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Originally published at:
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Abstract

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A study of cardiovascular function under controlled and spontaneous ventilation in isoflurane–medetomidine anaesthetized horses

Karin S Kalchofner DVM, Diplomate ECVAA, Stephanie Picek Med Vet, Simone K Ringer DVM, Michelle Jackson DVM, Michael Hässig DVM, PhD & Regula Bettchart-Wolfensberger DVM, PhD, PD, Diplomate ECVAA
Vetsuisse Faculty, Equine Hospital, University of Zurich, Zurich, Switzerland

Correspondence: Karin S Kalchofner, Vetsuisse Faculty, University of Zurich, Winterthurerstrasse 260, CH-8057 Zürich, Switzerland.
E-mail: kkalchofner@vetclinics.uzh.ch

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Results There were no differences between groups concerning age, weight, body position during anaesthesia and anaesthetic duration. Respiratory rate was significantly higher in group IPPV. Significantly more horses in group IPPV received supplemental ketamine. There were no other significant differences between groups. All horses recovered from anaesthesia without complications.

Conclusions There was no difference in cardiovascular function in horses undergoing elective surgery during isoflurane–medetomidine anaesthesia with SV in comparison with IPPV, provided the horses are maintained slightly hypercapnic.

Clinical relevance In horses with health status ASA I and II, cardiovascular function under general anaesthesia is equal with or without IPPV if the PaCO₂ is maintained at 50–60 mmHg.

Keywords anaesthesia, cardiovascular, horse, hypercapnia, ventilation.

Introduction

Respiratory depression is common during anaesthesia in clinically healthy horses. It can result in
arterial hypercapnia, hypoxaemia and acid-base abnormalities. These changes have been attributed to hypoventilation, ventilation perfusion inequality and right-to-left vascular shunt (Gillespie et al. 1969).

Intermittent positive-pressure ventilation (IPPV) is recognized as a means of improving alveolar ventilation. However, IPPV may cause detrimental cardiovascular effects (Cournand et al. 1948; Weaver & Walley 1975; Edner et al. 2005). Under general anaesthesia, mechanically ventilated normocapnic horses showed a lower cardiac output than spontaneously breathing hypercapnic horses (Hodgson et al. 1986). Suggested mechanisms include: increased intrathoracic pressure, leading to a reduction in venous return to the heart, decreased arterial carbon dioxide partial pressure (PaCO2) during IPPV, leading to a reduction in sympathetic drive or a combination of both (Steffey & Howland 1978; Hodgson et al. 1986). Carbon dioxide (CO2) induced direct and indirect circulatory effects in humans and animals. Acting directly, CO2 dilates peripheral arterioles and depresses myocardial contractility in humans (Cullen & Eger 1974). It also directly stimulates the central nervous system at several levels. At the vasomotor level, the stimulation is indirect by initiating afferent impulses from the peripheral chemoreceptors. Elevation of PaCO2 evokes potent sympathoadrenal responses that result in increased myocardial contractility and systemic arterial blood pressure (Morgan et al. 1966; Pryys-Roberts et al. 1968; Cullen & Eger 1974). Previous studies in anaesthetized horses have indicated that cardiovascular function during IPPV and normocapnia was more depressed than in spontaneously breathing hypercapnic horses (Steffey & Howland 1978, 1980; Steffey 1981). One study with halothane anaesthetized horses provided evidence that hypercapnia produces positive inotropic and haemodynamic effects and that these effects were associated with an increase in circulating catecholamines (Wagner et al. 1990). The catecholamine response was maximal at a PaCO2 in the range of 60 to 80 mmHg. In contrast with this, another study showed that hypercapnia in isoflurane-anaesthetized horses elicited a biphasic cardiopulmonary response. Mild hypercapnia (PaCO2, 59 ± 3.5 mmHg, 7.9 ± 0.47 kPa) decreased cardiac output and oxygen delivery despite an increase in mean arterial blood pressure, while moderate (PaCO2, 82 ± 4.9 mmHg, 10.9 ± 0.65 kPa) and severe (PaCO2, 110 ± 12 mmHg, 14.7 ± 1.6 kPa) hypercapnia produced an augmentation of the cardiopulmonary performance and oxygen delivery (Khanna et al. 1995). Arrhythmias were not observed at any level of hypercapnia. The authors could not pinpoint the reasons for the unexpected decrease in heart rate (HR) and cardiac index (CI) with mild hypercapnia. It is not clear if there is a difference in the degree of haemodynamic stimulation produced by hypercapnia during halothane and isoflurane anaesthesia. Wagner et al. (1990) observed a much greater effect of hypercapnia on mean arterial blood pressure (MAP), CI and stroke index in horses under halothane anaesthesia than did Khanna et al. (1995) during isoflurane anaesthesia at a similar level of hypercapnia. Isoflurane depressed the myocardium less than halothane in horses (Steffey & Howland 1980). Thus the apparently greater degree of hypercapnia-induced haemodynamic stimulation during halothane may simply be a reflection of the starting point. Differences in experimental design could also be responsible for the different results, e.g. horses in the study of Khanna et al. (1995) were ventilated just after endotracheal intubation throughout anaesthesia, whereas animals in the study of Wagner et al. (1990) were spontaneously breathing in the beginning and IPPV was induced later during anaesthesia.

Common practice in equine anaesthesia is to use inhalational anaesthesia for major procedures. To optimize analgesia and reduce the amount of inhalational agent necessary to maintain anaesthesia and thus improve cardiopulmonary function, various balanced anaesthetic regimes have been tested. In a study with 300 equids, isoflurane was combined with a constant rate infusion (CRI) of medetomidine (Kalchofner et al. 2006). Only three out of the 300 horses needed mechanical ventilation as no spontaneous respiration was present. As minimal respiratory depression was an important feature in this study, this was one reason to choose this protocol. In comparison with lidocaine/isoflurane balanced anaesthesia, medetomidine/isoﬂurane resulted in better recoveries and a reduced need for the application of intraoperative drugs to deepen anaesthesia (Ringer et al. 2007). As the present study aimed at comparing spontaneously breathing horses with mechanically ventilated horses, isoflurane was used in combination with medetomidine. We presumed that, with this combination, spontaneous respiration would be present and that the
amount of drug needed to deepen anaesthesia (that would influence cardiovascular function) would be minimal.

The present study aimed to determine whether the haemodynamic depressant effect produced by IPPV could be reduced if horses were maintained in a mildly hypercapnic state during isoflurane–medetomidine anaesthesia.

Material and methods

Study design

Prospective, randomized clinical study.

Animals

Sixty horses undergoing surgery at the Equine Hospital of the Vetsuisse Faculty of the University of Zurich were included in the study. Only elective cases were enrolled with an anticipated anaesthesia duration over 90 minutes, a minimum body weight (BW) of 200 kg and an ASA score of I or II. Surgeries of the head and neck area as well as horses with cardiac murmurs were excluded. Horses were determined to be healthy by clinical examination. Plasma sodium and blood haemoglobin concentration were determined for the cardiac output measurement. Haemoglobin concentration was calculated by dividing the haematocrit, which was measured with a micro-haematocrit reader (Hawksley; Milan Instruments SA, Plan-les-Ouates/Geneva, Switzerland) after centrifugation (Hematokrit 20; Hettich Zentrifugen, Tuttlingen, Germany), by three.

This study was performed in compliance with institutional guidelines of the Clinic for Horses of the University of Zurich. All owners signed a consent form allowing all documentation regarding their horse to be used for scientific research and publication.

Study protocol

Pre-anaesthetic data recorded were breed, age, gender, weight, surgical procedure and body position. Horses were of different breeds. Demographic data of the 60 horses as well as data concerning type of surgery and recumbency position are listed in Table 1. There were no significant differences between groups in age, body weight, gender, type of surgery and recumbency position.

<table>
<thead>
<tr>
<th>Variables</th>
<th>Group SV</th>
<th>Group CV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horses included</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>Age (years)</td>
<td>8 ± 4 (1–18)</td>
<td>7 ± 5 (1–16)</td>
</tr>
<tr>
<td>Body weight (kg)</td>
<td>508 ± 105 (210–630)</td>
<td>522 ± 96 (340–700)</td>
</tr>
<tr>
<td>Gender</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Male</td>
<td>18</td>
<td>20</td>
</tr>
<tr>
<td>Female</td>
<td>12</td>
<td>10</td>
</tr>
<tr>
<td>Type of surgery</td>
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<td></td>
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<tr>
<td>Arthroscopies</td>
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<td>14</td>
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<td>Fracture repair</td>
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<td>Other orthopaedic procedures</td>
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<td>Urogenital procedure</td>
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<td>8</td>
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<tr>
<td>Other soft tissue surgeries</td>
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<td>1</td>
</tr>
<tr>
<td>Recumbency</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dorsal</td>
<td>19</td>
<td>21</td>
</tr>
<tr>
<td>Right lateral</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Left lateral</td>
<td>6</td>
<td>4</td>
</tr>
<tr>
<td>Anaesthetic duration (minutes)</td>
<td>126 ± 32 (75–220)</td>
<td>124 ± 36 (65–225)</td>
</tr>
<tr>
<td>Time to standing (minutes)</td>
<td>52 ± 17 (15–80)</td>
<td>59 ± 20 (32–105)</td>
</tr>
</tbody>
</table>

No significant difference between the two groups (p < 0.05). Data are presented as mean ± standard deviation (range) (age, body weight, anaesthetic duration and time to standing) or number of horses (type of surgery and recumbency).

Food but not water was withheld for 8–14 hours. Horses were randomly assigned to one of two groups by computer-generated random numbers (Rancode 3.6; Nomina GmbH, Munich, Germany): spontaneous ventilation (group SV) or intermittent positive pressure ventilation (group IPPV). The same anaesthetist performed all anaesthetics (KSK).

A 14-gauge × 160 mm catheter (Secalon T; Becton Dickinson AG, Basel, Switzerland) was placed in the jugular vein. Sixty minutes before induction, antibiotics and a non-steroidal anti-inflammatory drug (flunixin (Flunixine® ad us. vet.; Biokema SA, Crissier, Switzerland) 1 mg kg⁻¹ or phenylbutazone (Butadion®, ad us. vet.; G. Streuli & Co. AG, Uznach, Switzerland) 4 mg kg⁻¹) were administered by intravenous (IV) injection. Immediately before induction of anaesthesia, horses were sedated with medetomidine (Domitor; Graeub AG, Bern, Switzerland) 7 μg kg⁻¹IV: one-third of the dose was administered in the stable before rinsing the mouth, the remaining two-thirds were injected in the
induction stall slowly over two minutes. If the horse was not deeply sedated within 5 minutes (e.g. no reaction when being approached to administer the ketamine), additional medetomidine was administered to effect and the amount noted. At anaesthesia time zero, the anaesthetic induction was performed with ketamine (Narketan® ad us. vet.; Vétoquinol AG, Belp, Switzerland) 2.2 mg kg⁻¹ and diazepam (Valium 10 mg; Roche Pharma Schweiz AG, Reinach, Switzerland) 0.02 mg kg⁻¹ IV. Once horses were laterally recumbent, an endotracheal tube was placed and horses were hoisted on a padded surgery table. Anaesthesia was maintained with isoflurane (Attane® Isofluran ad us. vet.; Provet AG, Lyssach, Switzerland) in oxygen (O₂) and air and a CRI of medetomidine (3.5 µg kg⁻¹ hour⁻¹). Isoflurane was delivered from a precision vaporizer (Isoflurane Vapor 19.3; Drägerwerk AG, Lübeck, Germany) and a large animal breathing circuit (LAVC-2000; JD Medical Distributing Co., Phoenix, AZ, USA). Medetomidine was diluted with saline (0.9% NaCl) to a concentration of 0.1 mg mL⁻¹ and administered with an infusion pump (Phoenix D; Schoch Electronics AG, Regensdorf, Switzerland). As soon as horses were connected to the breathing system, i.e. approximately 5 minutes after induction, acepromazine (Prequillan; Arovet AG, Zollikon, Switzerland) 0.03 mg kg⁻¹ was administered by intramuscular (IM) injection. In horses in group IPPV artificial ventilation was commenced immediately after connection to the breathing system and continued until the end of anaesthesia using a time-cycled, pressure-controlled bag in a bottle ventilator (Bird Mark 8; Medical Solution, Hünenberg, Switzerland). During IPPV, the respiratory rate, the inspiration: expiration ratio, the inspiratory flow rate and the peak airway pressure were set on the ventilator so that the PaCO₂ was maintained between 50 and 60 mmHg (6.7–8 kPa). Peak airway pressure (PIP) was maintained at 18 to 20 cmH₂O. Fraction of inspired oxygen (FiO₂) was kept constant at 0.40–0.50. When arterial oxygen partial pressure (PaO₂) fell below 80 mmHg, the administration of air was stopped and the flow of oxygen increased to maintain a constant flow rate. Ringer’s lactate was infused at a rate of 5 mL kg⁻¹ hour⁻¹. To maintain MAP above 70 mmHg, dobutamine (Dobutrex; Medika AG, Aesch, Switzerland) was administered. The initial dose in every horse was 0.63 µg kg⁻¹ minute⁻¹ from the beginning of anaesthesia. When MAP decreased below 70 mmHg, dobutamine infusion was increased by half of the initial dose (0.32 µg kg⁻¹ minute⁻¹). After another 5 minutes, if MAP was still below 70 mmHg, dobutamine was increased by a quarter of the initial dose (0.156 µg kg⁻¹ minute⁻¹) and so on until a maximum infusion rate of 1.25 µg kg⁻¹ minute⁻¹. In the opposite direction, dobutamine administration was decreased in the same stepwise manner when MAP reached values > 80 mmHg. The last reduction step after 0.156 µg kg⁻¹ minute⁻¹ was to stop the dobutamine infusion when MAP was still > 80 mmHg after another 5 minutes. The total amount (µg kg⁻¹) administered over the entire anaesthetic period was calculated. To correct for individual differences in anaesthetic duration, the amount of dobutamine was expressed as µg kg⁻¹ minute⁻¹ [total amount of dobutamine (µg kg⁻¹)/anaesthesia duration (minutes)] for statistical analysis. The aim was to keep MAP above 70 mmHg. A urinary catheter was placed following anaesthetic induction.

Qualitative parameters noted during anaesthesia were palpebral reflex, spontaneous blinking, nystagmus and movements. A ketamine bolus was administered (0.1 mg kg⁻¹) IV when horses showed nystagmus or when they were fighting the respirator (group IPPV). Thiopental (Pentothal; Abbott AG, Bar, Switzerland) 0.5–1 mg kg⁻¹ IV was injected in cases of movement. Ketamine and thiopental administration was recorded. The following cardiovascular and respiratory variables were measured continuously with a multiparameter monitor (Datex-Ohmeda Cardiocap/5; Anandic, AVL, Schaffhausen, Switzerland) and noted every 5 minutes: respiratory rate (fₚ), HR, arterial blood pressure, inspiratory and expiratory O₂, expiratory CO₂ (Pa’CO₂) and inspiratory/expiratory isoflurane concentrations. Occurrence of cardiac arrhythmias was noted. Arterial blood pressure was measured invasively by connecting a facial or transverse facial arterial catheter (Surflo IV Catheter 22-gauge 1”; Terumo, Medical Solution GmbH, Switzerland) to a pressure transducer (Pressure Transducer DTX/Plus; Becton Dickinson AG; Allschwil, Switzerland) positioned and zeroed at the level of the sternal manubrium. Arterial blood-gas analysis was performed with an i-Stat portable analyzer system (I-STAT Analyzer and G3+ Cartrdiges; Axon Lab AG, Baden-Dättwil, Switzerland). The first analysis was carried out 15 minutes following anaesthetic induction and then repeated every 30 minutes.
Cardiac output (CO; L minute⁻¹) was measured by use of a lithium dilution technique and a commercial computer (LiDCO cardiac sensor systems; LiDCO Ltd., Cambridge, UK). The sensor (a flow through cell housing a lithium-selective electrode) was connected to the arterial catheter. For determination of CO 1.5 mL (2.25 mmol) of lithium chloride 1.5 molar was injected through the jugular catheter while arterial blood passed through the sensor at a flow rate (4 mL minute⁻¹) that was controlled by a small battery operated pump. The first measurement was performed 45 minutes after anaesthetic induction and then repeated hourly. The last measurement was performed at the end of anaesthesia independent of the last measurement. Cardiac output determinations were performed at the end of expiration and before collection of arterial blood-gas samples. Stroke volume (SV), stroke volume index (SVI), CI, total peripheral resistance (TPR), arterial oxygen content (CaO₂) and oxygen delivery (DO₂) were calculated by the following formulas:

\[ SV (\text{mL beat}^{-1}) = \frac{CO}{100/HR}, \]

where CO was measured in L minute⁻¹ and heart rate (HR) in beats minute⁻¹.

\[ SVI (\text{mL beat}^{-1} \text{kg}^{-1}) = \frac{SV}{BW}, \]

where BW was measured in kilograms.

\[ CI (\text{mL kg}^{-1} \text{minute}^{-1}) = \frac{CO}{BW}. \]

\[ TPR (\text{dynes seconds cm}^{-5}) = \frac{80(MAP)}{CO}, \]

where MAP was measured in mmHg (Klabunde 2005).

\[ CaO₂ (\text{mL dL}^{-1}) = (Hb \times 1.36 \times SaO₂) + (0.0031 \times PaO₂), \]

where haemoglobin (Hb; g dL⁻¹) was calculated by dividing the haematocrit by three, and arterial oxygen saturation was measured in the arterial blood-gas sample and declared as decimal; the constant 1.36 is the amount of oxygen (mL at 1 atmosphere) bound per gram of haemoglobin; the constant 0.0031 represents the amount of oxygen dissolved in plasma at 1 atmosphere.

\[ DO₂ (\text{mL kg}^{-1} \text{minute}^{-1}) = CI (CaO₂/100). \]

Ten to 20 minutes before the end of surgery morphine (Morphin HCl 10 mg, Sintetica SA, Mendrisio, Switzerland) 0.1 mg kg⁻¹ was administered IM. Isoflurane and medetomidine were discontinued and duration of anaesthesia recorded. For recovery, horses were sedated with medetomidine 2 μg kg⁻¹ IV 5 to 10 minutes after disconnection from the anaesthetic system. Ten millilitres of phenylephrine 0.15% (Phenylephrin HCl 1.5 mg mL⁻¹; G. Streuli & Co. AG, Uznach, Switzerland) were instilled into the nares to decongest the nasal cavities. During recovery, oxygen was insufflated at 15 L minute⁻¹, initially through the endotracheal tube, after extubation via the ventral nasal meatus. Time of extubation, duration of lateral and sternal recumbency and total time to standing from disconnection of the anaesthetic circuit were recorded. The quality of recovery was graded on a scale of one (excellent) to five (very poor) (Table 2).

### Statistics

Data were analyzed using a commercially available software package (Statview 5.1 software: SAS Inc. Cary, NC, USA). Continuous data were evaluated for normality using visual inspection of the data using a percentile histogram and the Kolmogorov-Smirnov test adapted for quality control of normality. Continuous data were analyzed using analysis of variance (ANOVA) with repeated measures. Time was used as the in-between factor. Factorial data were analyzed using unpaired t-tests. Categorical data were analyzed using chi-square tests. Post-hoc cell contribution was performed according to StatView 5.1. Post-hoc cell contribution is a form of standardized residual that indicates what each cell in the table contributes to the chi-square statistics. A value of >±1.96 indicates a significant contribution of the respective cell.

A p-value of <0.05 was considered significant.

Data are reported as mean ± standard deviation (SD).

<table>
<thead>
<tr>
<th>Score</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Excellent, one attempt to stand, minimal or no ataxia</td>
</tr>
<tr>
<td>2</td>
<td>Good, 1–2 attempts to stand, some ataxia, horse calm</td>
</tr>
<tr>
<td>3</td>
<td>Fair, several attempts to stand, horse remains calm</td>
</tr>
<tr>
<td>4</td>
<td>Poor, more than one attempt to stand, horse excited</td>
</tr>
<tr>
<td>5</td>
<td>Very poor, bad recovery with high risk of injury</td>
</tr>
</tbody>
</table>

Table 2 Description of the recovery scores
Results

There were no significant differences between groups in total time of anaesthesia and time to standing (Table 1).

Twelve horses in each group required an additional dose of medetomidine to achieve deep sedation. In group SV, the mean (min–max) additional dose of medetomidine was 1.7 (0.6–4) μg kg⁻¹, in group IPPV, 1.4 (0.51–2.6) μg kg⁻¹.

The aim to maintain PaCO₂ of horses in group IPPV between 50 and 60 mmHg (6.7–10 kPa) was successfully achieved. Mean PaCO₂ was not different between the groups (Fig. 1).

Respiratory rate was significantly higher in group IPPV (p < 0.05; Fig. 2). Recording of central venous pressure (CVP) was impossible in 38 horses, as no typical pressure waves could be identified so TPR was calculated for all horses.

There were no significant differences in any of the other measured or calculated parameters between the groups. Values for CI, SV, SVI, TPR, CuO₂ and DO₂ were not different in time between groups (Table 3). Also arterial blood-gas parameters and pH did not differ significantly between groups (Table 4).

However, there were significant changes over time in the following parameters: HR increased between 25 and 115 minutes (p < 0.0001; Fig. 3); DO₂ (p < 0.05), PCO₂ (p < 0.0001; Fig. 1), and HCO₃⁻ (p < 0.0001) increased between 45 and 105 minutes; pH (p < 0.05) decreased between 45 and 105 minutes in both groups; and MAP decreased between 15 and 45 minutes in both groups (p < 0.0001; Fig. 4).

Two horses in group SV and four horses in group IPPV showed first- or second-degree atrioventricular blocks on the electrocardiogram. In every case, these arrhythmias disappeared within 60 minutes following anaesthesia induction without intervention.

The dose of dobutamine used to maintain MAP above 70 mmHg was not significantly different.
between groups (SV 0.29 and IPPV 0.36 µg kg\(^{-1}\) minute\(^{-1}\), \(p = 0.28\)).

End-tidal isoflurane concentration was similar in both groups (SV: 1.04 ± 0.122%; IPPV: 0.96 ± 0.09%) and constant over time. In 15 horses in group SV and in nine horses in group IPPV, the \(F_\text{O}_2\) was changed from 0.4 to >0.9 because of a measured \(P_\text{O}_2\) < 80 mmHg (<10.7 kPa).

The total dose of ketamine to deepen anaesthesia intraoperatively was not significantly different between groups (group SV: 0.094 ± 0.019 mg kg\(^{-1}\) hour\(^{-1}\); group IPPV: 0.098 ± 0.018 mg kg\(^{-1}\) hour\(^{-1}\)). But the number of horses, which received ketamine, was significantly different between groups: twelve horses in group SV (40%) and 21 horses in group IPPV (70%) received supplemental ketamine. No horse in any group needed supplemental thiopental. Recovery quality was assessed in group SV with \(17 \times 1\), \(9 \times 2\), and \(4 \times 3\); in group IPPV with \(19 \times 1\), \(7 \times 2\), \(3 \times 3\), and \(1 \times 4\). All horses recovered from anaesthesia without complications.

**Discussion**

This study was designed as a prospective randomized clinical study. Confounding variables were reduced as much as possible under clinical circumstances. In the current study, controlled ventilation did not produce significant cardiovascular effects during isoflurane–medetomidine balanced anaesthesia in mildly hypercapnic horses.

The impairment of circulation by IPPV has been demonstrated by numerous techniques. An important factor is peak inspiratory pressure (PIP). In 1948, Cournand et al. showed that cardiac output in humans decreased more or less in proportion to the increase in pressure. As airway pressure increased stroke volume and cardiac output progressively decreased (Morgan et al. 1966). Also in horses end-inspiratory pressures of 25 cmH\(_2\)O produced more pronounced cardiovascular depression than end-inspiratory pressures of 20 cmH\(_2\)O or spontaneous ventilation (Mizuno et al. 1994). The influence of \(CO_2\) was not tested in this study. In the group with lower inspiratory pressures as well as in the spontaneous ventilation group, \(P_\text{aCO}_2\)s were higher. Also in our study, peak inspiratory pressures were low (18–20 cmH\(_2\)O) and the horses in both groups were mildly hypercapnic. In horses, hypercapnia is generally associated with improvement in cardiovascular function (Wagner et al. 1990;
Taylor 1998). An increase in circulating catecholamines was associated with an increase in PaCO₂ and improved haemodynamics (Gillespie et al. 1969; Weaver & Walley 1975). In the present study, there was no difference between the groups concerning haemodynamics. The cardiac indices in our study were comparable to CIs during isoflurane–medetomidine anaesthesia in the study of Ringer et al. (2007). Cardiac index was also within a similar range or even higher compared with studies in horses using other anaesthesia protocols (Hillidge & Lees 1975; Umar et al. 2007).

Beside hypercapnia, increased venous admixture and a large alveolar–arterial oxygen tension difference are evidence of impaired gas exchange during general anaesthesia in horses. To prevent atelectasis formation, the use of oxygen combined with air or nitrous oxide is recommended. To improve PaO₂, some authors tried to use mechanical ventilation or increased FiO₂ fractions but mostly without success (Hodgson et al. 1986; Cuvelliez et al. 1990; Nyman et al. 1990). Positive end-expiratory pressure (PEEP) has been used successfully to improve oxygenation of arterial blood. However PEEP sufficient to increase functional residual capacity and arterial oxygenation, induced a marked reduction in cardiac output (Wilson & Soma 1990) which resulted in no improvement or even a decrease in total oxygen delivery to tissues. In the IPPV group, we chose a respiratory rate of 8–10 breaths minute⁻¹, as commonly suggested for controlled ventilation of healthy adult horses (Steffey 1981). Although the respiratory rate of the spontaneously breathing horses was slightly lower, the goal of an identical PaCO₂ in both groups was achieved. Nevertheless, PaCO₂ increased slightly in both groups during anaesthesia and this was paralleled by a decrease in pH. Whether this was a result of increased metabolism and therefore CO₂ production, or decreased ventilation as a result of slightly deeper anaesthesia levels, cannot be answered. The fact that this was paralleled by an increase in oxygen delivery suggests that some improvement of cardiovascular function was present.

Acepromazine was part of the anaesthetic protocol as it was associated with a reduced mortality rate in horses (Johnston et al. 2002) and as it causes vasodilatation and thus improved perfusion (Marntell et al. 2005). Acepromazine was administered following anaesthetic induction to standardize the use of oxygen combined with air or nitrous oxide is recommended. To improve PaO₂, some authors tried to use mechanical ventilation or increased FiO₂ fractions but mostly without success (Hodgson et al. 1986; Cuvelliez et al. 1990; Nyman et al. 1990). Positive end-expiratory pressure (PEEP) has been used successfully to improve oxygenation of arterial blood. However PEEP sufficient to increase functional residual capacity and arterial oxygenation, induced a marked reduction in cardiac output (Wilson & Soma 1990) which resulted in no improvement or even a decrease in total oxygen delivery to tissues. In the IPPV group, we chose a respiratory rate of 8–10 breaths minute⁻¹, as commonly suggested for controlled ventilation of healthy adult horses (Steffey 1981). Although the respiratory rate of the spontaneously breathing horses was slightly lower, the goal of an identical PaCO₂ in both groups was achieved. Nevertheless, PaCO₂ increased slightly in both groups during anaesthesia and this was paralleled by a decrease in pH. Whether this was a result of increased metabolism and therefore CO₂ production, or decreased ventilation as a result of slightly deeper anaesthesia levels, cannot be answered. The fact that this was paralleled by an increase in oxygen delivery suggests that some improvement of cardiovascular function was present.

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its application time. To avoid a sudden decrease in blood pressure, acepromazine was administered IM. Together with the onset of isoflurane and the waning medetomidine effect, it induced an initial decrease in MAP, which was paralleled by an increase in HR. This increase was likely caused by a physiological compensation to the decreasing blood pressure. Furthermore, the dose of dobutamine was increased according to the protocol to improve blood pressure, simultaneously leading to an increase in HR. The use of dobutamine clearly influenced cardiac performance and haemodynamics (Lee et al. 1998) and thus the results of the present study could have been influenced by its use. Nevertheless, we chose to use it as we aimed to mimic the clinical situation, where dobutamine is dosed according to variations in arterial blood pressure. The administration of dobutamine was standardized in both groups and no significant difference between groups with regard to dobutamine dose rates occurred. Therefore, it is unlikely that it influenced the results of the present study.

With the currently available technology, lithium dilution appears to be the best method of measuring CO in the horse under clinical circumstances (Corley et al. 2003). Lithium dilution requires catheterization of a peripheral artery and a jugular vein. It has been validated in anaesthetized horses and neonatal foals (Linton et al. 2000; Corley et al. 2002). One of the disadvantages of lithium dilution is the inaccuracy in the presence of intracardiac shunts. Therefore, we excluded horses with heart murmurs. This is not a valid method to exclude intracardiac shunting, but it is unlikely that healthy, symptom-free adult horses suffer from significant intracardiac shunts. To calculate systemic vascular resistance, CVP should be known. We did not use the values measured through our central venous catheters as we failed to record typical pressure waves in many horses. Probably, the catheters were not long enough to reach the intrathoracic cavity. Thus, we removed CVP from the calculation and calculated TPR (Klabunde 2005).

Ketamine does possess a sympathomimetic effect and might influence cardiovascular function. Significantly more horses in group IPPV received supplemental ketamine. This was necessary as they were fighting the ventilator. Under medetomidine–isoflurane anaesthesia relatively low isoflurane concentrations were necessary to maintain adequate anaesthesia (Ringer et al. 2007). As a result of the relatively high PaCO₂ chosen in this study and the low isoflurane end-tidal concentration, horses did not tolerate the ventilator, even though the effect of medetomidine was sufficient to provide anaesthesia depth adequate to perform surgery. Theoretically, it is possible that horses in group IPPV were more often sympathomimetically stimulated by ketamine. This could lead to a falsification of the cardiovascular data. To quantify the dimension of this falsification, the total dose of ketamine per bodyweight and time unit was calculated. As there was no significant difference between groups in the total dose of ketamine and the dose was very low, the authors concluded that there was no clinically significant influence on cardiovascular function caused by ketamine. If there is an error, cardiovascular parameters in group IPPV were falsely high. This possible error could have been avoided by inhibiting the fight against the ventilator by using increased doses of isoflurane. This would have negatively influenced cardiovascular function in group IPPV and this is certainly not an aim of equine anaesthesia. Simply ignoring the resistance to the ventilator was not an option in the authors’ opinion, as this would also impair cardiac output.

In conclusion, controlled ventilation in healthy horses undergoing elective surgical procedures using isoflurane–medetomidine anaesthesia did not impair cardiovascular function when they were slightly hypoventilated maintaining mild hypocapnia. It is unknown if cardiovascular function would have been impaired if the horses in group IPPV would have been maintained normocapnic. It has to be emphasized that the horses used in this study were elective patients, assigned to ASA classification I or II. Whether the same kind of IPPV has no negative cardiovascular effects in compromised horses remains to be determined.

References


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Received 6 November 2007; accepted 1 August 2008.