

Perioperative lung ultrasonography in healthy horses undergoing general anesthesia for elective surgery

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Abstract

Background: Lung ultrasound (LUS) is poorly evaluated in horses, especially perioperatively.

Objectives: (1) Describe LUS findings in healthy horses before and after general anesthesia (GA), (2) evaluate if GA induces ultrasonographic changes in healthy horses, (3) suggest a LUS scoring system, (4) identify horse variables that are associated to LUS changes after anesthesia.

Animals: Twenty-five healthy adult horses undergoing elective surgery.

Methods: Prospective hypothesis-driven observational study. LUS findings were recorded before anesthesia, 5 minutes in recovery, 15 minutes, 2H, 3H, 4H, 6H, and 24H after anesthesia in 8 lung regions. Clinical data were collected perioperatively.

Results: There was a significant increase in amount of I-lines (10.8 ± 8.7 vs 15.28 ± 8.19), B-lines (3.2 ± 3.5 vs 8.72 ± 4.86), and coalescent B-lines (0.04 ± 0.2 vs 1.12 ± 1.45) after anesthesia compared to before anesthesia, and a significantly higher LUS score 2H after anesthesia (4.92 ± 8.40) compared to before anesthesia (0.9 ± 1.8 ; $P = .02$). The maximal LUS score after anesthesia was correlated to total procedure time (Pearson $r = 0.4$, $P = .05$; Spearman $r = 0.44$, $P = .03$) and was significantly higher in horses with abnormal cardiorespiratory values during anesthesia ($P = .005$).

Conclusions: LUS changes can be induced by GA in healthy horses. This study did not investigate if and which LUS findings indicate lesions, however, this information can aid clinicians to identify pulmonary complications after anesthesia.

KEYWORDS

atelectasis, equine, postoperative, pulmonary, ultrasound

Abbreviations: ASA, American Society of Anesthesiologists; BCS, body condition score; CT, computed tomography; GA, general anesthesia; H, hour(s); ICS, intercostal space; LCAD, left caudodorsal region; LCAV, left caudoventral region; LCRD, left craniodorsal region; LCRV, left cranioventral region; LUS, lung ultrasound; MAP, mean arterial blood pressure; MRI, magnetic resonance imaging; PaO₂, partial pressure of arterial oxygen; PCO₂, partial pressure of arterial carbon dioxide; RCAD, right caudodorsal region; RCAV, right caudoventral region; RCRD, right craniodorsal region; RCRV, right cranioventral region; SAT, saturation.

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1 | INTRODUCTION

Lung ultrasound (LUS) allows for easy detection of lesions close to the pleural surface. It is increasingly used for the diagnosis of pulmonary disease in human medicine and in equine practice.^{1,2} However, detailed descriptive studies of LUS findings in healthy horses are lacking.

Pulmonary disease after surgery is well described in human medicine with an incidence varying between 0.5% and 54%.³ In horses, the incidence of pulmonary disease after surgery is currently unknown. Nevertheless, GA is a predisposing factor in horses for pleuritis and pneumonia.^{4,5} Atelectasis occurs in most humans and domestic animals undergoing GA.^{6,7} In horses, gravity-dependent atelectasis is the predominant cause of impaired gas exchange during GA.⁸ Atelectasis is also associated with development of lung injury^{8,9} and might contribute to pulmonary infections after surgery.^{7,10} Other perioperative factors involved in the development of pulmonary lesions after surgery are alterations of the pulmonary defense mechanisms, ventilator associated lung injury, nosocomial contamination by the anesthetic equipment and aspiration pneumonitis.¹¹⁻¹⁴

In human medicine, LUS is a valuable, practical and accurate tool for the rapid diagnosis and monitoring of pulmonary complications after surgery, superior to physical examination and thoracic radiography.¹⁵ Also, LUS has a high sensitivity and specificity compared to Computed Tomography (CT; 87.7% and 92.1%) and magnetic resonance imaging (MRI; 90% and 89%).¹⁵⁻¹⁷ In dogs, there is a significant increase in LUS abnormalities after anesthesia, especially after a long GA.¹⁸ Understanding perioperative LUS changes in horses would be useful for the early detection of pulmonary complications after anesthesia and guide appropriate treatment implementation.

Therefore, the aims of this study were to (1) describe the findings of LUS in healthy horses before and after GA, (2) evaluate if GA in healthy horses induces ultrasonographic changes after anesthesia, (3) suggest a LUS scoring system, (4) identify horse variables that can be associated with LUS changes after anesthesia.

Our hypotheses are that GA induces changes in LUS findings in healthy horses, and that increased abnormal findings will be linked to duration of GA and recovery and to cardiorespiratory abnormalities during GA.

2 | MATERIAL AND METHODS

2.1 | Animals

Clinically healthy, adult horses admitted to Dierenkliniek de Morette (Asse, Belgium) for elective surgery between April and June 2020 were included in the study. Only adult horses (>1 year old) with an American Society of Anesthesiologists Classification (ASA) risk of 1 were included. Owners agreed to the study by signing an owner consent form.

2.2 | Preparation, anesthesia, and recovery protocol

All horses were anesthetized using typical standard equine GA protocol¹⁹; details can be found in the Supporting Information.

2.3 | Clinical data collection

Clinical data were collected at 3 time-points: (1) the phase before anesthesia, (2) the phase of inhalation anesthesia and recovery (defined as the period between induction and standing again and further called "total procedure time"), and (3) the phase after anesthesia (defined as the period between the horse standing after GA and the subsequent 24 hours). The following variables were recorded for every horse: age, weight, body condition score (BCS according to Henneke),²⁰ duration of anesthesia, duration of recovery, total procedure time (anesthesia plus recovery time), recovery quality score (according to recovery quality scoring used by Schauvliege et al).¹⁹ Cardiorespiratory variables recorded during GA included: PaO₂ (partial pressure of arterial oxygen), PCO₂ (partial pressure of arterial carbon dioxide), saturation (SAT), mean arterial blood pressure (MAP). PaO₂, PaCO₂, and SAT were also measured at 5 min in recovery and 15 minutes after standing. The following were categorized as cardiorespiratory anesthetic or recovery problems: *hypoxia* defined as PaO₂ below 60 mm Hg; *suboptimal oxygenation* defined as PaO₂ between 60 and 80 mm Hg; *hypercapnia* defined as PCO₂ above 60 mm Hg; *hypotension* defined as a mean arterial blood pressure below 60 mm Hg. After anesthesia, the presence of tachypnea (defined as above 20 rpm) and the presence of fever (defined as above 38.5°C) were recorded.²¹

2.4 | Lung ultrasound protocol

LUS was performed on all horses at 8 time points: before surgery, 5 minutes after the horse was placed from the operation room into the recovery box (still recumbent), 15 minutes after the horse regained a standing position and at 2H, 3H, 4H, 6H, and 24H after anesthesia. To ensure standardization, all LUS's were performed by the same clinician (the first author, last year ECEIM resident). Horse preparation was achieved by cleaning the skin and wetting the hair with isopropyl alcohol and slicking down the hair. To record the ultrasonographic findings in a systematic manner, the left and right hemithoraxes were each divided in 4 defined regions, similarly as for thoracic radiography²² (Figure 1):

1. the caudodorsal region, between 11th and 16th intercostal space (ICS).
 - a. left caudodorsal region (LCAD).
 - b. right caudodorsal region (RCAD).
2. the craniodorsal region, between 5th and 10th ICS dorsal to the level of the shoulder.
 - a. left craniodorsal region (LCRD).
 - b. right craniodorsal region (RCRD).

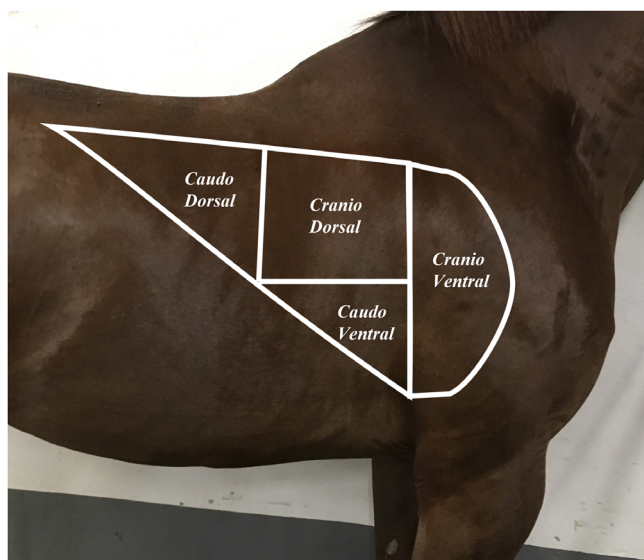


FIGURE 1 Lung ultrasound regions. Location of the ultrasound regions used for the study

3. the caudoventral region, between 5th and 10th ICS ventral to the level of the shoulder.
 - a. left caudoventral region (LCAV).
 - b. right caudoventral region (RCAV).
4. the cranioventral region, between 3th and 4th ICS scanned over the triceps muscle.
 - a. left cranioventral region (LCRV).
 - b. right cranioventral region (RCRV).

B-mode ultrasound images were obtained with the same ESAOTE MyLabDeltaVET ultrasound machine, using the low-frequency AC2541 curved array transducer for the cranioventral part of the lung and the high-frequency SL1543 linear transducer for the other regions. For all cases, the low-frequency transducer was set at a frequency of 3 MHz and a depth of 20 cm. The high frequency linear transducer was set at a frequency of 7.5 MHz and a depth of 7 cm. The gain was adjusted to optimize the image quality and the single focus was set at the level of the pleural line. The entire thorax was examined by scanning every ICS in a dorsal to ventral direction.

2.5 | LUS findings

During the 8 examinations, the presence and number of LUS findings was recorded per region: I-lines, B-lines, lung rockets, coalescent B-lines, irregular pleura, pleural effusion and consolidation. Definitions and examples are provided in Table 1 and Figure 2. Since the commonly used term “comet tail artifact” is a rather imprecise term, that covers several types of vertical artifacts, the authors applied recently reviewed definitions from the humane literature,²³ to differentiate the types of LUS findings present in this study. A-lines and lung comets were not recorded, as these are considered normal findings.²³ Based

TABLE 1 Description of the different LUS findings

LUS finding	Description
A-lines	Normal horizontal lines that represent the presence of air at the pleural line ¹
Lung comets	Short hyperechoic vertical lines arising from the pleural line, moving with lung sliding and always less than 1 cm long and visible in the normal lung ²³
B-lines	Long vertical hyperechoic artifacts originating from the pleural line and erasing the normal horizontal A-lines. B-line artifacts “ring-down” to the end of the screen without fading and move with lung sliding. Depending on their number and localization, the presence of B-lines can be physiological or pathological ^{1,23}
I-lines	I-lines are similar to B-lines except they do not “ring-down” the screen but are shorter, usually 3 to 4 cm length. Their clinical relevance is unknown, but they could be partially visualized B-lines ²³
Lung rockets	Lung rockets are defined when 3 or more B-lines are visible simultaneously between 2 ribs in a longitudinal scan. Lung rockets are always considered abnormal ²⁴
Coalescent B-lines	Large B-lines. In this study, B-lines were considered coalescent if their width was above 9 mm
Lung consolidation	Varying shapes (irregular to spherical) of hypoechoic areas within the lung produced by the accumulation of fluid and cellular infiltration ²
Shred signs	Ring-down artifacts, similar to B-lines but they do not arise from the pleural line but at the interface between a consolidated lung or pleural effusion and aerated lung ^{1,23}
Pleural effusion	Pleural effusion is visible as the presence of anechoic fluid. In healthy horses, pleural effusion up to 3.5 cm depth can be visualized ²⁵
Irregular pleura	Irregular lining of the pleural surface visible with LUS

on measurements of the width of B-lines recorded during this study, B-lines were arbitrarily considered coalescent if their width was over 9 mm. Shred signs (ringdown artifacts appearing below a consolidation) were recorded as B-lines in this study. A cine-loop or freeze-image was recorded for every visible finding.

2.6 | LUS score

A LUS score was developed based on the mean and SD of the LUS findings before anesthesia from all included horses (Table 2). The frequency of each finding was recorded for the entire thorax, the right thorax and the left thorax. LUS scores were calculated for the right hemithorax (LUS score-R), the left hemithorax LUS score

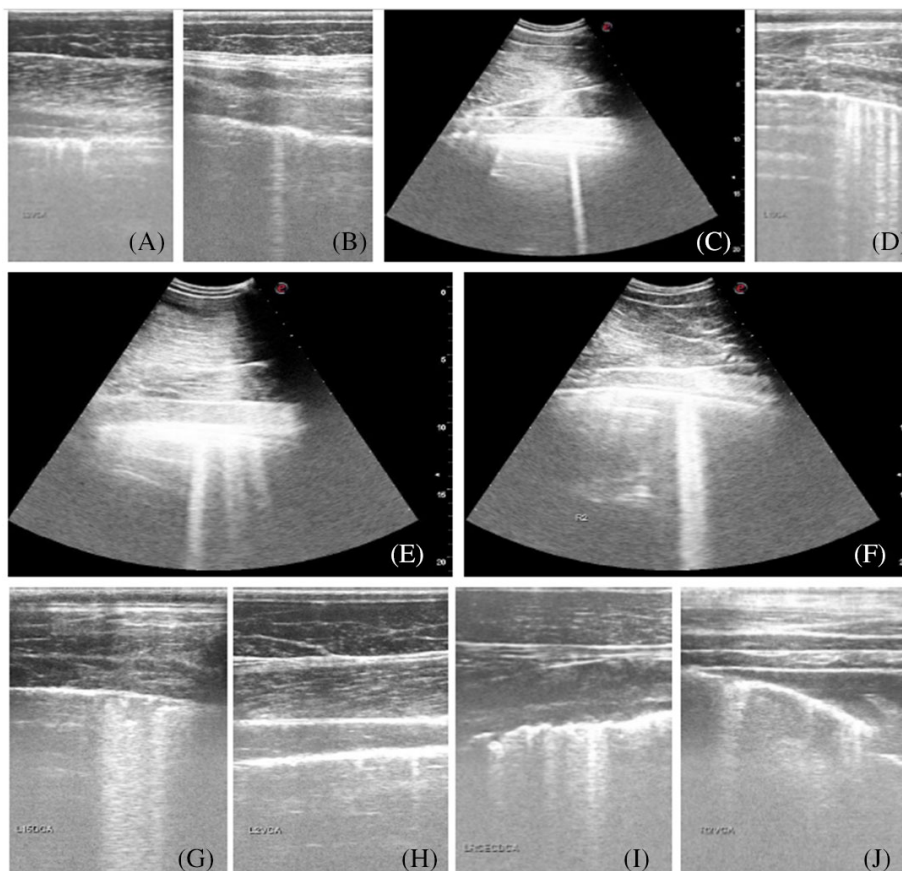


FIGURE 2 Lung ultrasound findings. The thorax was scanned with the transducer placed in the intercostal spaces parallel to the ribs and orientated as such that the right side of the ultrasound image corresponded with dorsal and the left side with ventral. (A) Three small lung comets visible in the left caudoventral region of the lung of Case 11, 2 hours after standing. (B) Image of a single B-line in the left caudoventral region of the lung of Case 3, 2 hours after standing with the linear transducer. (C) Image of a single B-line visible with the convex transducer in the cranioventral region of the lung of Case 3, 2 hours after standing. (D) Lung rockets in the left caudodorsal region of the lung of Case 10, 1 hour after standing. On the left of the image, horizontal A-lines, which are normal ultrasonographic artifacts are evident. On the right of the image, the normal A-lines are interrupted by lung rockets. (E) Lung rockets visible with the convex transducer in the right cranioventral region of the lung of Case 3, 2 hours after standing. (F) Coalescent B-lines in the cranioventral region of the right lung of Case 5, 2 hours after standing. B-lines were considered coalescent if their width was above 9 mm. (G) Small area of lung consolidation with visible shred or sub B-lines in Case 10, 15 minutes after standing with the linear transducer. (H) Image of an I-line on the right and 1 small lung comet in the center of the image recorded from the left caudoventral region of the lung of Case 11, 2 hours after standing. (I) Presence of irregular pleura in the caudodorsal region of left lung in Case 24 during recovery. (J) Presence of pleural effusion in the right caudoventral region of Case 25, 2 hours after standing. Note the presence of the caudoventral mediastinal reflection on the right of the image

(LUS score-L) and for the entire thorax (LUS score-H). For the entire thorax, a LUS score of 1 was attributed when a finding was seen more often in that specific horse than the mean + 1 SD before anesthesia of that finding in all studied horses. A LUS score of 2 was given when a finding was present more than the mean + 2 SD's of that finding. A LUS score of 3 was given when a finding was present more than the mean + 3 SD's, etc. For findings that were very rare (maximum 1 finding in 1 horse) or absent before anesthesia in all horses, a score of 4 was attributed for every presence of that finding. For the LUS scores of each hemithorax, the same calculation was applied except that for I-lines and B-lines the same score was attributed for half of the numbers of I-lines and B-lines. For example, 14 I-lines in 1 hemithorax would add a score of 2, but 1 area of consolidation would add 4 to the score of 1 hemithorax. That way, the sum of the LUS score-R and LUS score-L would not necessarily equal LUS

score-H. LUS scores were calculated for every time point. For every individual horse, the highest score after anesthesia during the study (maximal LUS score-H) was identified.

2.7 | Statistical analysis

Descriptive statistics (mean, SD, range) were applied to all variables.

Statistical comparison of the LUS findings and of the LUS scores between time points and regions was performed with a negative binomial regression test.

Scores of both hemithoraxes were compared to each other with a negative binomial regression test, thereby excluding the time point of 5 minutes in the recovery since bilateral scanning was not feasible at this timepoint.

Correlations were sought between the maximal LUS score-H after anesthesia and age, weight, body condition score, duration of GA, duration of recovery, total procedure time, recovery quality score, lowest PaO₂ detected at any time point, highest PaCO₂ detected at any time point, lowest SAT detected at any time point and lowest MAP with a Pearson correlation coefficient test (linear relation) and a Spearman correlation coefficient (nonparametric relation) test.

With a negative binomial regression test the maximal LUS score-H after anesthesia of horses with normal cardiorespiratory GA variables (PaO₂, PCO₂, MAP, SAT) and those with abnormal cardiorespiratory GA variables (regardless of which) was compared.

For all statistical analyses, significance was set at $P < .05$.

3 | RESULTS

3.1 | Study sample and data before anesthesia

The study sample consisted of 25 horses. They were 12 stallions, 8 mares and 5 geldings and 17 Belgian Warmbloods, 2 Dutch Warmbloods, 2 Hanoverians, 1 Belgian Draft, 1 Quarter Horse, 1 Standardbred and 1 Henson horse. Age, body weight, BCS are described in Table 2. All had a normal clinical examination and hematology (the white blood cell count was considered normal between 6 and $15 \times 10^9/L$) before anesthesia.

The horses underwent elective surgery for the following procedures: closed castration ($n = 4$), cryptorchid castration ($n = 4$), arthroscopy ($n = 7$), arthroscopy combined with closed castration ($n = 4$), tenoscopy ($n = 1$), electrochemotherapy ($n = 1$), sarcoid excision ($n = 1$), keratoma debridement ($n = 1$), cast change ($n = 1$) and pastern arthrodesis ($n = 1$).

3.2 | Inhalation anesthesia and recovery phase data

Twenty horses were placed in dorsal recumbency during GA and in right lateral recumbency during recovery. One horse was placed in dorsal recumbency during GA and in left lateral recumbency in recovery. Three horses were placed in right lateral recumbency and 1 horse was placed in left lateral recumbency during both GA and recovery. Mean duration of GA, mean surgery time, mean duration of recovery, and mean recovery quality score are described in Table 3. Tables 3 and 4 describe PaO₂, PCO₂, SAT, and MAP values for the study sample.

Hypoxia was not detected in any horse during GA, but was recorded in 8/22 during recovery and in 1/21 recovered horse; 3/8 horses that were hypoxic during recovery improved their oxygenation and 4/8 horses normalized their oxygenation by the time they were standing for 15 minutes. A suboptimal oxygenation was recorded in 1/25 horse during GA, in 8/22 horses during recovery and 6/21 horses 15 minutes after standing.

Hypercapnia was recorded in 1 horse during GA, but not during recovery or while standing. Two horses were hypotensive and 4 had a low oxygen saturation at some point during GA.

3.3 | Clinical data after anesthesia

All but 2 horses had an uneventful recovery after surgery. One horse undergoing a closed castration had a fever of unknown origin (40.4°C) for 2 days and tachypnea (respiratory rate 40/min), together with leukopenia and neutropenia, and a negative bacterial culture from a tracheal lavage. Another horse undergoing left hind pastern arthrodesis, with the longest total procedure time (337 minutes), developed acute myopathy and acute kidney injury after surgery.

3.4 | Description of LUS findings and LUS score before anesthesia

An overview of the LUS findings before anesthesia is presented in Figure 3. In general, only few LUS abnormalities were identified before anesthesia. I-lines were the most common finding in all 4 lung regions, but most prevalent in the LCAD region. This was followed by individual B-lines that were most prevalent in the RCAV region. Before anesthesia, a mean of 10.8 ± 8.7 I-lines and 3.2 ± 3.5 B-lines were visible over the entire thorax per horse. Two horses had 1 lung rocket and another horse 1 coalescent B-line. Consolidation, irregular pleural lining or pleural effusion greater than 3 cm of depth were not detected before anesthesia in any of the horses. In 1 horse, however, pleural effusion with a depth of 2.7 cm was seen before anesthesia.

The few LUS findings before anesthesia resulted in low LUS scores (LUS score-H 0.9 ± 1.8 ; range, 0-6; Figures 3 and 4). The mean LUS score-L was 1.08 ± 2.08 , range, 0 to 6, and LUS score-R was 0.6 ± 1.3 , range, 0 to 5, before anesthesia.

3.5 | Description LUS findings and LUS score after anesthesia

An overview of the LUS findings after anesthesia throughout the 24-hour study period is presented in Figure 3. The most predominant LUS findings in any region at any time point after anesthesia were I-lines, followed by individual B-lines, similarly as before anesthesia (mean maximal amount after anesthesia 15.28 ± 8.19 and 8.72 ± 4.86 , respectively). The highest mean number of B-lines was detected in the RCAV region 3H after anesthesia. Twenty horses had more B-lines (all types of B-lines considered: individual, coalescent, lung rockets) at some point after anesthesia than before anesthesia. Moreover, after anesthesia 13 horses showed lesions that were not present before, such as consolidation ($n = 7$), irregular pleura ($n = 11$), or pleural effusion ($n = 1$). The only horse that had pleural effusion 3H after anesthesia in the RCAV region, is the same horse that had nonrelevant pleural effusion before anesthesia; this horse did not develop clinical disease after anesthesia.

The evolution of the mean LUS score-H is represented in Figure 4. The mean LUS scores-H from each time point after anesthesia were all above the mean LUS score-H before anesthesia. From all the timepoints,

TABLE 2 Development of a lung ultrasound score

I-lines		B-lines individual		Lung rockets		B-lines coalescent		Consolidation zones		Irregular pleura zones		Pleural effusion	
Before anesthesia over entire thorax													
Mean ± SD	10.8 ± 8.7	3.24 ± 3.5	0.08 ± 0.3	0.04 ± 0.2	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0 ± 0
Before anesthesia over entire thorax													
Range	1-35	0-14	0-1	0-1	0	0	0-1	0	0	0	0	0	0
Amount of I-lines	Score for I-lines	Amount of B-lines individual	Score for B-lines individual	Amount of lung rockets	Score for lung rockets	Amount of B-lines coalescent	Score for B-lines coalescent	Amount of consolidation zones	Score for consolidation zones	Amount of irregular pleura zones	Score for irregular pleura zones	Amount of pleural effusion zones	Score for pleural effusion
0	0	0	0	0	0	0	0	0	0	0	0	0	0
19	1	7	1	0	0	0	0	0	0	0	0	0	0
28	2	10	2	0	0	0	0	0	0	0	0	0	0
37	3	14	3	1	3	0	0	0	0	0	0	0	0
46	4	17	4	2	6	1	4	1	4	1	4	1	4
55	5	20	5	3	9	2	8	2	8	2	8	2	8
64	6	23	6	4	12	3	12	3	12	3	12	3	12
73	7	26	7	5	15	4	16	4	16	4	16	4	16
87	8	29	8	6	18	5	20	5	20	5	20	5	20
91	9	32	9	7	21	6	24	6	24	6	24	6	24
100	10	35	10	8	24	7	28	7	28	7	28	7	28

Note: A LUS score was developed based on the mean and SD of the LUS findings before anesthesia from all included horses. The first 2 rows of this table show the mean, SD and range of each finding over the entire thorax. The columns below each show the amount of a finding that had to be seen to grant the score in the column right next to it.

TABLE 3 Perioperative clinical variables in 25 healthy horses undergoing elective surgery and their correlation with the maximal LUS score after anesthesia

	Age (y)	Weight (kg)	BCS (1-9)	Duration of anesthesia (min)	Duration of recovery (min)	Total procedure time (min)	Recovery quality score (0-6)	Lowest detected PaO ₂ (mm Hg)	Highest detected PaCO ₂ (mm Hg)	Lowest detected saturation (%)	Lowest detected MAP (mm Hg)
Mean	4.6	517.64	5.04	103.16	47.64	150.8	2	69.98	53.104	93.536	70.791
SD	2.90	65.70	1.27	52.35	18.54	55.90	1.41	19.57	4.44	4.47	10.77
Range	1-12	400-645	3-7	25-284	15-76	95-337	1-5	44.2-123.4	46.10-64.9	82.2-99.1	50-95
Correlation to the maximal LUS score after anesthesia entire thorax Pearson correlation	r = 0.05; P = .81	r = 0.032; P = .88	r = 0.13; P = .55	r = 0.41; P = .04*	r = 0.044; P = .83	r = 0.4; P = .05*	r = 0.17; P = .42	r = -0.16; P = .43	r = 0.33; P = .1	r = -0.13; P = .52	r = -0.28; P = .19
Correlation to the maximal LUS score after anesthesia entire thorax Spearman correlation	r = 0.07; P = .75	r = 0.05; P = .8	r = 0.07; P = .76	r = 0.53; P = .006*	r = -0.05; P = .82	r = 0.44; P = .03*	r = 0.23; P = .26	r = -0.25; P = .23	r = 0.36; P = .08	r = -0.13; P = .52	r = -0.1; P = .65

Abbreviations: BCS, body condition score; LUS, lung ultrasound; MAP, mean arterial pressure (mm Hg); PaCO₂, partial pressure of carbon dioxide in arterial blood; PaO₂, partial pressure of oxygen in arterial blood; r, correlation coefficient.

*Statistically correlated ($P < .05$).

the mean LUS score-H after anesthesia was highest at 2H (mean 4.92 ± 8.40) and it was lowest at 6H (mean 2.56 ± 5.28).

The mean value of the maximal LUS score-H after anesthesia of all horses was 9.8 ± 10.23 (range, 0-35), for the left hemithorax (mean maximal LUS score-L after anesthesia) 7.2 ± 6.3 (range, 0-27) and for the right hemithorax (mean maximal LUS score-R after anesthesia) 7.32 ± 9.34 (range, 0-38). The maximal LUS score-H was detected at different time points for the different horses: 15 minutes after standing (5/25 horses), after 2H (4/25 horses), after 3H (2/25 horses), after 4H (1/25), after 6H (1/25) and after 24H (2/25). One horse had the maximal LUS score-H at both 3H and 4H, 1 horse at 15 min and 2H, and 1 horse at 15 min and 3H. In 2 horses the maximal LUS score-H was detected before anesthesia (the maximal LUS score-H was 4 for both these horses). Five horses maintained a LUS score-H of 0 during the entire study period.

The LUS score-H after anesthesia decreased again to a value equal or lower than the LUS score-H before anesthesia at the following time moments after anesthesia: at 2H for 2 horses, at 3H for 3 horses, at 4H for 3 horses, at 6H for 2 horses, at 24H for 3 horses. In 5 horses, the LUS score-H 24H after anesthesia had not yet returned to values before anesthesia.

The LUS score before anesthesia of the horse with fever after surgery was 0 and the maximal LUS score-H after anesthesia of this horse was 10 at 24H. The horse with myopathy and acute kidney injury had a LUS score before anesthesia of 0, a maximal LUS score-H after anesthesia of 17 at 2H (with a LUS score-H of 8 at 24H).

3.6 | Statistical comparison of LUS findings

No statistical comparisons were made for consolidation, irregular pleura or pleural effusion, because these findings were only rarely detected throughout the study.

For each of the other LUS findings, their number at each time point after anesthesia was compared to the number before anesthesia (Figure 3). Compared to before anesthesia, I-lines were found significantly more often 5 minutes after anesthesia, but less at 3H, 4H, and 6H. B-lines were found significantly more often 5 minutes and 2H after anesthesia. Overall, the number of coalescent B-lines were present in low numbers in all regions and time points, but were found significantly more 5 min, 3H, 4H, and 6H after anesthesia compared to before anesthesia.

For each type of finding and over all time points, also an effect of the region was sought; all regions were compared to the LCRV region. The amount of I-lines, B-lines, coalescent B-lines, and lung rockets was statistically different between regions (Figure 3).

A significant difference in the amount of I-lines was detected at the following time point after anesthesia compared to before anesthesia: higher at 5 minutes ($P = .04$), but lower at 3H ($P = .007$), 4H ($P = .01$), and 6H after anesthesia ($P = .01$). There was a statistical difference in the amount of B-lines compared to before anesthesia: higher at 5 minutes ($P = .00$) and 2H after anesthesia ($P = .01$). Compared to before anesthesia there was a statistical difference in the

TABLE 4 Relation of anesthesia variables with the highest lung ultrasound score (max LUS score)

Anomaly defined as	PaO ₂		PCO ₂		Saturation		Mean arterial pressure		Any anomaly	No anomaly	
	Hypoxia (PaO ₂ <60 mm Hg) at any time point	Suboptimal PaO ₂ (60-80 mm Hg) at any time point	Normal oxygenation (>80 mm Hg) at any time point	Hypercapnea: PCO ₂ >60 mm Hg	Normal PCO ₂ <60 mm Hg	Low SAT <90%	Normal SAT >90%	Low MAP <60 mm Hg			Normal MAP >60 mm Hg
Mean of the horses with that abnormality/normality	51.678	68.878	94.929	60.800	58.392	84.150	95.048	50.00	72.682	Not relevant	Not relevant
SD of the horses with that abnormality/normality	5.013	7.402	13.952	/	9.787	2.645	2.795	0.000	9.057	Not relevant	Not relevant
Range of the horses with that abnormality/normality	44.2-58.4	60.8-79.8	81.7-123.4	60.8-60.8	46.1-79.8	82.2-87.8	90.7-99.1	50-50	60-95	Not relevant	Not relevant
Nr of horses monitored	25	25	25	25	25	25	25	24	24	25	25
Nr of horses with anomaly/normality	9	9	7	1	24	4	21	2	22	19	6
Max LUS score after anesthesia entire thorax of the horses with that anomaly/normality M ± SD	13 ± 11.456	8.78 ± 6.26	7 ± 12.858	4	10.04 ± 10.377	9.75 ± 13.672	9.81 ± 9.877	26 ± 12.728	8.77 ± 9.013	12.16 ± 10.526	2.33 ± 3.933
Comparison MAX LUS AFTER ANESTHESIA score between groups with abnormal as reference	Normal vs hypoxemic group: P = .34		Normal vs hypercapnic: P = .51		Normal vs low saturation: P = .99		Normal vs low MAP: P = .2		Normal vs Any anomaly: P-value = .005*		
Abnormal/suboptimal/normal P-values	Suboptimal oxygenation vs abnormal: P = .57										

Abbreviations: LUS, lung ultrasound; MAP, mean arterial pressure (mm Hg); PaCO₂, partial pressure of carbon dioxide in arterial blood; PaO₂, partial pressure of oxygen in arterial blood; SAT, saturation. *Statistically correlated (P < .05).

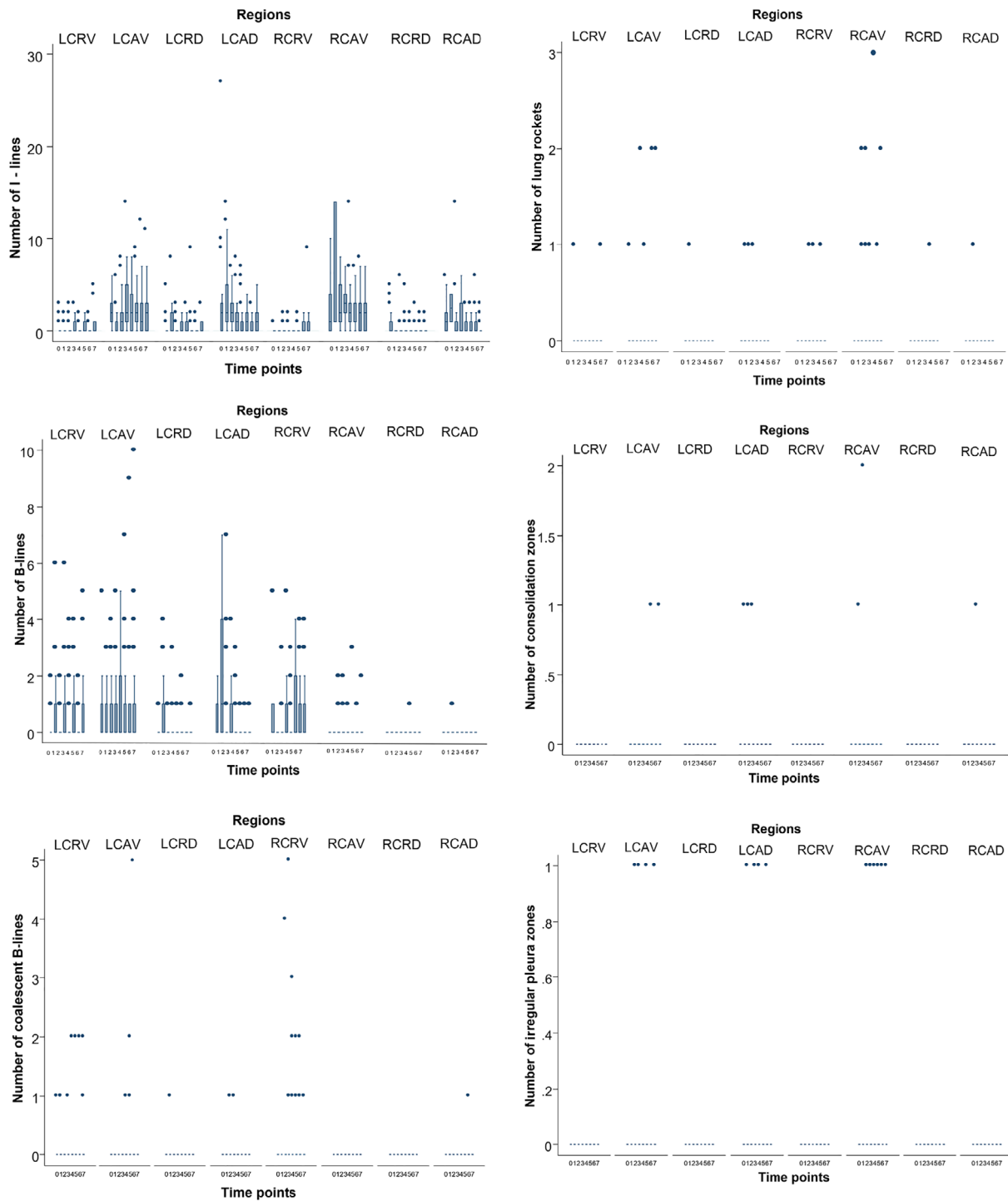


FIGURE 3 Lung ultrasound (LUS) findings before and after anesthesia of 25 healthy horses undergoing elective surgery, illustrated per thoracic region over the different time points. Legend: LCAD, left caudodorsal region; LCAV, left caudoventral region; LCRD, left craniodorsal region; LCRV, left cranioventral region; RCAD, right caudodorsal region; RCAV, right caudoventral region; RCRD, right craniodorsal region; RCRV, right cranioventral region; Time 0, before anesthesia; 1, 5 minutes in the recovery; 2, 15 minutes after standing; 3, 2 hours after anesthesia; 4, 3 hours after anesthesia; 5, 4 hours after anesthesia; 6, 6 hours after anesthesia; 7, 24 hours after anesthesia

amount of coalescent B-lines: higher at 5 minutes ($P = .03$), 3H ($P = .05$), 4H ($P = .04$), and 6H ($P = .05$).

Compared to the LCRV region, more I-lines were found in the LCAV ($P = .000$), LCAD ($P = .00$), RCAV ($P = .00$), and RCAD

($P = .000$) region. Compared with the LCRV region, more B-lines were found in the LCAV ($P = .002$) and RCAV ($P = .000$) region; less B-lines were found in the LCRD ($P = .00$), RCRD ($P = .00$), and RCAD ($P = .006$). Compared with the LCRV region, less coalescent B-lines

children undergoing GA, considered juxtapleural consolidations on LUS the most common sign of atelectasis, followed by the presence of B-lines. The absence of A-lines, the presence of air bronchograms, the absence of lung sliding, and presence of the pulse sign were other LUS changes associated with atelectasis in these children but were not seen in any of the horses in the current study.²⁸ A CT-scan and morphological study showed that atelectasis of the dependent lung developed early in GA in horses.⁶ This could explain why most horses in the this study, independent of the duration of the procedure, had more findings and higher scores after anesthesia than before anesthesia. Gravity-dependent atelectasis could also explain why the total procedure time had a significant impact on the maximal LUS score after anesthesia in this study. Prolonged GA in dogs induces a significant increase in LUS abnormalities after anesthesia, whereas only minimal changes are seen after a typically short procedure such as elective surgical sterilization.¹⁸

In line with previous findings in humans that showed correlations between after anesthesia LUS changes and oxygenation during and shortly after GA, the present study showed a higher maximal LUS score after anesthesia in horses having at least 1 cardiorespiratory abnormality during GA.

In equine medicine, the effects of atelectasis during GA have been scarcely studied. Previous studies showed changes in pulmonary secretions in the dependent lung at the end of GA²⁹ but no decrease in lung function in horses undergoing castration.³⁰ Lung ultrasound changes resolved within 1 to 3 hours after extubation in dogs undergoing long anesthetic procedures.¹⁸ Most likely there is an effect of body size, leading to less gravity-dependent atelectasis and cardiorespiratory problems in smaller animals and subsequently a faster resolution of LUS changes after anesthesia compared to horses.

Based on the LUS findings before anesthesia of the 25 healthy horses, a LUS score system was suggested in this study. The aim of this scoring system was to attribute a clinical significance or weight to the several LUS findings. Therefore, the LUS score allowed to assess in an objective manner the pulmonary changes induced by GA. The score developed in the current study is different from the ones in human medicine as human scores are not directly applicable to the horse. Namely, different divisions of the thoracic regions are applied, according to the human thoracic anatomy, and lesion scoring is typically limited to B-lines and consolidation.^{31,32} Therefore, an entirely new score was developed based on the normal findings before anesthesia of the horses in the current study. LUS findings were included that are for horses typically described as pathological (such as consolidation and irregular pleura),² and those that were more prevalent after anesthesia and of which the importance is still unsure (such as I-lines). The other LUS findings of the score are simply variants of B-lines (individual, coalescent B-lines, lung rockets). Validating the LUS score in a larger group of healthy and sick horses could allow determining if LUS scores can indicate disease, however this was not an objective for this study.

Ultrasonography is a sensitive modality for imaging of the surface of the lungs in humans and animals, even for smaller lesions or

changes. Nevertheless, the ultrasound waves do not penetrate air and information remains therefore limited to the most superficial parts of the lungs. This leaves a large volume of the equine lung unexamined. CT or MRI cross sectional images would theoretically be the ideal choice, but these are unavailable for adult horses. Thoracic radiography in horses is more commonly used in equine medicine, but has the downside of being unable to detect smaller and subtle pleural and lung changes.² Therefore no comparison between LUS and other imaging techniques was performed in this study. After human studies and our equine study, it can be hypothesized that LUS could be a useful predictor of after anesthesia pulmonary complications.³²⁻³⁴

The quality of the ultrasound images and therefore the visibility of LUS lesions can be reduced by a high BCS or significant amount of sweating, such as commonly encountered directly after GA. The latter could have impacted the results. I-lines were less recorded in the cranioventral regions, this could be due to the large muscle mass overlying the lung and the use of a different transducer and settings, as these are subtle findings. In contrast to I-lines, coalescent B-lines were more often seen in the cranioventral regions of the lung. Coalescent B-lines being a more obvious finding, they are unlikely to be missed by suboptimal scanning conditions or unlikely to be superimposed by other findings, so that LUS likely reveals their true amount. Since no guidelines currently exist, an empirical cut-off of 0.9 cm of width was used to classify B-lines as a coalescent B-lines.

The main limitation of this study is the use of a small number of horses that were determined healthy based only on history, clinical examination and blood analysis before anesthesia. Therefore, it was impossible to determine with certainty that they were free of pulmonary disease. Due to the relatively small study sample, the statistical power of the study was limited. This could possibly explain why no difference in maximal LUS score-H was found between normal or abnormal oxygenation in this study. This could also have been influenced because only healthy horses were included. More pronounced findings and differences are likely to be found in sick horses. Sick human patients undergoing long major surgeries have LUS changes after anesthesia that are associated with pulmonary complications and morbidity and death in the subsequent 8 days.³⁵

In conclusion, the description of LUS findings in healthy horses in this study provides detailed information on the common findings, their typical frequency and distribution and what can be expected as normal, both before anesthesia and the first 24H after anesthesia. The developed LUS scoring system was successfully used to objectify LUS findings in this study. After anesthesia changes in LUS findings and in LUS scores were demonstrated after undergoing elective surgery in most horses. Abnormal cardiorespiratory anesthetic variables and longer procedure times lead to higher LUS scores after anesthesia.

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CONFLICT OF INTEREST DECLARATION

Authors declare no conflict of interest.

OFF-LABEL ANTIMICROBIAL DECLARATION

Off-label antimicrobials were used in some horses consisting of intravenous benzylpenicillin.

INSTITUTIONAL ANIMAL CARE AND USE COMMITTEE (IACUC) OR OTHER APPROVAL DECLARATION

Authors declare no IACUC or other approval was needed. Owners agreed to the study by signing an owner consent form.

HUMAN ETHICS APPROVAL DECLARATION

Authors declare human ethics approval was not needed for this study.

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SUPPORTING INFORMATION

Additional supporting information may be found in the online version of the article at the publisher's website.

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