RESEARCH PAPER

Cardiopulmonary effects of reverse Trendelenburg position at 5° and 10° in sevoflurane-anesthetized steers

Marcelo A Araújo[a], Maurício Deschk[b], Juliana T Wagatsuma[b], Beatriz P Floriano[b], Carlos E Siqueira[b], Valéria NLS Oliva[b] & Paulo SP Santos[b]

[a]Faculty of Veterinary Medicine and Animal Science, Federal University of Mato Grosso do Sul (UFMS), Campo Grande-MS, Brazil

[b]Department of Animal Clinic, Surgery and Reproduction, Faculty of Veterinary Medicine, (UNESP) − São Paulo State University, Araçatuba-SP, Brazil

Correspondence: Paulo SP Santos, Department of Animal Clinic, Surgery and Reproduction, Faculty of Veterinary Medicine, UNESP−São Paulo State University, 16050-680 Araçatuba-SP, Brazil. E-mail: patto@fmva.unesp.br

Abstract

Objective To assess the cardiopulmonary effects caused by reverse Trendelenburg position (RTP) at 5° and 10° in sevoflurane-anesthetized yearling steers.

Study design Prospective, experimental study.

Animals Eight Holstein steers aged (mean ± standard deviation) 12 ± 2 months and weighing 145 ± 26 kg.

Methods In the first phase of the study, the individual minimum alveolar concentration (MAC) of sevoflurane was determined using electrical stimulation. In the second phase, the effects of RTP were assessed. The animals were anesthetized on three separate events separated by ≥ 7 days in an incomplete crossover design: control treatment using a table without tilt (RTP0); treatment with the table at 5° RTP (RTP5) and table tilted 10° RTP (RTP10). Subjects were physically restrained in dorsal recumbency on the table, which was already tilted according to each treatment. Anesthesia was induced with sevoflurane at 8% in 5 L minute^{-1} oxygen via face mask followed by maintenance with sevoflurane at 1.3 MAC and spontaneous breathing. Cardiopulmonary variables were obtained immediately after instrumentation (T_0) and then after 30, 60, 120 and 180 minutes (T_{30}, T_{60}, T_{120} and T_{180}, respectively).

Results The mean sevoflurane MAC for the eight steers was $2.12 \pm 0.31\%$. Cardiac output was lower at all time points and the systemic vascular resistance index was higher at T_{120} and T_{180} in RTP10 compared with RTP0. Oxygen consumption was lower at T_0 and at T_{180} in RTP10 compared with RTP0 and at all time points except T_{30} compared with RTP5. Oxygen extraction was lower at T_0 in RTP10 compared with RTP0 and RTP5, and at T_{60} and T_{180} compared with RTP5.

Conclusions and clinical relevance RTP 5° and 10° did not improve ventilatory and oxygenation variables in sevoflurane-anesthetized steers when compared with no tilt, however the cardiovascular variables were adversely affected in RTP10.

Keywords bovine, dorsal recumbency, hemodynamic, minimum alveolar concentration, reverse Trendelenburg, sevoflurane.

Introduction

Cattle and horses are subject to hypoventilation and hypoxemia during recumbency (Klein & Fisher 1988; Wagner et al. 1990). Fundamental causes are disturbances in the ventilation−perfusion ($\dot{V}/\dot{Q}$) coupling and pulmonary shunting (Wagner et al. 1990).

When large animals are in dorsal recumbency, the abdominal organs exert pressure on the diaphragm resulting in lung compression and impaired spontaneous ventilation reducing residual capacity and blood flow and leading to $\dot{V}/\dot{Q}$ mismatching (Klein & Fisher 1988; Wagner et al. 1990). Additionally, the weight of the abdominal viscera on the caudal vena cava will result in a decrease in venous return and cardiac output (CO) (Klein & Fisher 1988; Meyer et al. 2010).

Prolonged recumbency in cattle can enhance these alterations as eructation cannot occur in this position. Insufficient fasting prior to general anesthesia results in a greater impact on dynamic compliance (C_{dyn}) and decreased arterial oxygen tension (PaO_2) owing to the rumen volume and accumulation of gas (Blaze et al. 1988). Furthermore, the dose-related cardiopulmonary depression of inhalation anesthesia couples with the impact of recumbency on changes in respiratory function (Arai et al. 2006; Steffey & Mama 2007).

A maneuver that has been successfully employed in humans during anesthesia with dorsal recumbency is the cranial upward tilting of the surgical table [reverse Trendelenburg position (RTP)]. Studies have demonstrated that 30° RTP improves respiratory function in obese human patients subjected to abdominal surgery when compared with dorsal recumbency without a tilt (Perilli et al. 2000, 2003). In contrast, RTP may impair cardiovascular function by further reducing venous return and CO (Perilli et al. 2003; Hazebroek & Bonjer 2006).

In one study of the effect of epidural injection on cardiopulmonary function in calves weighing on average 58 kg, the surgical table was tilted such that the shoulder was the most dorsal point of the spinal column and the head was positioned downward (Meyer et al. 2010). Cardiopulmonary changes were less pronounced than reported in larger cattle in dorsal recumbency. No other studies of the cardiopulmonary effects of RTP in cattle have been found.

The aim of this study was to assess the cardiopulmonary effects of RTP with the table at 5° and 10° in sevoflurane-anesthetized steers lying in dorsal recumbency. The hypothesis was that RTP would improve ventilation and oxygenation, and would impair cardiovascular function.

Material and methods

The study comprised two phases: 1) determination of individual minimum alveolar concentration (MAC) of sevoflurane for each steer; and 2) assessment of the effects of RTP at 5° and 10° on cardiopulmonary variables in steers anesthetized with sevoflurane at $1.3 \times$ individual MAC.

Animals

The study was approved by the Animal Usage Ethics Committee of the Faculty of Odontology of Araçatuba, São Paulo State University (no. FOA-00346-2013). Eight male Holstein steers aged [mean ± standard deviation (SD)] 12 ± 2 months and weighing 142 ± 26, 149 ± 29 and 145 ± 26 kg in the three treatments were used in the study. The animals were housed together in the same paddock and fed corn silage and a ration specific for their species and age. All animals were considered healthy based on physical examination and complete blood count. The animals were docile and used to being handled daily. Prior to anesthesia, each animal was placed in a stall and food was withheld for 24 hours and water for 12 hours.

Phase 1: MAC determination

The unsedated animal was restrained in right lateral recumbency using a rope harness technique. The animal was restrained by tying the limbs together and using an electric lift to place the animal onto the table. Two members of the team were needed for positioning. Sevoflurane (Sevocris; Cristália Produtos Químicos e Farmacêuticos Ltda, SP, Brazil) was administered via face mask at 8% in oxygen delivered at 5 L minute^{-1} to a rebreathing system (Conquest Big; HB Hospitalar Ind. Com. Ltda, SP, Brazil). Once general anesthesia was induced, the trachea was intubated using a laryngoscope and a guide wire (number 18 gastric probe with a central wire; Embramed Indústria e Comércio de Produtos Hospitalares Ltda, SP, Brazil). Tracheal intubation was accomplished in approximately 5 minutes, after which anesthesia was maintained with sevoflurane in oxygen at 20 mL kg^{-1} minute^{-1}. The lungs were mechanically ventilated (Conquest Big; HB Hospitalar Ind. Com. Ltda) to a peak inspiratory pressure (PIP) of 15 cmH$_2$O and respiratory rate (f_R) of 7 breaths minute^{-1} to maintain end-tidal carbon dioxide tension (Pe′CO$_2$) at 35−45 mmHg (4.7−6.0 kPa). End-tidal gas concentrations were sampled through a line connected between the endotracheal tube and the circuit and Pe′CO$_2$ and end-tidal sevoflurane concentration (Fe′Sevo) were measured by a gas analyzer (DX-2020; Dixtal Biomédica, AM, Brazil) using the manufacturer's internal calibration.

A 16 gauge catheter (Insyte; Becton Dickinson Industrias Cirúrgicas Ltda, SP, Brazil) was inserted in the left jugular vein for administration of lactated Ringer's solution (Eurofarma Laboratórios, SP, Brazil) at 3 mL kg^{-1} minute^{-1} via an infusion pump (ST550T2; Samtronic Indústria e Comércio, SP, Brazil). Systolic (SAP), diastolic (DAP) and mean (MAP) arterial pressures were recorded from the

auricular artery catheter (22 gauge, Insyte; Becton Dickinson Industrias Cirúrgicas Ltda) through heparinized saline solution (Hemofol, 10 UI mL^{-1}; Cristália Produtos Químicos e Farmacêuticos Ltda) filled tubing to a pressure transducer (MX960 LogiCal; Smiths Medical, OH, USA) placed at the level of the xiphoid process. The transducer was calibrated with a mercury column, zeroed before use and the dynamic response evaluated by the square wave (fast flush) test. The MAP was maintained above 70 mmHg during MAC determinations through increases in the fluid rate up to 10 mL kg^{-1} hour^{-1} or fluid boluses (15 mL kg^{-1} in 10 minutes) until the minimum value was reached and maintained for 15 minutes. Body temperature was monitored through an esophageal thermometer and maintained between 37.5 and 39.5 °C by the use of a warm-air blanket (TC3000; Gaymar Industries Inc., NY, USA) positioned over the body when necessary.

Sevoflurane was administered at a stable FE′Sevo for 15 minutes. Two 21 gauge needles were inserted subcutaneously 5 cm distal to the elbow joint and 5 cm apart, and an electrode was attached to each needle. Electrical stimulation (Grass-S48; Astromed Inc., CA, USA) was then administered, with each stimulus comprising 2 × 10 ms followed by 2 × 3 second electrical currents at 50 V and 50 Hz (Valverde et al. 2003). FE′Sevo was decreased by 0.2% after each negative response (single or repeated neck or limb flexions, chewing or swallowing, coughing, sympathetic changes, or any movement that did not coincide with a stimulus) and increased 0.1% after the first positive response (two or more consecutive evident flexions of the limbs or neck, or sustained flexion of the neck) (Ewing et al. 1993). MAC was calculated for each steer as the mean value between the lowest concentration at which a negative response was detected and the highest concentration at which a positive response was detected (Quasha et al. 1980). The individual MAC was used in the phase 2 experiments, which was initiated after a minimum of 7 days.

Phase 2: Cardiopulmonary effects of RTP

All eight animals were anesthetized on two occasions for cardiopulmonary measurements during dorsal recumbency with no table tilt (RTP0) and with RTP at 5° tilt (RTP5). Randomization between RTP0 and RTP5 was done using a crossover design. The first four animals were included in the RTP0 and the next four in the RTP5, so that each steer was administered both treatments. Subsequently, five of the original eight animals were anesthetized for measurements during 10° tilt (RTP10). All anesthetic episodes were separated by at least 7 days.

On the day of the experiment, the animal was physically restrained and positioned, as described for phase 1, in dorsal recumbency on the surgical table (Large Animal Surgery Table k05698; Kimzey Inc., CA, USA), tilted according to the treatment assigned. The correct angle was achieved using a wood template (5° or 10°) coupled to a leveler (4902; Tramontina, RS, Brazil).

General anesthesia was induced, the trachea intubated and anesthesia maintained with sevoflurane as described in phase 1. In phase 2, anesthesia was maintained with FE′Sevo 1.3 × individual MAC based on the previously determined MAC values, and the animal was allowed to breathe spontaneously. An equilibration period of 40 minutes after mask induction, inclusive of instrumentation, was allowed prior to the first time point of data collection.

A Swan−Ganz catheter (7 Fr, 110 cm, 131HF&P; Edwards Lifesciences Com Prod Médicos Cirúrgicos, SP, Brazil) was inserted through an introducer (Intro-Flex 8.5 Fr; Edwards Lifesciences Com Prod Médicos Cirúrgicos,) into the left jugular vein and advanced into the distal branch of the pulmonary artery. Correct positioning was confirmed though observation of the waveforms of the right atrium, right ventricle and pulmonary artery (DX-2020; Dixtal Biomédica). Core temperature recorded from the Swan−Ganz thermistor, central venous pressure (CVP), mean pulmonary arterial pressure (MPAP), pulmonary arterial occlusion pressure (PAOP) and CO were recorded through the Swan−Ganz catheter (in that order). To assess CO, the catheter was connected to the cardiac output module (DX-2020; Dixtal Biomédica). CO was measured in triplicate at the end of the expiration phase using thermodilution with the constant for the 7 Fr catheter and 10 mL of 0.9% saline solution cooled to 0−5 °C.

Lactated Ringer's solution was infused intravenously (IV) at 3 mL kg^{-1} hour^{-1} through the introducer side port using an infusion pump. A 22 gauge catheter was inserted into the left auricular artery for measurement of SAP, MAP and DAP using the same equipment and technique as described for Phase 1. Heart rate (HR) was derived from the computerized electrocardiogram (DX-2020; Dixtal Biomédica) using lead II.

Cardiac index (CI), systemic vascular resistance index (SVRI), pulmonary vascular resistance index (PVRI) and stroke index (SI) were calculated according to the following formulae (Araújo et al. 2014):

$$CI = CO/BSA \left(L \ minute^{-1} \ m^{-2} \right)$$

where BSA = body surface area in m^2 (BSA = weight$^{0.06667}$/10);

$$SVRI = [(MAP - CVP/CI)]$$
$$\times \ 80 \left(dyne \ second \ cm^{-5} \ m^{-2} \right);$$

$$PVRI = [(MPAP - PAOP/CI)]$$
$$\times \ 80 \left(dyne \ second \ cm^{-5} \ m^{-2} \right);$$

$$SI = 1000 \times CI/HR \left(mL \ beat^{-1} \ kg^{-1} \right).$$

Tidal volume (V_T), minute volume ($\dot{V}_E$), peak inspiratory flow (PIF) and f_R were obtained from the ventilatory module (DX-2020; Dixtal Biomédica).

Arterial and mixed-venous blood samples (0.6 mL) were drawn from the auricular artery and the pulmonary artery, respectively, into heparinized syringes (A-Line; Becton Dickinson Industrias Cirúrgicas Ltda) for blood gas analysis (Omni C; Roche Diagnostics, Germany), which included pH and arterial and mixed venous oxygen and carbon dioxide tensions (PaO$_2$, P$\bar{v}$O$_2$, PaCO$_2$ and P$\bar{v}$CO$_2$), oxygen saturations (SaO$_2$ and S$\bar{v}$O$_2$), base excess and bicarbonate. Samples were immediately analyzed and the values were corrected to core temperature. Additional arterial and mixed venous blood samples (4 mL) were obtained, placed in ethylenediaminetetraacetic acid (EDTA) tubes and stored at 5 °C for hemoglobin (Hb) measurement (Labquest; Labtest Diagnóstica S.A., MG, Brazil), which was performed within 6 hours. Hematocrit was obtained through centrifugation.

To obtain the oxygen content-based indices, the arterial, venous and capillary oxygen contents (CaO$_2$, C$\bar{v}$O$_2$ and Cc′O$_2$, respectively) were calculated (Araos et al. 2012):

$$CaO_2 = Hb \times 1.31 \times SaO_2 + 0.0031$$
$$\times \ PaO_2 \left(mL \ dL^{-1} \right);$$

$$C\bar{v}O_2 = Hb \times 1.31 \times S\bar{v}O_2$$
$$+ \ 0.0031 \ x \ P\bar{v}O_2 \left(mL \ dL^{-1} \right); \ and$$

$$Cc′O_2 = Hb \times 1.31 \times 1$$
$$+ \ 0.0031 \ x \ P_AO_2 \left(mL \ dL^{-1} \right),$$

where 1.31 is the carrying capacity of Hb in mL g^{-1}; 0.0031 is the solubility of oxygen in plasma;

and P$_A$O$_2$ is the alveolar oxygen tension in mmHg (Araos et al. 2012):

$$P_AO_2 = \left[FIO_2 \times (P_B - P_{H_2O}) \right] - (PaCO_2 \times 0.8)$$

where P$_B$ is the barometric pressure in mmHg; P$_{H_2O}$ is the water vapor pressure in mmHg; and 0.8 is the respiratory coefficient. Both P$_B$ and P$_{H_2O}$ were results obtained from the blood gas machine.

Venous admixture ($\dot{Q}_s/\dot{Q}_t$), oxygen delivery (DO$_2$), oxygen consumption $\dot{V}O_2$ and oxygen extraction ratio (O$_2$ER) were calculated (Araos et al. 2012; Floriano et al. 2016):

$$\dot{Q}_s/\dot{Q}_t = (Cc′O_2 - CaO_2)/(Cc′O_2 - C\bar{v}O_2)$$
$$\times \ 100 \ (\%);$$

$$DO_2 = CaO_2 \times CI \times 10 \left(mL \ minute^{-1} \ m^{-2} \right);$$

$$\dot{V}O_2 = (CaO_2 - C\bar{v}O_2) \times CI$$
$$\times \ 10 \left(mL \ minute^{-1} \ m^{-2} \right); \ and$$

$$O_2ER = (CaO_2 - C\bar{v}O_2)/CaO_2$$

After instrumentation (approximately 40 minutes of anesthesia) cardiopulmonary variables were recorded: the first time point after the preparation period (T$_0$) and then at 30, 60, 120 and 180 minutes (T$_{30}$, T$_{60}$, T$_{120}$ and T$_{180}$).

At the end of the procedure, the animal was lifted from the surgical table by an electrical lift and taken to the recovery room where it was positioned in right lateral recumbency to be observed until full recovery was accomplished. Flunixin meglumine (2.2 mg kg^{-1}; Desflan; Ouro Fino Saúde Animal, SP, Brazil) was administered IV after complete recovery from anesthesia.

Statistical analysis

Data are expressed as means ± SD. The Kolmogorov−Smirnov test was performed to evaluate normality. Data presenting normal distribution (parametric) were analyzed through analysis of variance for repeated measures (RM-ANOVA) via the SASMIXED procedure (Statistical Analysis System Version 9.3; SAS Institute Inc., NC, USA). Multiple comparisons were performed by least squares means (LSMEANS) and Tukey's test adjustment. Data that failed normality test (nonparametric) were analyzed through Friedman's test. Wilcoxon's test was performed to analyze every pair of treatments when statistical significance was found. In all analyses,

significance was considered when $p < 0.05$ (SAS Version 9.3; SAS Institute Inc.).

Results

In phase 1, the mean sevoflurane MAC of the individual MAC determinations for the eight steers was $2.12 \pm 0.31\%$.

In phase 2, there were no significant differences between treatments with respect to body weight, time for instrumentation and anesthetic time. There were no differences in HR over 180 minutes of anesthesia within each treatment or among treatments (Table 1). SAP, MAP and DAP increased over time in RTP5 and DAP increased in RTP0 (Table 1; $p < 0.05$). CI was significantly lower in RTP10 than in RTP0 at all time points ($p < 0.05$). SVRI was increased in RTP5 at T_{60} and T_{120} over T_0 and T_{30}, and was significantly higher in RTP10 compared

Table 1 Mean $\pm$ standard deviation of hemodynamic variables and core (pulmonary artery) temperature of sevoflurane-anesthetized steers breathing spontaneously during dorsal recumbency with $0°$ tilt (RTP0, $n = 8$) or in reverse Trendelenburg position (RTP) at $5°$ (RTP5, $n = 8$) or $10°$ (RTP10, $n = 5$) for 180 minutes (T_0 to T_{180})

Variable	RTP	Time points				
		T_0	T_{30}	T_{60}	T_{120}	T_{180}
HR (beats minute^{-1})	0	79 ± 10	80 ± 14	77 ± 12	75 ± 11	73 ± 11
	5	71 ± 11	72 ± 13	75 ± 16	73 ± 13	72 ± 13
	10	73 ± 5	72 ± 3	71 ± 2	69 ± 3	69 ± 4
SAP (mmHg)	0	126 ± 16	139 ± 28	145 ± 21	144 ± 18	137 ± 14
	5	115 ± 12^a	130 ± 22^{ab}	136 ± 14^{ab}	148 ± 13^b	146 ± 9^b
	10	129 ± 12	131 ± 11	139 ± 18	147 ± 21	147 ± 16
MAP (mmHg)	0	98 ± 18	109 ± 25	114 ± 22	114 ± 19	105 ± 17
	5	87 ± 9^a	101 ± 18^{ab}	109 ± 16^b	117 ± 13^b	113 ± 10^b
	10	102 ± 13	107 ± 14	113 ± 19	121 ± 22	120 ± 18
DAP (mmHg)	0	77 ± 19^a	87 ± 27^{ab}	92 ± 22^b	91 ± 21^b	81 ± 19^{ab}
	5	66 ± 8^a	79 ± 17^{ab}	87 ± 17^b	93 ± 14^b	87 ± 11^{ab}
	10	82 ± 13	86 ± 13	97 ± 21	99 ± 23	96 ± 20
CVP (mmHg)	0	-4 ± 2	-3 ± 3	-3 ± 3	-2 ± 3	-3 ± 3
	5	-2 ± 4	-2 ± 4	-2 ± 4	-2 ± 4	-3 ± 4
	10	-2 ± 2	-2 ± 2	-2 ± 2	-2 ± 2	-1 ± 2
CI (L minute^{-1} m^{-2})	0	5.0 ± 1.0^A	5.1 ± 0.6^A	5.2 ± 0.9^A	5.3 ± 0.9^A	5.3 ± 1.1^A
	5	4.8 ± 0.6^{AB}	4.7 ± 0.6^{AB}	4.6 ± 0.7^{AB}	4.9 ± 0.9^{AB}	5.0 ± 0.9^{AB}
	10	4.2 ± 0.6^B	4.3 ± 0.4^B	4.3 ± 0.2^B	4.1 ± 0.6^B	4.4 ± 0.5^B
SI (mL beat^{-1} kg^{-1})	0	1.2 ± 0.2	1.3 ± 0.2	1.3 ± 0.2	1.4 ± 0.2	1.4 ± 0.3
	5	1.3 ± 0.3	1.3 ± 0.2	1.2 ± 0.2	1.3 ± 0.2	1.3 ± 0.2
	10	1.1 ± 0.2	1.1 ± 0.2	1.2 ± 0.1	1.2 ± 0.2	1.2 ± 0.2
MPAP (mmHg)	0	9 ± 2	9 ± 2	9 ± 3	10 ± 3	10 ± 3
	5	8 ± 4	8 ± 4	10 ± 4	12 ± 4	12 ± 4
	10	8 ± 3	9 ± 3	9 ± 4	10 ± 4	11 ± 4
PAOP (mmHg)	0	1 ± 3	0 ± 3	1 ± 3	1 ± 3	0 ± 4
	5	1 ± 4	1 ± 4	2 ± 4	3 ± 3	2 ± 4
	10	—	—	—	—	—
SVRI (dyne second cm^{-5} m^{-2})	0	1683 ± 496^{AB}	1756 ± 300	1871 ± 508	1805 ± 451^A	1703 ± 445^A
	5	1510 ± 284^{Aa}	1800 ± 407^{ab}	1987 ± 454^b	1998 ± 438^{ABb}	1916 ± 366^{ABab}
	10	2006 ± 357^B	2049 ± 322	2120 ± 287	2406 ± 574^B	2227 ± 427^B
PVRI (dyne second cm^{-5} m^{-2})	0	154 ± 37	137 ± 23	126 ± 34	131 ± 13	128 ± 35
	5	162 ± 31	148 ± 32	169 ± 31	167 ± 35	175 ± 37
	10	—	—	—	—	—
Core temperature (°C)	0	38.4 ± 0.4	38.4 ± 0.4	38.5 ± 0.5	38.6 ± 0.5	38.7 ± 0.6
	5	38.2 ± 0.3	38.2 ± 0.3	38.2 ± 0.4	38.2 ± 0.6	38.3 ± 0.5
	10	38.0 ± 0.4	38.0 ± 0.5	38.1 ± 0.3	38.1 ± 0.3	38.2 ± 0.4

Means followed by different lowercase letters (time points) or uppercase letters (treatments) are significantly different ($p < 0.05$).

HR, heart rate; SAP, systolic arterial pressure; MAP, mean arterial pressure; DAP, diastolic arterial pressure; CVP, central venous pressure; CI, cardiac index; SI, stroke index; MPAP, mean pulmonary arterial pressure; PAOP, pulmonary artery occlusion pressure; SVRI, systemic vascular resistance index; PVRI, pulmonary vascular resistance index.

with RTP0 at T_{120} and T_{180} (Table 1; $p < 0.05$). CVP and MPAP were unchanged during anesthesia and not different among treatments (Table 1).

Arterial pH and PaO_2 were unchanged during anesthesia and were not different among treatments (Table 2). Hypercarbia was present in animals in all treatments and persisted through the 180 minutes of monitoring (Table 2). $P\bar{v}O_2$ was higher in RTP10 than

RTP5 at T_{30} and T_{60} but was not different from RTP0 (Table 2; $p < 0.05$). $S\bar{v}O_2$ was higher in RTP10 than in RTP5 at all time points (Table 2; $p < 0.05$). The hematocrit was higher in RTP10 at T_0 and T_{60} than in RTP0. No significant differences were found in FIO_2, f_R, $\dot{V}_E$ or V_T over time or among treatments (Table 3).

The $\dot{Q}_s/\dot{Q}_t$ was lower at T_0 in RTP0 and RTP5 and at T_{60} in RTP5 compared with RTP10 (Table 4; $p < 0.05$).

Table 2 Mean $\pm$ standard deviation of blood gas variables of sevoflurane-anesthetized steers breathing spontaneously during dorsal recumbency with 0° table tilt (RTP0, $n = 8$) or in reverse Trendelenburg position (RTP) at 5° (RTP5, $n = 8$) or 10° (RTP10, $n = 5$) for 180 minutes (T_0 to T_{180})

Variable	RTP	Time points				
		T_0	T_{30}	T_{60}	T_{120}	T_{180}
Arterial pH	0	7.27 ± 0.02	7.27 ± 0.03	7.27 ± 0.03	7.28 ± 0.03	7.27 ± 0.04
	5	7.27 ± 0.02	7.27 ± 0.02	7.27 ± 0.02	7.27 ± 0.03	7.26 ± 0.03
	10	7.28 ± 0.02	7.28 ± 0.04	7.28 ± 0.01	7.29 ± 0.03	7.29 ± 0.03
PaO_2 (mmHg)	0	277 ± 52	276 ± 41	273 ± 39	274 ± 46	293 ± 61
	5	248 ± 57	243 ± 68	260 ± 63	247 ± 59	262 ± 63
	10	252 ± 51	280 ± 55	290 ± 42	294 ± 52	302 ± 52
PaO_2 (kPa)	0	36.9 ± 6.9	36.7 ± 5.4	36.4 ± 5.2	36.4 ± 6.1	39.0 ± 8.1
	5	33.0 ± 7.6	32.3 ± 9.1	34.7 ± 8.4	32.9 ± 7.9	34.9 ± 8.4
	10	33.6 ± 6.8	37.3 ± 7.3	38.7 ± 5.6	39.2 ± 7.0	40.3 ± 6.9
$PaCO_2$ (mmHg)	0	72 ± 2	73 ± 5	74 ± 5	73 ± 4	76 ± 6
	5	68 ± 5	71 ± 4	72 ± 4	73 ± 4	74 ± 4
	10	72 ± 5	72 ± 8	72 ± 5	72 ± 7	73 ± 6
$PaCO_2$ (kPa)	0	9.6 ± 0.3	9.7 ± 0.6	9.9 ± 0.6	9.7 ± 0.5	10.1 ± 0.8
	5	9.1 ± 0.6	9.5 ± 0.6	9.5 ± 0.5	9.8 ± 0.6	9.9 ± 0.6
	10	9.6 ± 0.7	9.6 ± 1.1	9.6 ± 0.7	9.6 ± 1.0	9.7 ± 0.7
SaO_2 (%)	0	99.8 ± 0.1	99.8 ± 0.1	99.8 ± 0.1	99.8 ± 0.2	99.8 ± 0.1
	5	99.6 ± 0.6	99.6 ± 0.4	99.7 ± 0.2	99.7 ± 0.2	99.7 ± 0.2
	10	99.7 ± 0.2	99.8 ± 0.1	99.8 ± 0.1	99.8 ± 0.1	99.8 ± 0.1
$P\bar{v}O_2$ (mmHg)	0	66.8 ± 5.7	70.0 ± 7.5^{AB}	68.0 ± 5.0^{B}	67.0 ± 4.5	66.1 ± 6.2
	5	63.3 ± 4.9	62.7 ± 6.3^{A}	62.7 ± 3.5^{A}	62.4 ± 3.5	64.8 ± 5.9
	10	72.0 ± 4.8	73.3 ± 5.7^{B}	70.4 ± 2.4^{B}	73.0 ± 7.1	70.9 ± 7.1
$P\bar{v}CO_2$ (mmHg)	0	79.4 ± 4.1^{a}	78.9 ± 4.2^{ab}	81.8 ± 3.6^{ab}	81.7 ± 3.4^{ab}	84.7 ± 4.7^{b}
	5	75.5 ± 3.8^{a}	79.0 ± 3.9^{ab}	79.6 ± 3.8^{ab}	81.7 ± 3.5^{b}	82.1 ± 3.9^{b}
	10	79.4 ± 5.7	78.9 ± 6.0	81.1 ± 6.5	80.8 ± 5.7	81.9 ± 6.8
$S\bar{v}O_2$ (%)	0	86.1 ± 3.5^{AB}	87.7 ± 4.1^{AB}	86.8 ± 3.6^{AB}	86.4 ± 3.5^{AB}	85.9 ± 3.8^{AB}
	5	83.9 ± 3.8^{A}	83.9 ± 3.8^{A}	83.7 ± 3.0^{A}	83.7 ± 3.2^{A}	84.3 ± 4.2^{A}
	10	88.9 ± 2.2^{B}	88.8 ± 2.6^{B}	89.8 ± 2.2^{B}	89.4 ± 2.5^{B}	89.3 ± 2.9^{B}
Arterial bicarbonate (mmol L^{-1})	0	31.5 ± 1.3	31.9 ± 1.2	32.4 ± 1.1	32.5 ± 1.5	32.9 ± 1.5
	5	30.7 ± 2.1	32.0 ± 2.0	31.9 ± 1.8	32.7 ± 2.2	32.5 ± 2.5
	10	32.4 ± 2.3	32.6 ± 2.1	33.2 ± 2.2	33.5 ± 2.9	33.7 ± 2.5
Arterial base excess (mmol L^{-1})	0	3.6 ± 1.2	4.2 ± 1.3	4.6 ± 1.3	4.9 ± 1.5	4.9 ± 1.8
	5	2.8 ± 2.1	3.6 ± 2.0	3.3 ± 1.9	4.1 ± 2.3	4.0 ± 2.6
	10	4.2 ± 2.5	4.7 ± 1.9	5.0 ± 2.2	5.7 ± 2.7	5.8 ± 2.5
Arterial hemoglobin (g dL^{-1})	0	9.8 ± 0.4	9.7 ± 0.4	9.5 ± 0.5	9.6 ± 0.5	9.8 ± 0.5
	5	9.8 ± 0.4	9.7 ± 0.4	9.7 ± 0.4	9.7 ± 0.5	9.9 ± 0.6
	10	9.7 ± 0.9	9.8 ± 0.9	9.7 ± 0.9	10.1 ± 0.9	10.2 ± 1.0
Arterial hematocrit (%)	0	29 ± 1^{A}	29 ± 1	29 ± 1^{A}	29 ± 1	29 ± 1
	5	31 ± 3^{AB}	31 ± 3	31 ± 3^{AB}	31 ± 3	32 ± 3
	10	33 ± 4^{B}	32 ± 4	33 ± 4^{B}	33 ± 4	34 ± 5

Means followed by different lowercase letters (time points) or uppercase letters (treatments) are significantly different ($p < 0.05$).
PaO_2, arterial oxygen tension; $PaCO_2$, arterial carbon dioxide tension; SaO_2, arterial oxygen saturation; $P\bar{v}O_2$, mixed venous oxygen tension; $P\bar{v}CO_2$, mixed venous carbon dioxide tension; $S\bar{v}CO_2$, mixed venous oxygen saturation.

Table 3 Mean $\pm$ standard deviation of respiratory variables of sevoflurane-anesthetized steers breathing spontaneously during dorsal recumbency (RTP0; $n = 8$) or in reverse Trendelenburg position at 5° (RTP5; $n = 8$) or 10° (RTP10; $n = 5$) for 180 minutes (T_0 to T_{180})

Variable	RTP	Time points				
		T_0	T_{30}	T_{60}	T_{120}	T_{180}
f_R (breaths minute^{-1})	0	32 $\pm$ 3	33 $\pm$ 4	33 $\pm$ 4	34 $\pm$ 3	34 $\pm$ 4
	5	30 $\pm$ 3	32 $\pm$ 5	32 $\pm$ 5	32 $\pm$ 5	33 $\pm$ 4
	10	30 $\pm$ 4	30 $\pm$ 4	31 $\pm$ 4	32 $\pm$ 5	32 $\pm$ 5
$\dot{V}_E$ (L minute^{-1})	0	21 $\pm$ 4	22 $\pm$ 3	23 $\pm$ 4	22 $\pm$ 4	23 $\pm$ 5
	5	19 $\pm$ 5	20 $\pm$ 5	22 $\pm$ 5	22 $\pm$ 6	22 $\pm$ 7
	10	20 $\pm$ 4	20 $\pm$ 4	23 $\pm$ 3	23 $\pm$ 4	23 $\pm$ 3
V_T (mL kg^{-1})	0	4.7 $\pm$ 0.7	4.7 $\pm$ 0.7	4.8 $\pm$ 0.8	4.7 $\pm$ 0.9	4.8 $\pm$ 0.9
	5	4.2 $\pm$ 1.1	4.2 $\pm$ 0.9	4.8 $\pm$ 1.1	4.6 $\pm$ 1.0	4.7 $\pm$ 1.0
	10	4.6 $\pm$ 0.9	4.8 $\pm$ 0.6	4.9 $\pm$ 0.7	5.1 $\pm$ 0.4	5.1 $\pm$ 0.3
PIF (L minute^{-1})	0	82 $\pm$ 19	86 $\pm$ 17	89 $\pm$ 20	91 $\pm$ 19	94 $\pm$ 20
	5	81 $\pm$ 13	84 $\pm$ 17	90 $\pm$ 19	93 $\pm$ 19	95 $\pm$ 20
	10	81 $\pm$ 12	92 $\pm$ 14	97 $\pm$ 14	92 $\pm$ 13	93 $\pm$ 12
FIO$_2$ (%)	0	91 $\pm$ 3	90 $\pm$ 3	90 $\pm$ 3	90 $\pm$ 2	90 $\pm$ 2
	5	89 $\pm$ 3	89 $\pm$ 4	89 $\pm$ 5	88 $\pm$ 3	88 $\pm$ 2
	10	91 $\pm$ 2	92 $\pm$ 1	91 $\pm$ 2	90 $\pm$ 2	90 $\pm$ 1
$P_E'CO_2$ (mmHg)	0	47 $\pm$ 6	46 $\pm$ 6	47 $\pm$ 6	46 $\pm$ 3	46 $\pm$ 4
	5	46 $\pm$ 3	45 $\pm$ 5	45 $\pm$ 5	46 $\pm$ 3	46 $\pm$ 3
	10	49 $\pm$ 8	50 $\pm$ 7	51 $\pm$ 4	49 $\pm$ 3	51 $\pm$ 2
$P_E'CO_2$ (kPa)	0	6.3 $\pm$ 0.8	6.1 $\pm$ 0.8	6.3 $\pm$ 0.8	6.1 $\pm$ 0.4	6.1 $\pm$ 0.5
	5	6.1 $\pm$ 0.4	6.0 $\pm$ 0.7	6.0 $\pm$ 0.7	6.1 $\pm$ 0.4	6.1 $\pm$ 0.4
	10	6.5 $\pm$ 1.1	6.7 $\pm$ 0.9	6.8 $\pm$ 0.5	6.5 $\pm$ 0.4	6.8 $\pm$ 0.3

No significant differences ($p > 0.05$).

f_R, respiratory rate; $= \dot{V}_E$ minute volume; V_T, tidal volume; PIF, peak inspiratory flow; FIO$_2$, inspired oxygen fraction; $P_E'CO_2$, end-tidal carbon dioxide tension.

Over time, $\dot{Q}_s/\dot{Q}_t$ was higher at T_{60} compared with T_0 in RTP0 and lower at T_{120} and T_{180} compared with T_0 in RTP10 (Table 4; $p < 0.05$). No significant differences were found in DO$_2$ over time or among treatments (Table 4). The $\dot{V}O_2$ was lower at T_0 in RTP10 compared with RTP0 and lower at all times except T_{30} in RTP10 compared with RTP5 (Table 4; $p < 0.05$). The O$_2$ER was lower at T_0 in RTP10 compared with RTP0 and lower at T0, T_{60} and T_{120} in RTP10 compared with RTP5.

All steers recovered from all anesthesia episodes without complications.

Discussion

The MAC for sevoflurane was previously determined for each calf in phase 1 of this study to minimize the influence of anesthetic depth on cardiopulmonary variables during phase 2. This was considered necessary owing to the absence of reported MAC value for sevoflurane in cattle and because inhalation anesthesia causes dose-dependent cardiopulmonary depression (Arai et al. 2006; Steffey & Mama 2007). The MAC values determined for steers in this study, mean 2.12%, were close to the reported values in dogs (Alvillar et al. 2012), goats (Hikasa et al. 1998), horses (Gozalo-Marcilla et al. 2013) and sheep (Okutomi et al. 2009).

The decision to include the RTP10 treatment after completion of RTP0 and RTP5 procedures aimed at improving the information provided in this study by using the higher degree of tilting. However, the late inclusion of RTP10 together with the lowest number of animals in this treatment may have contributed to a reduction or increase in the differences between treatments.

It is possible that physical restraint, positioning of the animal on the surgical table and mask induction to anesthesia may have stimulated the animals, and thereby influenced subsequent cardiopulmonary variables. However, these animals were accustomed to handling and all the study procedures were completed without difficulties.

The angles (5 and 10°) for tilting the table in this study seem small compared with the 30° tilt used in humans. However, there was a concern that greater adverse cardiovascular changes would occur at a higher degree of RTP and that associated anatomical repositioning may interfere with some surgical procedures (Perilli et al. 2003).

Table 4 Mean ± standard deviation of oxygen content-based indices of sevoflurane-anesthetized steers breathing spontaneously during dorsal recumbency (RTP0; $n = 8$) or in reverse Trendelenburg position at 5° (RTP5; $n = 8$) or 10° (RTP10; $n = 5$) for 180 minutes (T_0 to T_{180})

Variable	RTP	Time points				
		T_0	T_{30}	T_{60}	T_{120}	T_{180}
$\dot{Q}_s/\dot{Q}_t$ (%)	0	27.3 ± 5.2^{Aa}	31.8 ± 13.8^{ab}	34.9 ± 13.3^{Ab}	30.1 ± 6.2^{ab}	26.6 ± 5.1^{ab}
	5	27.5 ± 5.9^{A}	26.5 ± 7.4	25.7 ± 5.9^{B}	26.7 ± 5.4	24.1 ± 6.6
	10	39.4 ± 4.5^{Ba}	33.4 ± 5.5^{ab}	33.2 ± 8.2^{ABab}	31.3 ± 8.2^{b}	28.9 ± 4.4^{b}
DO$_2$ (mL minute^{-1} m^{-2})	0	687 ± 133	691 ± 81	686 ± 118	713 ± 116	719 ± 130
	5	688 ± 83	660 ± 77	650 ± 86	701 ± 105	719 ± 97
	10	566 ± 102	583 ± 91	590 ± 53	584 ± 85	634 ± 110
$\dot{V}O_2$ (mL minute^{-1} m^{-2})	0	121 ± 37^{A}	107 ± 40	97 ± 48^{AB}	112 ± 40^{AB}	118 ± 24^{A}
	5	124 ± 29^{A}	105 ± 44	123 ± 32^{A}	128 ± 29^{A}	145 ± 41^{A}
	10	63 ± 10^{B}	76 ± 9	70 ± 9^{B}	76 ± 25^{B}	84 ± 16^{B}
O$_2$ER	0	0.17 ± 0.03^{A}	0.15 ± 0.06	0.14 ± 0.06^{AB}	0.15 ± 0.04	0.16 ± 0.03^{AB}
	5	0.18 ± 0.03^{A}	0.16 ± 0.06	0.19 ± 0.04^{A}	0.18 ± 0.03	0.20 ± 0.04^{A}
	10	0.11 ± 0.02^{B}	0.13 ± 0.02	0.12 ± 0.01^{B}	0.13 ± 0.03	0.13 ± 0.02^{B}

Means followed by different lowercase letters (time points) or uppercase letters (treatments) are significantly different ($p < 0.05$).
$\dot{Q}_s/\dot{Q}_t$, venous admixture; DO$_2$, oxygen delivery; $\dot{V}O_2$, oxygen consumption; O$_2$ER, oxygen extraction ratio.

The study results identified significantly decreased CI in RTP10 when compared with animals anesthetized without tilting, and increased SVRI after 2 and 3 hours of anesthesia. The RTP is purported to result in a change in blood volume distribution to the periphery, thus decreasing CI and SI. Matzen et al. (1991) reported an initial 24% reduction in central blood volume followed by an 18% decrease in plasma and 68% increase in blood volume to the pelvic limbs in awake humans in RTP. Others suggested that this blood shift to the periphery may reduce venous return, preload and CO (Hazebroek & Bonjer 2006). Additionally, increased SVR may result in increased MAP, thus augmenting the afterload.

There are few studies of cardiovascular changes caused by RTP reported in the veterinary literature. No significant changes in CO were recorded in swine (weighing approximately 40 kg) anesthetized with tiletamine–zolazepam and isoflurane positioned in RTP when compared with dorsal and lateral recumbency (Shih et al. 2013). Similar results were observed when comparing 10° RTP with dorsal recumbency in swine during constant rate infusions of thiopental, fentanyl and pancuronium (Klopfenstein et al. 1998). However, when tilted to 20°, MAP, MPAP, PAOP, CVP, CO and hepatic blood flow significantly decreased (Klopfenstein et al. 1998).

RTP improves respiratory function in humans. This effect is ascribed to a decrease in the pressure of abdominal viscera on the diaphragm, thus improving diaphragm mobility, C_{dyn}, functional residual capacity and decreasing PIP (Hazebroek & Bonjer 2006). Some studies in mechanically ventilated obese humans subjected to 30° RTP and inhalation anesthesia for bariatric surgery corroborate those facts. Significant improvements in respiratory variables and oxygenation have been found when compared with dorsal recumbency (Perilli et al. 2000, 2003). However, in the present study, RTP at 5 and 10° associated with spontaneous breathing did not improve ventilation or blood gas variables compared with dorsal recumbency.

Respiratory depression was present in all treatments, with decreased pH and increased $PaCO_2$ at all time points. This is consistent with similar results in other studies of spontaneously breathing bovine subjects under inhalation anesthesia regardless of recumbency (Hikasa et al. 1994; Arai et al. 2006; Offinger et al. 2012). By contrast, studies of cattle physically restrained in dorsal recumbency revealed no significant increases in $PaCO_2$ (Klein & Fisher 1988; Wagner et al. 1990; Meyer et al. 2010). This suggests that the increases in $PaCO_2$ in the animals in the present study are more likely to be the result of respiratory depression induced by sevoflurane rather than the body position. As expected, mechanical ventilation is effective treatment for hypercarbia (Greene et al. 2002; Vesal et al. 2011; Araújo et al. 2014) and it has been recommended that mechanical ventilation be implemented in cattle after 45 minutes of spontaneous breathing

during inhalation anesthesia (McDonell & Kerr 2007). Of clinical relevance, the $PaCO_2$ values were substantially higher than the corresponding $PE'CO_2$ values, emphasizing the limited value of $PE'CO_2$ measurements for assessing adequacy of ventilation in spontaneously breathing cattle without a measurement of $PaCO_2$ for comparison.

In this study, $\dot{Q}_s/\dot{Q}_t$ was significantly increased at T_0 in RTP10 compared with the other treatments, but had decreased to a value similar to RTP0 by 30 minutes and within the treatment was significantly smaller than T_0 at 120 minutes. A possible explanation for the initial higher shunt in RTP10 could be the abrupt impact of a 10° RTP on circulation immediately after the animals were positioned on the tilted table. This hypothesis is supported by the recommendation that gradual tilting is advisable when RTP is employed.

There was no difference between treatments in DO_2, even though the values were notably lower in RTP treatments, especially RTP10, compared with RTP0. According to Gutierrez & Theodorou (2012), DO_2 is quantitatively related to a number of factors, such as Hb, oxygen content, CO, preload, heart contractility, afterload and HR and thus one can suggest that the lower DO_2 in RTP10 could be related to the lower CI in that treatment.

No reference values of DO_2 have been found for the bovine species under inhalation anesthesia. However, one study reported DO_2 of 0.658 ± 0.129 L minute^{-1} (411.3 ± 80.6 mL minute^{-1} m^2) in standing calves weighing approximately 65.2 kg (Picavet et al. 2004). Higher values of 1266 ± 103 mL minute^{-1} (844.0 ± 68.7 mL minute^{-1} m^2) were measured in standing calves weighing 57.7 kg (Meyer et al. 2010). In calves physically restrained in dorsal recumbency, reported values for DO_2 were $1072-1125$ mL minute^{-1} ($718-753$ mL minute^{-1} m^2; Meyer et al. 2010). For comparison, DO_2 in dorsally recumbent isoflurane-anesthetized horses breathing spontaneously was $2.9-3.0$ L minute^{-1} ($465-481$ mL minute^{-1} m^2; Edner et al. 2005). The results of the present study are close to the findings of Meyer et al. (2010) using dorsally recumbent calves, and greater than the findings of Edner et al. (2005) using adult horses under inhalation anesthesia. This suggests that these results are within the expected range, since the differences in animal weights between the studies and the use of anesthesia could justify the differences.

In this study both $\dot{V}O_2$ and O_2ER were significantly decreased in RTP10 compared with RTP0 and RTP5. These findings suggest that tissue perfusion was improved and cellular metabolism reduced in RTP10 compared with RTP0 and RTP5. One possible explanation for the lower $\dot{V}O_2$ and O_2ER in RTP10 is that respiratory effort was reduced during RTP10 compared with the other treatments. The cost of breathing to metabolism, although usually <5% of the total $\dot{V}O_2$, can increase up to 30% in humans with some degree of respiratory effort (Gutierrez & Theodorou 2012).

The $S\bar{v}O_2$ also significantly increased in RTP10 compared with RTP5. This variable reflects the relationship between DO_2 and $\dot{V}O_2$, indicating the amount of oxygen that was not extracted and consumed by tissues and returned to the lungs, and can be used as an index of global oxygenation (Figueiredo et al. 2008). Values >70% correlate with an adequate DO_2 (Leach & Treacher 2002).

No reference values for $\dot{V}O_2$ were found for the bovine species during inhalation anesthesia. However, a $\dot{V}O_2$ of 476 ± 66 mL minute^{-1} (319 ± 44 mL minute^{-1} m^2) was reported for standing calves, which decreased to $361-438$ mL minute^{-1} ($242-293$ mL minute^{-1} m^2) after the animals were restrained in dorsal recumbency (Meyer et al. 2010). The lower values for $\dot{V}O_2$ measured in the anesthetized steers in this study probably resulted from general anesthesia which decreases the metabolic rate and thus the $\dot{V}O_2$ (Gutierrez & Theodorou 2012). In addition, the $\dot{V}O_2$ and O_2ER measured in the present study were similar to those previously reported in dogs during inhalation anesthesia (Haskins 2007).

One limitation of the study design was the weight of the subjects (145 ± 26 kg). Ventilatory changes during anesthesia may be greater in heavier animals and the impact of RTP may have been better illustrated in the measured variables of larger cattle. Another limitation is that the RPT10 treatment was studied after the RPT0 and RPT5 experiments were completed. The lack of randomization of RPT10 may have influenced the results.

In conclusion, the reverse Trendelenburg position at 5° and 10°, compared with dorsal recumbency and no tilt, did not improve pulmonary variables in spontaneously breathing steers anesthetized with sevoflurane. However, tilting the surgical table at 10° worsened cardiovascular variables, increasing SVRI and decreasing CI.

Acknowledgements

Authors' contributions

MAA: conception, study design, data collection and interpretation, preparation of manuscript. MD: study design, technical procedures, data collection and interpretation. JTW: study design, technical procedures, data collection and management. BPF: study design, data collection and interpretation, statistical analysis. CES: study design, technical procedures, data collection. VNLSO: study design, data interpretation, manuscript preparation. PSPS: conception, study design, data interpretation, preparation of manuscript.

Conflict of interest

The authors declare no conflict of interest.

References

Alvillar BM, Boscan P, Mama KR et al. (2012) Effect of epidural and intravenous use of the neurokinin-1 (NK-1) receptor antagonist maropitant on the sevoflurane minimum alveolar concentration (MAC) in dogs. Vet Anaesth Analg 39, 201−205.

Arai S, Yoshioka K, Suzuki C et al. (2006) Development of a neurosurgical operating table for adult cattle and changes in intracranial pressure and blood pressure in adult cattle undergoing long-time isoflurane anesthesia. J Vet Med Sci 68, 337−343.

Araos JD, Larenza MP, Boston RC et al. (2012) Use of the oxygen content−based index, Fshunt, as an indicator of pulmonary venous admixture at various inspired oxygen fractions in anesthetized sheep. Am J Vet Res 73, 2013−2020.

Araújo MA, Dias BP, Bovino F et al. (2014) Cardiovascular effects of a continuous rate infusion of lidocaine in calves anesthetized with xylazine, midazolam, ketamine and isoflurane. Vet Anaesth Analg 41, 145−152.

Blaze CA, LeBlanc PH, Robinson NE (1988) Effects of withholding feed on ventilation and the incidence of regurgitation during halothane anesthesia in adult cattle. Am J Vet Res 49, 2126−2129.

Edner A, Nyman G, Essén-Gustavsson B (2005) The effects of spontaneous and mechanical ventilation on central cardiovascular function and peripheral perfusion during isoflurane anaesthesia in horses. Vet Anaesth Analg 32, 136−146.

Ewing KK, Mohammed HO, Scarlett JM, Short CE (1993) Reduction of isoflurane anesthetic requirement by medetomidine and its restoration by atipamezole in dogs. Am J Vet Res 54, 294−299.

Figueiredo LFP, Silva E, Corrêa TH (2008) Macro and micro circulatory hemodynamics evaluation in sepsis. Rev Med (São Paulo) 87, 84−91 [In Portuguese].

Floriano BP, Wagatsuma JT, Ferreira JZ et al. (2016) Effects of indicators of tissue perfusion in dogs

anesthetized with isoflurane at two multiples of the minimum alveolar concentration. Am J Vet Res 77, 24−31.

Gozalo-Marcilla M, Hopster K, Gasthuys F et al. (2013) Effects of a constant-rate infusion of dexmedetomidine on the minimal alveolar concentration of sevoflurane in ponies. Equine Vet J 45, 204−208.

Greene SA, Keegan RD, Valdez RA, Knowles DK (2002) Cardiovascular effects of sevoflurane in Holstein calves. Vet Anaesth Analg 29, 59−63.

Gutierrez JA, Theodorou AA (2012) Oxygen delivery and oxygen consumption in pediatric critical care. In: Pediatric Critical Care Study Guide. Text and Review. Lucking SE, Maffei FA, Tamburro RF, Thomas NJ (eds). Springer, UK. pp. 19−38.

Haskins SC (2007) Monitoring anesthetized patients. In: Lumb & Jones' Veterinary Anesthesia (4th edn). Tranquilli WJ, Thurmon JC, Grimm KA (eds). Blackwell Publishing, UK. pp. 533−558.

Hazebroek MD, Bonjer HJ (2006) Effect of patient position on cardiovascular and pulmonary function. In: The SAGES (Society of American Gastrointestinal Endoscopic Surgery) Manual of Perioperative Care in Minimally Invasive Surgery. Whelan RL, Fleshman JW, Fowler DL (eds). Springer, USA. pp. 410−417.

Hikasa Y, Takase K, Kondou K, Ogasawara S (1994) Sevoflurane anesthesia following administration of atropine−guaifenesin−thiopental in spontaneous-breathing adult cattle. J Vet Med Sci 56, 613−616.

Hikasa Y, Okuyama K, Kakuta T et al. (1998) Anesthetic potency and cardiopulmonary effects of sevoflurane in goats: comparison with isoflurane and halothane. Can J Vet Res 62, 299−306.

Klein L, Fisher N (1988) Cardiopulmonary effects of restraint in dorsal recumbency on awake cattle. Am J Vet Res 49, 1605−1608.

Klopfenstein CE, Morel DR, Clergue F, Pastor CM (1998) Effects of abdominal CO_2 insufflation and changes of position on hepatic blood flow in anesthetized pigs. Am J Physiol 275, H900−H905.

Leach RM, Treacher DF (2002) The pulmonary physician in critical care 2: oxygen delivery and consumption in the critically ill. Thorax 57, 170−177.

Matzen S, Perko G, Groth S et al. (1991) Blood volume distribution during head-up tilt induced central hypovolaemia in man. Clin Physiol 11, 411−422.

McDonell WN, Kerr CL (2007) Respiratory system. In: Lumb & Jones' Veterinary Anesthesia (4th edn). Tranquilli WJ, Thurmon JC, Grimm KA (eds). Blackwell Publishing, UK. pp. 117−151.

Meyer H, Kästner SBR, Beyerbach M, Rehage J (2010) Cardiopulmonary effects of dorsal recumbency and high-volume caudal epidural anaesthesia with lidocaine or xylazine in calves. Vet J 186, 316−322.

Offinger J, Meyer H, Fischer J et al. (2012) Comparison of isoflurane inhalation anaesthesia, injection anaesthesia

and high volume caudal epidural anaesthesia for umbilical surgery in calves; metabolic, endocrine and cardiopulmonary effects. Vet Anaesth Analg 39, 123−136.

Okutomi T, Whittington RA, Stein DJ, Morishima HO (2009) Comparison of the effects of sevoflurane and isoflurane anesthesia on the maternal-fetal unit in sheep. J Anesth 23, 392−398.

Perilli V, Sollazzi L, Bozza P et al. (2000) The effects of the reverse Trendelenburg position on respiratory mechanics and blood gases in morbidly obese patients during bariatric surgery. Anesth Analg 91, 1520−1525.

Perilli V, Sollazzi L, Modesti C et al. (2003) Comparison of positive end-expiratory pressure with reverse Trendelenburg position in morbidly obese patients undergoing bariatric surgery: effects on hemodynamics and pulmonary gas exchange. Obes Surg 13, 605−609.

Picavet MT, Gasthuys FM, Laevens HH, Watts SA (2004) Cardiopulmonary effects of combined xylazine−guaifenesin−ketamine infusion and extradural (inter-coccygeal lidocaine) anesthesia in calves. Vet Anaesth Analg 31, 11−19.

Quasha AL, Eger EI 2nd, Tinker JH (1980) Determination and applications of MAC. Anesthesiology 53, 315−334.

Shih PC, Hung YC, Chen YL et al. (2013) Agreement of cardiac output measurement between pulse contour analysis and thermodilution in various body positions: a porcine study. J Surg Res 181, 315−322.

Steffey EP, Mama KR (2007) Inhalation anesthetics. In: Lumb & Jones' Veterinary Anesthesia (4th edn). Tranquilli WJ, Thurmon JC, Grimm KA (eds). Blackwell Publishing, UK. pp. 355−393.

Valverde A, Morey TE, Hernández J, Davies W (2003) Validation of several types of noxious stimuli for use in determining the minimum alveolar concentration for inhalation anesthetics in dogs and rabbits. Am J Vet Res 64, 957−962.

Vesal N, Spadavecchia C, Steiner A et al. (2011) Evaluation of the isoflurane-sparing effects of lidocaine infusion during umbilical surgery in calves. Vet Anaesth Analg 38, 451−460.

Wagner AE, Muir WW 3rd, Grospitch BJ (1990) Cardiopulmonary effects of position in conscious cattle. Am J Vet Res 51, 7−10.