopioid sedative analgesics, and opioid analgesics. In: Muir WW, Hubbell JAE, eds. *Equine anesthesia: monitoring and emergency therapy*. 2nd ed. St Louis: Saunders, 2009;185–209.
40. Muir WW. Intravenous anesthetic drugs. In: Muir WW, Hubbell

JAE, eds. *Equine anesthesia: monitoring and emergency therapy*. 2nd ed. St Louis: Saunders, 2009;243–259.
41. Schroeder CA, Smith LJ. Respiratory rates and arterial blood gas tensions in healthy rabbits given buprenorphine, butorphanol, midazolam, or their combinations. *J Am Assoc Lab Anim Sci* 2011;50:205–211.
42. Bidwell LA. Sedation, anesthesia and analgesia. In: McKinnon AO, Squires EL, Vaala WE, et al, eds. *Equine reproduction*. 2nd ed. Ames, Iowa: Wiley-Blackwell, 2011;221–229.
43. Hedenstierna G, Tokics L, Strandberg A, et al. Correlation of gas exchange impairment to development of atelectasis during anaesthesia and muscle paralysis. *Acta Anaesth Scand* 1986;30:183–191.
44. Wisner ER, O'Brien TR, Lakritz J, et al. Radiographic and microscopic correlation of diffuse interstitial and bronchointerstitial pulmonary patterns in the caudodorsal lung of adult Thoroughbred horses in race training. *Equine Vet J* 1993;25:293–298.
45. Lamb CR, Pfeiffer DU, Mantis P. Errors in radiographic interpretation made by veterinary students. *J Vet Med Educ* 2007;34:157–159.
46. Nolan AM, Hall LW. Total intravenous anaesthesia in the horse with propofol. *Equine Vet J* 1985;17:394–398.
47. Lundquist H, Hedenstierna G, Strandberg A, et al. CT assessment of dependent lung densities in man during general anaesthesia. *Acta Radiol* 1995;36:626–632.