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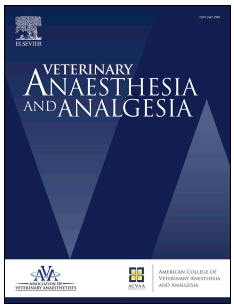

Regional ventilation distribution and dead space in anaesthetised horses treated with and without continuous positive airway pressure (CPAP)

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PII: S1467-2987(17)30241-6

DOI: 10.1016/j.vaa.2017.06.004

Reference: VAA 180

To appear in: *Veterinary Anaesthesia and Analgesia*

Received Date: 22 March 2017

Revised Date: 11 May 2017

Accepted Date: 15 June 2017

Please cite this article as: Mosing M, Auer U, MacFarlane P, Bardell D, Schramel JP, Böhm SH, Bettschart-Wolfensberger R, Waldmann AD, Regional ventilation distribution and dead space in anaesthetised horses treated with and without continuous positive airway pressure (CPAP), *Veterinary Anaesthesia and Analgesia* (2017), doi: 10.1016/j.vaa.2017.06.004.

RESEARCH PAPER

Regional ventilation distribution and dead space in anaesthetised horses treated with and without continuous positive airway pressure (CPAP)

Novel insights by electrical impedance tomography and volumetric capnography

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Running head EIT and VCap during CPAP in horses

Acknowledgements and Conflict of interest statement

We want to thank the “Stiftung Forschung für das Pferd” for financing this project. None of the authors of this paper has a financial or personal relationship with other people or organisations that could inappropriately influence or bias the content of this paper.

Authors’ contributions

All authors contributed to conception and design of research; MM, UA, PM, RB, DB performed experiments; ADW, UA, SHB and JPS analysed data and did statistical analysis; all authors interpreted results; MM, UA, JPS drafted manuscript; all authors edited, revised and approved final version of the manuscript.

Regional ventilation distribution and dead space in anaesthetized horses treated with and without continuous positive airway pressure (CPAP).

Abstract

Objective The aim of this study was to evaluate the effect of continuous positive airway pressure (CPAP) on regional distribution of ventilation and dead space in anaesthetised horses.

Study design Randomized, experimental, crossover study.

Animals Eight healthy adult horses.

Methods Horses were anaesthetised twice with isoflurane in 50% oxygen and medetomidine as continuous infusion in dorsal recumbency, and administered in random order either CPAP (8 cmH_2O) or NO CPAP for 3 hours. Electrical impedance tomography (EIT) and volumetric capnography (VCap) measurements were performed every 30 minutes. Lung regions with little ventilation [dependent (DSS) and non-dependent silent spaces (NSS)], centre of ventilation (CoV) and dead space variables as well as venous admixture were calculated. Statistical analysis was performed using MANOVA and Pearson correlation.

Results Data from six horses were statistically analysed. In CPAP the CoV shifted to dependent parts of the lungs (P <0.001) and DSS were significantly smaller (P<0.001), while no difference was seen in NSS. Venous admixture was significantly correlated with DSS with the treatment time taken as covariate (P <0.0001; r=0.65). No differences were found for any VCap parameters.

Conclusions and clinical relevance In dorsally recumbent anaesthetised horses, CPAP of 8 cmH_2O results in redistribution of ventilation towards the dependent lung regions thereby improving ventilation-perfusion matching. This improvement was not

associated with an increase in dead space indicative for a lack in distension of the airways or impairment of alveolar perfusion.

Keywords centre of ventilation, EIT, electrical impedance tomography, equine, silent space, spontaneous ventilation

Introduction

General anaesthesia and change in body position results in a reduction of functional residual capacity (FRC) of the lung to a level approximating that of residual volume (Wahba 1991). This phenomenon promotes small airway closure, particularly in dependent lung regions. Alveolar atelectasis develops distal to these closed airways as a result of continued gas absorption, leading to lung regions with low ventilation / perfusion ratios. In anaesthetised horses this is further compounded by compression of lung tissue by the weight of the abdominal organs (Nyman et al. 1990).

Continuous positive airway pressure (CPAP) is a ventilation mode where airway pressure is kept above ambient pressure throughout inspiration and expiration in spontaneously breathing patients. The positive pressure applied to the lungs is expected to keep small airways and alveoli open by maintaining FRC. Two recent studies have demonstrated CPAP decreases venous admixture in anaesthetised horses and improves gas exchange (Mosing et al. 2012b; Mosing et al. 2016a). Ventilation was not affected by the airway pressure applied, indicated by unchanged end-tidal ($P_E´CO_2$) and arterial partial pressure of carbon dioxide ($PaCO_2$) (Mosing et al. 2016a). However, CPAP did not prevent hypoventilation and $PaCO_2$ levels were unacceptably high in both groups. Half of the horses (in both groups) required controlled mechanical ventilation over the 6 hour study period.

Electrical impedance tomography (EIT) is a non-invasive monitoring modality that provides imaging of regional lung function (Frerichs et al. 2016) using an array of electrodes placed around the thorax. A small current is applied sequentially via two electrodes while the voltage is measured by the remaining, allowing calculation of

impedance changes resulting from the varying gas and fluid content in the thorax. The impedance map gained from these measurements can be analysed to elucidate regional changes in ventilation distribution within the lung. Electrical impedance tomography therefore offers new investigative possibilities to compare ventilation modes particularly in horses where computed tomography is not possible (Mosing et al. 2016b; Ambrisko et al. 2017). In humans it has been shown that CPAP causes a redistribution of tidal ventilation towards dependent regions of the lungs in healthy subjects in supine position (Andersson et al. 2011).

Volumetric capnography (VCap) enables the calculation of airway, alveolar and physiologic dead space values by generating a plot of the expiratory partial pressure of CO_2 against expired tidal volume (Tusman et al. 2009). Using a custom-made flow-partitioning device for large animals, positioned between the endotracheal tube and the Y-piece of the anaesthetic breathing system, VCap and spirometry data can be measured by standard human mainstream capnography sensors by recalculating the volume measurements (Schramel et al. 2014; Ambrisko et al. 2017). Dead space measurements have been suggested as a bedside method to determine the appropriate level of CPAP and positive end-expiratory pressure (PEEP) consistent with keeping the small airways open without over distending them (Spalding et al. 1999; Blankman et al. 2016).

The aim of this study was to evaluate regional ventilation distribution and dead space parameters in anaesthetised horses treated with a CPAP level of 8 cmH_2O and without CPAP. We hypothesised that CPAP would redistribute ventilation towards the dependent parts of the lungs without overdistending non-dependent lung regions.

Material and methods

This experimental prospective cross-over study was performed with the ethical approval of the local committee for animal experimentation of the Swiss government (TV-4985). This study was part of an original study performed to evaluate the effects of CPAP on venous admixture, cardiac output and oxygen delivery in horses (Mosing et al. 2016a) and the sample size was based on paramaters from the original study.

Animals

Eight healthy adult horses from the original study (Mosing et al. 2016a) were included in this study. Horses were considered healthy based on clinical examination, routine haematology, biochemistry and arterial blood gas analysis before anaesthesia. They were fasted for 12 hours, but had free access to water until 2 hours prior to induction. Each horse was anaesthetised twice for 6 hours with one week rest and randomly (using opaque envelopes) allocated to either administration of NO CPAP (anaesthetic machine set to 0 cmH_2O CPAP) or CPAP (continuous positive airway pressure of 8 cmH_2O) during the first anaesthesia. During the second anaesthesia the alternative protocol was applied.

Pre-experimental preparation and instrumentation

The day before anaesthesia a narrow 5 cm wide circumferential strip of hair was clipped around the thorax at the level of the fifth to sixth intercostal space behind the elbow joint to allow optimal electrical contact of the EIT electrodes with the skin. This clipping also guaranteed the correct position of the belt during attachment in dorsal recumbency during the first and second anaesthesia to guarantee comparable EIT results.

On the day of the experiment a jugular catheter (SecalonT; Ohmeda, Switzerland) and a pulmonary artery catheter (8F 110 cm angiography balloon catheter; Arrow Swiss, Switzerland and Intro-flex, Edwards Lifesciences, Switzerland) were placed using pressure guidance to determine correct positioning.

Anaesthesia

Horses were premedicated with medetomidine (0.007 mg kg^{-1}) (Dorbene; Graeub AG, Switzerland) IV and phenylbutazone (4 mg kg^{-1}) IV (Butadion; Streuli Pharma AG, Switzerland). Anaesthesia was induced with diazepam (0.02 mg kg^{-1}) (Valium; Roche, Switzerland) and ketamine (2 mg kg^{-1}) (Ketanarkon 100; Streuli Pharma AG, Switzerland) IV. The trachea of all horses were intubated using a 26 mm internal diameter cuffed silicone tube. After placing the horse in dorsal recumbency, the endotracheal tube was connected to a circle breathing system (Tafonius; Vetronic Services LTD, UK). Isoflurane (Attane Isoflurane; Provet, Switzerland) vaporised in an oxygen/air mix (inspiratory oxygen fraction: 0.5) in combination with a medetomidine continuous rate intravenous infusion (CRI) (0.0035 mg kg^{-1} $hour^{-1}$) was used to maintain anaesthesia. A ketamine bolus (50-100 mg) was administered IV in case of spontaneous movement. Anaesthesia was performed by the same experienced anaesthetist throughout the experiments.

Ringer's lactate (Ringer-Lactat Fresenius; Fresenius Kabi, Switzerland) was infused at a rate of 10 mL kg^{-1} $hour^{-1}$ and after two hours an infusion of hydroxyethyl starch (HAES-steril 10% ad us. vet.; Fresenius Kabi, Switzerland) was started (1 mL kg^{-1} $hour^{-1}$). Hydroxyethyl starch was added to the standard cristalloid infusion to compensate for the high urinary output expected with a medetomidine CRI (Mosing et al. 2016a). If mean arterial pressure dropped below 75 mmHg dobutamine was infused intravenously

initially at 0.03 mg kg^{-1} $hour^{-1}$, increasing or decreasing by 0.006 mg kg^{-1} $hour^{-1}$ steps every 5 minutes to maintain mean arterial pressure between 75 and 85 mmHg.

If arterial partial pressure of CO_2 ($PaCO_2$) exceeded 100 mmHg (13.3 kPa) at any measurement point, horses were excluded from further data acquisition and assisted mechanical ventilation was initiated (Fig. 2).

Anaesthesia was maintained in all horses for six hours. However, for this study only the first three hours of each anaesthesia were analysed as too many horses dropped out in both treatment groups after that time point because of hypoventilation and the requirement for mechanical ventilation. After the 6 hours of anaesthesia, horses recovered unassisted in a padded recovery box.

Monitoring and data collection

After positioning the horse in dorsal recumbency on an air mattress, electrically non-conductive ultrasound gel was applied to the previously clipped region of the thorax. Thereafter a custom-made EIT electrode belt was passed under and around the thorax. The EIT Pioneer-Set (Swisstom AG, Switzerland) was used to acquire EIT data at a rate of 46 frames per second. A modified Graz consensus reconstruction algorithm for EIT (GREIT) (Adler et al. 2009) adapted to the horse's anatomy was used to generate EIT images for each horse representing breathing-related regional changes of impedance (ΔZ). Further details on EIT technology and image reconstruction can be found elsewhere (Costa et al. 2008).

The flow-partitioning device consisted of two identical flow splitter adapters – one connected to the endotracheal tube and the other to the Y-piece of the anaesthetic breathing system. Each adapter partitioned and merged the airflow to four equal parts

and directed the flow through four identical human adult connectors of a combined mainstream CO_2 infrared and differential pressure sensor (NICO, Respironics, Wallingford, CT, USA) via transparent silicone tubes. Further details on the flow-partitioning device can be found elsewhere (Schramel et al. 2014). The CO_2 mainstream sensor and the spirometer interface were connected to one of the four NICO sensors. Volumetric capnography and spirometry data were recorded using dedicated software Datacoll (Respironics; Wallingford, CT, USA).

Electrical impedance tomography, VCap and spirometry data were recorded over three minutes every 30 minutes during the first three hours of anaesthesia (M30, M60, M90, M120, M150, M180).

At each measurment point arterial and mixed venous blood samples were taken simultaneously from the facial and pulmonary artery catheters under anaerobic conditions and PO_2, PCO_2 and haemoglobin concentration (Hb) were analysed immediately (Rapidpoint; Siemens, Switzerland).

The blood gas analyser and NICO were calibrated following manufacturers' guidelines before each experiment.

Standard cardiopulmonary monitoring was employed using multi-parameter monitors (Datex-Ohmeda S/3 Anaesthesia Monitor; Datex-Ohmeda and Tafonius). Values were recorded manually every five minutes and are reported elsewhere (Mosing et al., 2016a).

Data Analysis

The EIT regions of interest (ROI) for the right and left lung were determined by creating individualized lung contours for each horse based on the assumption that the large ventilation-induced impedance changes (ΔZ) within the lungs will exceed by far those of other thoracic structures. Therefore, ΔZ values of more than 10% of the maximal impedance amplitude in any of the recorded breaths were used to define the outer boundaries of the 'EIT-based lung region' for each individual. This means that every pixel showing an amplitude of more than 10% during a breath was included in the individual ROI. Only pixels within these ROIs were analysed. At each time point, tidal EIT images were created from 10 consecutive stable breaths by calculating the impedance difference between inspiration and the preceding end-expiration for each pixel.

The Centre of ventilation (CoV; Fig. 1) was determined as a percentage of ventro-dorsal extension of the lung region, where 0% referred to ventilation occurring in the most ventral part of the lung and 100% to that in the most dorsal part (Frerichs et al. 1998; Mosing et al. 2016b) (Fig. 1). For dorsal recumbency this means that values < 50% represented predominant ventilation of the non-dependent parts, while values > 50 % indicated a CoV in dependent parts of the lungs. For each breath a virtual line was drawn horizontally through the CoV defined as the ventilation horizon.

Silent spaces indicate lung regions with < 10% impedance change of the maximum within the tidal image and are expressed as percentages of the total lung area (Ukere et al 2016). Dependent silent spaces (DSS) lie below the ventilation horizon and indicate collapsed or poorly ventilated lung regions, while non-dependent silent spaces (NSS) are located above the ventilation horizon and indicate over-distended lung regions (Ukere et al. 2016) (Fig. 1).

Figure 1 near here

Raw CO_2 and flow data recorded by the dedicated NICO software were used to evaluate spirometry data and construct VCap curves for all or a maximum of 10 breaths recorded over the 3 minutes. The latter was computed with a custom-made macro routine in Excel (Excel; Microsoft Corporation, WA, USA). The curve-fitting algorithm was realized by the solver function according to the formula developed by Tusman and colleagues (2009).

The following spirometry, capnography and VCap parameters were analysed: Tidal volume (V_T), respiratory rate (f_R), end-tidal PCO_2 ($P_E´CO2$), Bohr´s dead space ratio (VD_{Bohr}), Bohr-Enghoff's dead space ratio ($VD_{B\text{-}Eng}$), airway dead space to tidal volume ratio (VD_{aw}/VT), alveolar dead space (calculated from $VD_{B\text{-}Eng}$) to alveolar tidal volume ratio (VD_{alv}/VT_{alv}) and volume of expired CO_2 per breath ($VCO_{2,br}$).

Venous admixture ($\dot{Q}s/\dot{Q}t$) was calculated retrospectively using the standard equation (Lumb 2010): $\dot{Q}s/\dot{Q}t = (Cc'O_2\text{-}CaO_2)/(Cc'O_2\text{-}C\bar{v}O_2)$. Details on the equation and absolute values are reported elsewhere (Mosing et al., 2016a).

Statistics

Analysis was performed using NCSS statistical software, (NCSS V 11.0.3, Statistical Software (2016). NCSS, LLC. Kaysville, Utah, USA, ncss.com/software/ncss.) Data were assessed for normality by Kolmogorov-Smirnov-test. Data of CPAP and NO CPAP were analyzed with MANOVA in regards to influence of treatment and time on

232 results, followed by post-hoc Bonferroni test. Pearson correlation was calculated for
233 venous admixture and DSS. Statistical significance was set at $P < 0.05$. Results are given
234 as mean values ± standard deviation and range.
235

Results

A total of eight horses were enrolled in this study. Data from two horses was excluded because of technical difficulties with the EIT device in one horse and with volumetric capnography data collection in the other (Fig. 2). Therefore, data of six horses were included in the statistical analysis. Only the first three hours of anaesthesia were analysed because of the small number of horses remaining in both groups after this time point (Fig. 2). The six horses had an age of 10 ± 6 years and body weight 539 ± 35 kg (1 Thoroughbred, 5 Freiberger).

One and two horses required mechanical ventilation because of high $PaCO_2$ levels after M150 in group CPAP and NO CPAP, respectively. One horse in group CPAP moved after M60 and did not regain spontaneous ventilation for more than 10 minutes after administration of a bolus of ketamine. Data from this horse was excluded after M60 (Fig. 2).

The airway pressure swings during inspiration and expiration for these spontaneously breathing horses were 8 ± 8 cmH_2O and 0 ± 10 cmH_2O for CPAP and NO CPAP, respectively.

Figure 2 near here

Respiratory variables, VCap and EIT data of the six horses are given in Table 1. Dependent silent spaces were significantly lower in CPAP (P<0.001), while no difference was seen in NSS. The CoV was higher in CPAP, located more dorsally, in the dependent parts of the lungs (P<0.001). Venous admixture was significantly correlated with DSS when time was taken as covariate (P <0.0001; r=0.65).

No difference was found for V_T (P=0.932), f_R (P=0.986), $P_{E'}CO2$ (P=0.981), VD_{aw}/VT (P=0.456), VD_{alv}/VT_{alv} (P=0.955), VD_{Bohr} (P=0.835), $VD_{B\text{-}Eng}$ (P=0.456) or $VCO_{2,br}$ (P=0.971) between the two groups.

Table 1 near here

Discussion

This study demonstrates that CPAP of 8 cmH_2O in dorsally recumbent anaesthetised horses decreases the amount of silent spaces in the dependent parts of the lungs. This results in an improved matching of ventilation and perfusion, seen as a decrease in venous admixture. At the given airway pressure CPAP did not cause an increase in any dead space parameters neither overdistending the airways (no change in VD_{aw}/VT) nor the alveoli (no change in VD_{alv}/VT_{alv}).

Electrical impedance tomography is a radiation free, breath-by-breath functional imaging modality, which can be used to monitor regional lung ventilation in different species (Frerichs et al. 2016; Ambrisko et al. 2017; Mosing et al. 2017) and has been used in humans to verify the efficacy of CPAP (Andersson et al. 2011). In awake supine humans as well as in our anaesthetised horses in dorsal recumbency a redistribution of tidal ventilation towards dorsal (dependent) parts of the lungs was found with administration of CPAP (Andersson et al. 2011). In the horse - as it is in all quadrupeds, lung perfusion is considered higher in dorsal parts of the lungs unrelated to posture (Hlastala et al. 1996). This is even more marked in anaesthetised horses (Dobson et al. 1985). The shift of the distribution of ventilation into the well perfused dorsal parts of the lungs caused by CPAP in our horses lead to an improvement in ventilation / perfusion matching and gas exchange indicated by lower venous admixture in CPAP. Both, induction of general anaesthesia and dorsal recumbency reduce functional residual capacity (FRC) and cause collapse of the small airways (Hedenstierna & Edmark 2010; Spaeth et al. 2016). This decrease in FRC is because of the loss of respiratory muscle tone and compression by viscera, causing a marked decrease in lung volume. Applying CPAP increases FRC and counteracts airway collapse and therefore

atelectasis formation (Edmark et al. 2014). Dependent silent spaces of the EIT represent poorly ventilated areas in the dependent parts of the lungs and correspond to collapsed or poorly ventilated lung areas (Ukere et al. 2016). We found a significantly lower percentage of DSS when CPAP was applied to the lungs of the horses. This confirms that CPAP reduces lung collapse, probably by keeping small airways patent in the dependent lung areas. We furthermore found a direct correlation between the decrease in DSS and venous admixture over time, which agrees with previous findings in humans that CPAP not only improves V/Q matching but also reduces venous admixture by counteracting airway collapse and formation of atelectasis (Edmark et al. 2014).

It has been previously reported (Mosing et al. 2016b; Ambrisko et al. 2017) that the effects of controlled mechanical ventilation (CMV) are different from those of CPAP in dorsal recumbent anaesthetised horses. CPAP and lung recruitment manoeuvres shift the CoV towards the better perfused dependent parts of the lungs, while just switching from spontaneous ventilation to CMV moved the CoV towards the ventral non-dependent parts (Mosing et al. 2016b; Ambrisko et al. 2017). This ventral shift was explained by the loss of dorsal movement of the diaphragm when switching from spontaneous ventilation to CMV (Froese & Bryan 1974; Mosing et al. 2016b). During spontaneous ventilation, the dorsal dependent parts of the diaphragm show greater movement than the ventral non-dependent parts thereby drawing the inflowing gas towards the dependent parts. When switching to CMV the diaphragm is pushed caudally to the same extent in the ventral and dorsal parts, which causes the ventilation to shift ventrally (Radke et al. 2012; Mosing et al. 2016b). Performing a recruitment manoeuvre initially shifted the CoV towards the dorsal dependent parts of the lungs during CMV possibly as a result of opening atelectasis at those sites (Ambrisko et al.

2017). However, because of the insufficient amounts of PEEP applied after the manoeuvre, the CoV returned to baseline and therefore towards the ventral non-dependent less perfused lung parts. Despite the relatively low CPAP level of 8 cmH_2O in our study, the CoV was located more dorsally throughout the study period with CPAP.

The volumetric capnogram is the dynamic representation of the CO_2 elimination plotting the partial pressure of CO_2 over the exhaled volume. The best fit approximation of the measurements by a mathematical model curve proposed by Tusman et al. (2009) enables the calculation of different pulmonary dead space parameters.
This method can be applied to all mammals as long as the trachea and lung follow similar architectures. A precondition for the measurement is the use of a mainstream capnograph (i.e. a fast infrared) CO_2 sensor and flow meter to avoid a time delay between theses signals. The integration of a human mainstream airway adapter in a special flow-partitioning device for large animals and mathematical correction for the splitting of the tidal volume enables the calculation of VCap parameters also in large animals such as horses (Moens et al. 2014; Sacks & Mosing 2016; Ambrisko et al. 2017). In recent papers, VCap variables have been shown to detect distension of the lung tissue during a recruitment manoeuvre in horses (Ambrisko et al. 2017) and can be used to distinguish between distension of the airways and overdistension of the alveolar compartment during PEEP titration in humans (Blankman et al. 2016). Furthermore, it has been used to detect optimal CPAP levels by observing changes in $VD_{B\text{-}Eng}$ (Spalding et al. 1999). In our study, no differences in physiologic, airway or alveolar dead space were found between groups. Overdistension of alveoli would be rather unphysiological during spontaneous breathing and is unlikely with administration of CPAP in contrast to

use of CMV or recruitment manoeuvres where high peak inspiratory pressures are used. However, the continuous positive pressure in the alveoli can impair capillary blood flow around the alveoli causing an increase in lung units with high V/Q mismatch or even an increase in alveolar dead space. The small difference we found between CPAP and NO CPAP in all dead space parameters suggests that a positive airway pressure of 8 cmH_2O neither causes airway distension nor interruption of alveolar perfusion in healthy anaesthetised horses.

However, one would expect a higher airway dead space in CPAP because positive pressures keep small airways open, especially the terminal and respiratory bronchioles, the typical site of airway collapse. Airway dead space by definition is the volume of the airways in which movement of gases occurs by convection (Fletcher et al. 1981). As gas movement in terminal bronchioles takes place by diffusion and not convectional flow, the volume of gas within this 'space' does not contribute to the volume of airway dead space. As long as the alveoli corresponding to these terminal bronchioles are still perfused, alveolar dead space will remain constant as well (Fletcher et al. 1981). This again suggests that the CPAP level used in our study had no negative impact on gas flow in the airways or blood flow in the capillaries.

Another evidence for similar pulmonary perfusion conditions in both groups is the small difference in $VCO_{2,br}$. The volume of expired CO_2 per breath is a key VCap variable and a very sensitive indicator of changes in pulmonary blood flow (Suarez-Sipman et al. 2016). It can also be used to identify the efficiency of ventilation (Tusman et al. 2012; Suarez-Sipman et al. 2016). The small difference we found between the two groups for $VCO_{2,br}$ confirms the finding of our previous study where CPAP had no influence on the efficiency of ventilation per breath when compared to NO CPAP (Mosing et al.

2016a). However, minute ventilation was insufficient in both groups leading to an increase in $P_{E'}CO_2$ over time. For this reason, CMV might be necessary for the longer clinical procedures even when applying CPAP.

One limitation of our study is that all findings are only related to a CPAP of 8 cmH_2O. Hence we cannot extrapolate them to lower or higher CPAP levels. This pressure was chosen based on findings of a previous study showing that a CPAP of 8 cmH_2O was the minimal pressure necessary to maintain airway pressure above 0 cmH_2O during the entire breathing circle in anaesthetised horses in dorsal recumbency (Mosing et al. 2012b). However, based on the shifts in the CoV over time it is likely that a higher airway pressures may have been needed to prevent collapse of the dependent lungs.

Despite the limitation of only a small number of animals included in this study a significant difference was found for EIT variables, while a very high agreement between the two groups was seen for the dead space variables. However, too many horses dropped out of the study after the first three hours of anaesthesia to allow for statistical analysis after this time point. The benefits of CPAP on cardiorespiratory variables were shown over 6 hours of anaesthesia in the same horses reported in an earlier paper (Mosing et al., 2016a). It remains unknown if those benefits are reflected by EIT and VCap variables after the first three hours of anaesthesia.

Conclusion

In anaesthetised horses in dorsal recumbency a CPAP level of 8 cmH_2O reduces collapsed lung areas in the dependent dorsal part of the lungs and distributes ventilation towards these regions thereby improving the matching of ventilation and perfusion. This

390 is likely to be a result of maintained small airway patency without causing an increase

391 in airway or alveolar dead space.

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485
486 **Figure legend**

487

488 **Figure 1** Left: Graph of a horse in dorsal recumbency with a projected electrical
489 impedance tomography (EIT) image. Right: Schematic illustration of the measured
490 variables within the EIT image and the two regions of interest. Centre of ventilation
491 (CoV), non-dependent (NSS) and dependent (DSS) silent space and ventilation horizon.

492

493 **Figure 2** Flow diagram showing the number of horses included in this study and drop
494 out at each measurement point (M).
495 CPAP; continuous positive airway pressure.

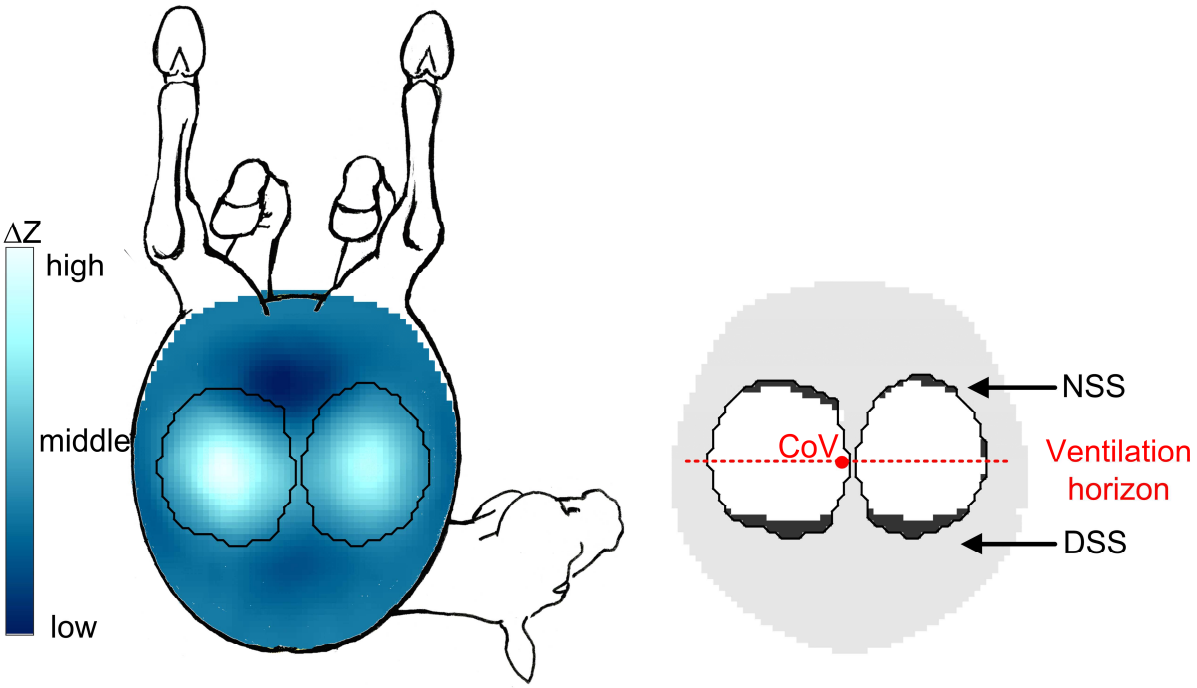
496

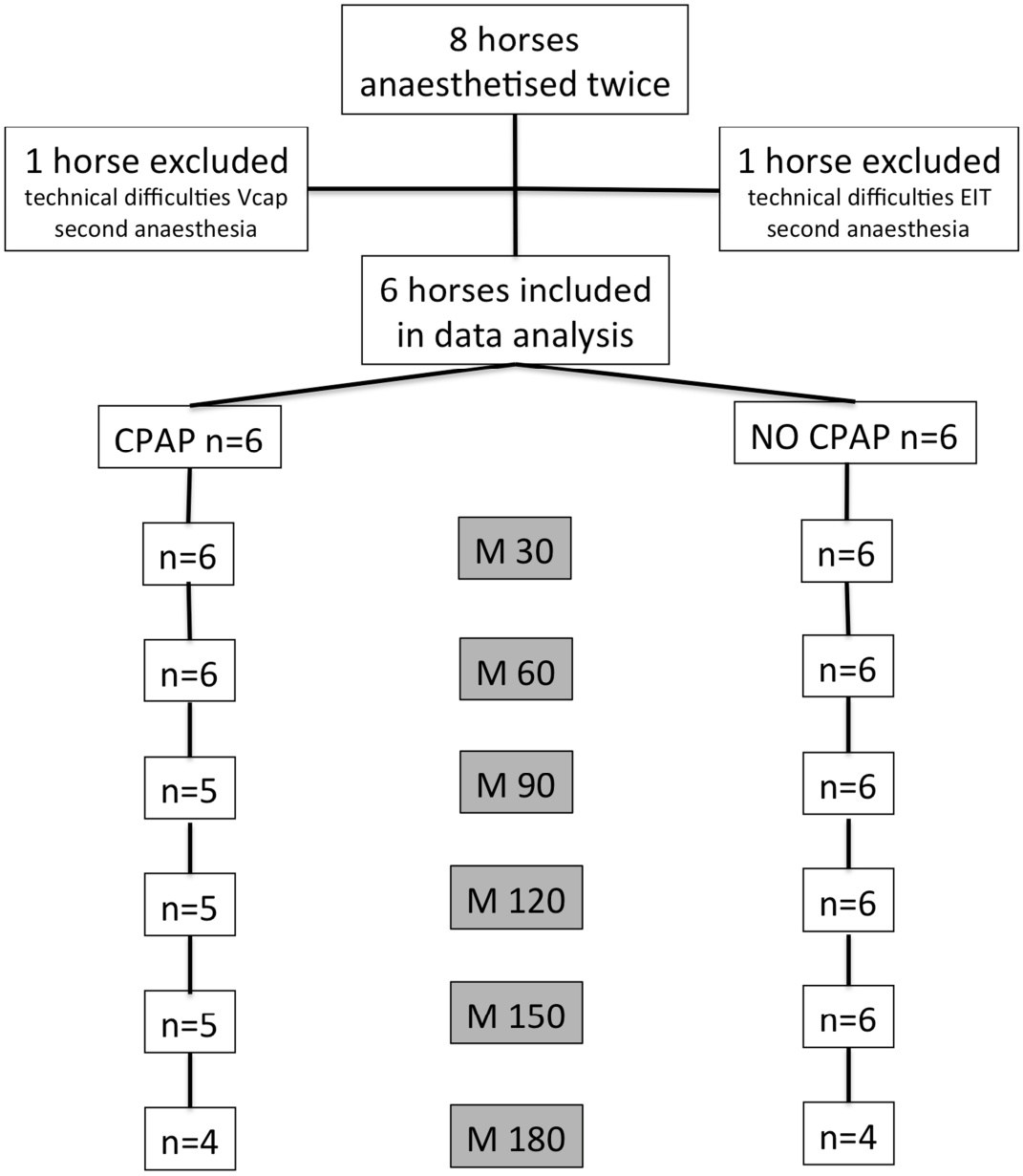
Table 1: Mean ± standard deviation of respiratory, volumetric capnography and electrical impedance tomography EIT parameters in horses without positive airway pressure (NO CPAP) or administered continuous positive airway pressure of 8 cmH_2O (CPAP) at different time points (30 – 180 min after induction = M30 – 180).

	M30		M60		M90		M120		M150		M180	
	NO CPAP	CPAP	NO CPAP	CPAP	NO CPAP	CPAP	NO CPAP	CPAP	NO CPAP	CPAP	NO CPAP	CPAP
V_T (L)	6.1±2.10	6.0±0.9	6.6±1.5	7.2±2.3	6.3±1.5	6.6±1.4	6.9±1.8	8.2±2.2	6.1±1.4	7.5±3.0	6.2±0.9	6.4±1.3
f_R (breaths minute^{-1})	7±6	7±5	6±3	6±4	6±3	6±4	6±3	6±4	6±3	6±4	7±2	6±3
$P_{E'}CO_2$ (kPa)	7.0±0.5	6.8±0.7	7.6±0.9	7.3±0.7	8.0±1.2	7.7±0.9	8.2±1.3	8.0±1.2	8.2±0.9	8.1±1.2	8.4±1.1	8.0±0.9
VD_{Bohr}	0.37±0.1	0.41±0.06	0.36±0.1	0.36±0.07	0.37±0.1	0.34±0.09	0.36±0.1	0.32±0.06	0.38±0.05	0.35±0.07	0.38±0.04	0.37±0.06
$VD_{B\text{-}Eng}$	0.54±0.05	0.55±0.05	0.51±0.03	0.53±0.04	0.51±0.05	0.54±0.05	0.56±0.05	0.50±0.05	0.59±0.06	0.54±0.06	0.53±0.06	0.57±0.05
VD_{aw}/VT	0.36±0.08	0.39±0.08	0.34±0.06	0.33±0.08	0.35±0.06	0.32±0.09	0.32±0.07	0.29±0.06	0.36±0.08	0.33±0.08	0.33±0.05	0.35±0.08
VD_{alv}/VT_{alv}	0.26±0.07	0.27±0.07	0.29±0.06	0.26±0.06	0.30±0.11	0.25±0.06	0.30±0.05	0.35±0.06	0.31±0.05	0.35±0.06	0.33±0.02	0.29±0.15
$VCO_{2,br}$ (mL)	279±131	264±66	326±118	356±197	303±99	350±157	356±99	461±199	331±86	431±309	283±56	324±116
CoV (%)*	51.6±2.01	55.2±4.1	51.3±3.1	54.8±2.5	52.5±1.5	55.0±1.6	52.3±1.6	55.3±0.7	54.6±1.8	56.4±1.2	55.2±0.9	56.5±0.9
NSS (%)	12.8±2.5	12.3±7.9	10.2±5.3	12.1±5.2	12.2±1.7	11.5±4.5	11.7±3.6	13.3±3.6	14.8±3.6	14.3±5.0	17.4±2.4	14.8±2.7
DSS (%)*	16.6±6.4	6.8±5.5	12.8±4.8	8.3±2.8	13.7±5.3	8.2±2.8	13.01±4.5	8.3±3.7	11.8±3.6	6.7±4.5	11.5±4.6	7.0±2.6
Venous admixture (%)*	23.1±12.6	11.0±4.6	25.4±12.6	15.4±8.3	35.7±11.6	28.9±14.3	30±11.4	23.3±11.3	33.5±13.6	24.1±13.0	34.4±12.6	27.5±7.2

V_T, tidal volume; f_R, respiratory rate; $P_{E'}CO_2$, end-tidal carbon dioxide; VD_{Bohr}, Bohr's dead space ratio; $VD_{B\text{-}Eng}$, Bohr-Enghoff's dead space ratio; VD_{aw}/VT, airway dead space per tidal volume; VD_{alv}/VT_{alv}, alveolar dead space as a ratio to alveolar tidal volume; $VCO_{2,br}$, volume of expired CO_2 per

breath; CoV, centre of ventilation; NSS, non-dependent silent space; DSS, dependent silent space and venous admixture (%). *Significant difference between groups ($p < 0.05$)




8 horses anaesthetised twice
1 horse excluded technical difficulties Vcap second anaesthesia
1 horse excluded technical difficulties EIT second anaesthesia
6 horses included in data analysis
CPAP n=6
NO CPAP n=6
n=6
n=6
n=5
n=5
n=5
n=4
M 30
M 60
M 90
M 120
M 150
M 180
n=6
n=6
n=6
n=6
n=6
n=4