Effects of body position on intracranial and cerebral perfusion pressures in isoflurane-anesthetized horses

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Brosnan, Robert J., Eugene P. Steffey, Richard A. LeCouteur, Ayako Imai, Thomas B. Farver, and Gregg D. Kortz. Effects of body position on intracranial and cerebral perfusion pressures in isoflurane-anesthetized horses. J Appl Physiol 92: 2542–2546, 2002. First published February 15, 2002; 10.1152/japplphysiol.00055.2002.—Inhalant anesthetics may interfere with normal cerebrovascular autoregulation. It was, therefore, hypothesized that intracranial pressure (ICP) and cerebral perfusion pressure (CPP) in isoflurane-anesthetized horses would be especially sensitive to body and head position because of the potential for large hydrostatic gradients between the brain and heart in this species. Anesthesia was induced and maintained in six clinically healthy, unmedicated geldings with 1.57% isoflurane in O2; mechanical ventilation was used to maintain normocapnia. ICP was measured by using a subarachnoid strain-gauge transducer. Blood gases and carotid arterial, right atrial, and airway pressures were also measured. Five body positions were studied in a semirandomized order: dorsal recumbency (DR) with head down (HD), DR with head level (HL), lateral recumbency (LR), sternal recumbency (SR) with HL, and SR with head up (HU). Data were analyzed by using paired t-tests. ICP and CPP values, respectively, are as follows (means ± SD): 36 ± 4 and 55 ± 18 mmHg (DR-HD); 34 ± 6 and 51 ± 32 mmHg (DR-HL); 24 ± 5 and 48 ± 4 mmHg (LR); 19 ± 11 and 87 ± 12 mmHg (SR-HL); and −14 ± 7 and 71 ± 10 mmHg (SR-HU). Significant differences were found among all positions, except for SR-HL vs. LR. Significant increases in CPP were observed only in sternal positions. In conclusion, ICP in isoflurane-anesthetized horses changes inversely with the brain-to-heart hydrostatic gradient. DR may also cause increases in ICP, irrespective of head position.

posture; equine

BODY AND HEAD POSITION DIRECTLY impact the brain-to-heart hydrostatic gradient, which, in turn, can alter intracranial (ICP) and cerebral perfusion pressures (CPP), especially in the presence of drugs or diseases that interfere with normal cerebrovascular autoregulation. Depression of the head relative to the heart, for example, has been shown to increase ICP in awake rats (22) and anesthetized rabbits (4), monkeys (11), cats (13), and humans (14); no significant difference in CPP was found in the latter two studies. Conversely, elevation of the head relative to the heart has been shown to consistently decrease ICP during anesthesia in both dogs (8) and humans (12), although variable increases (15), decreases (16, 20, 21), and no change (7, 9) in CPP have all been reported. In addition to head position, ICP can be affected by body posture alone. A study of human neurosurgical patients showed that the supine position was associated with a lower ICP than either the prone or lateral body positions; significant differences in CPP, however, were not observed (2).

Head position has minimal effect on ICP in standing, awake horses (R. J. Brosnan, R. A. LeCouteur, E. P. Steffey, A. Imai, and G. D. Kortz, unpublished observations), presumably because of normal cerebrovascular regulatory mechanisms. Yet mean arterial pressure (MAP) in horses increases with head elevation (19), which may arise from a need to maintain CPP. Because of dose-dependent cardiovascular depression and a tendency to decrease cerebrovascular resistance, inhalant anesthetics may impede normal responses to hydrostatic stress in the horse caused by unnatural positioning of the head and body. As a result of their large size and potential for large hydrostatic gradients, it is predicted that ICP and CPP in the isoflurane-anesthetized horse might, therefore, be especially sensitive to changes in body and head position.

MATERIALS AND METHODS

Animals. Six healthy geldings, consisting of one Holsteiner, one quarter horse, and four Thoroughbreds, were studied. Animals were aged from 3 to 8 yr (mean ± SD: 4.5 ± 1.9 yr) and weighed from 490 to 576 kg (518 ± 37 kg). This protocol was approved by the Animal Use and Care Committee at the University of California, Davis.

Anesthesia. Food, but not water, was withheld 12 h before the experiment. Anesthesia was induced with isoflurane in unmedicated horses by using a procedure that has been previously described (5, 10, 23). Horses were then intubated with a 30-mm cuff atotracheal tube that was connected to a standard, large-animal, semiclosed anesthetic circuit. For the first hour after induction, end-tidal isoflurane concentration (CETiso) was maintained between 1.7 and 2.0% to provide

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a surgical plane of anesthesia during instrumentation; no gross or purposeful movement was observed during this time. For the remainder of the experiment, horses were maintained at a constant dose of 1.57% isoflurane, corresponding to 1.2 times the minimum alveolar concentration for this species (24). Respiration was controlled by using intermittent positive-pressure ventilation to maintain normocapnia. Peak-inspiratory and end-expiratory pressures were kept between 18.3 and 23.9 cmH2O (20.8 ± 1.2 cmH2O) and 0.0 to 2.2 cmH2O (1.1 ± 0.6 cmH2O), respectively. Blankets and heat lamps were used as needed to maintain normothermia (37.4 ± 0.6°C).

**Body positions.** During a single anesthesia, each horse was studied in three body positions on a padded cart in randomized order: left lateral recumbency (LR), dorsal recumbency (DR), and sternal recumbency (SR). During DR, horses were studied with the head measured from the lateral canthus to the thoracic inlet (DR-HL) and with the head down 20 cm vertically from the thoracic inlet (DR-HD). During SR, horses were studied with the head level with the thoracic inlet (SR-HL) and with the head up 65 cm vertically from the lateral canthus to the thoracic inlet (SR-HU); legs were positioned in front of the animal with both elbows flexed. The order of head position within the DR and SR positions was randomized. Head position was always kept level with the thoracic inlet during LR. After each change in body or head position, steady-state CETiso and end-tidal carbon dioxide concentration were maintained for a minimum of 30 min before data collection.

**Instrumentation and data collection.** Systolic and diastolic arterial blood pressures were recorded from a percutaneous, 14-gauge, 17.6-cm polytetrafluoroethylene right carotid arterial catheter with the catheter tip at or near the thoracic inlet; mean blood pressure was obtained via an electronic signal mean. A second 6.5-Fr, 110-cm polyethylene catheter was placed percutaneously in the right jugular vein and advanced into the right atrium, as confirmed by pressure waveform tracing, to measure central venous pressure (CVP). Both catheters were connected to calibrated strain-gauge transducers (model P23D, Statham Division of Mark IV Industries, Oxnard, CA) positioned at the level of the thoracic inlet. Airway pressure within the endotracheal tube was measured by a calibrated differential pressure transducer (model PM131TC, Statham Division of Mark IV Industries). Signal output from blood and airway pressure transducers was recorded by a multichannel physiograph (Grass model 7D, Statham Medical Instruments, Hato Rey, PR).

Body temperature was measured within the nasopharynx by using a calibrated temperature probe (Yellow Springs Instruments, Yellow Springs, OH). CETiso and end-tidal carbon dioxide concentration were measured by using infrared gas analyzers (LB2, Sensormedics, Anaheim, CA), and inspired O2 fraction was measured by a polarographic oxygen sensor (OM-11, Sensormedics). All machines were calibrated against multiple certified standards. Arterial PO2 (PaO2), arterial PCO2 (PaCO2), and arterial pH were measured by an automated blood-gas analyzer (ABL 5, Radiometer America, Westlake, OH); values were later corrected by using standard curves obtained through tonometry of horse blood with certified standard gas mixtures.

Direct ICP was obtained via a Codman Microsensor strain-gauge transducer (Codman & Shurtleff, Raynham, MA) placed through a right parietal craniotomy into the subarachnoid space (Brosnan et al., unpublished observations). Accuracy of all transducers was verified by post hoc calibration within a column of water from −20 to +30 mmHg. CPP was calculated as the difference between MAP at the circle of Willis (MAPCW) and the ICP. In turn, MAPCW was estimated by the following equations

\[
\text{MAPCW} = \text{MAP} - [\Delta h + 1.36] \text{ head up (1)}
\]

\[
\text{MAPCW} = \text{MAP} + [\Delta h + 1.36] \text{ head down (2)}
\]

where Δh is the vertical distance (in cm) between the thoracic inlet (at the jugular vein) and lateral canthus of the eye, and 1.36 represents the conversion factor between mmHg and cmH2O.

**Statistical analysis.** Because of missing data, screening tests involving repeated measures could not be performed easily without estimation and replacement of these values.

### Table 1. Summary of cardiovascular and respiratory responses for mechanically ventilated, isoflurane-anesthetized horses in five body and head positions

<table>
<thead>
<tr>
<th>Variable</th>
<th>DR-HD</th>
<th>DR-HL</th>
<th>LR</th>
<th>SR-HL</th>
<th>SR-HU</th>
</tr>
</thead>
<tbody>
<tr>
<td>Systolic</td>
<td>97.8 ± 17.8</td>
<td>106.0 ± 33.8</td>
<td>93.6 ± 9.1</td>
<td>127.2 ± 19.3</td>
<td>124.1 ± 20.6</td>
</tr>
<tr>
<td>Diastolic</td>
<td>63.4 ± 16.3</td>
<td>71.0 ± 27.3</td>
<td>59.3 ± 2.8</td>
<td>89.0 ± 12.6</td>
<td>90.8 ± 11.9</td>
</tr>
<tr>
<td>Mean (MAP)</td>
<td>76.3 ± 17.1</td>
<td>84.8 ± 29.3</td>
<td>71.5 ± 5.9</td>
<td>105.1 ± 12.8</td>
<td>105.2 ± 15.7</td>
</tr>
<tr>
<td>MAPcw, mmHg</td>
<td>91.0 ± 17.1</td>
<td>84.8 ± 29.3</td>
<td>71.5 ± 5.9</td>
<td>105.1 ± 12.8</td>
<td>105.2 ± 15.7</td>
</tr>
<tr>
<td>ICP, mmHg</td>
<td>36.4 ± 4.3</td>
<td>33.7 ± 5.5</td>
<td>23.6 ± 5.0</td>
<td>18.6 ± 11.0</td>
<td>13.7 ± 7.0</td>
</tr>
<tr>
<td>CPP, mmHg</td>
<td>54.6 ± 17.5</td>
<td>51.1 ± 32.2</td>
<td>47.9 ± 3.9</td>
<td>86.5 ± 11.9</td>
<td>71.1 ± 9.9</td>
</tr>
<tr>
<td>CVP, mmHg</td>
<td>5.4 ± 1.6</td>
<td>6.2 ± 2.6</td>
<td>9.0 ± 2.8</td>
<td>9.0 ± 1.7</td>
<td>7.2 ± 5.5</td>
</tr>
<tr>
<td>HR, beats/min</td>
<td>31.1 ± 4.9</td>
<td>34.5 ± 3.7</td>
<td>32.8 ± 4.9</td>
<td>35.4 ± 4.7</td>
<td>36.2 ± 4.3</td>
</tr>
<tr>
<td>RR, breaths/min</td>
<td>8.6 ± 1.5</td>
<td>10.1 ± 2.3</td>
<td>7.8 ± 2.9</td>
<td>8.8 ± 2.6</td>
<td>8.0 ± 2.9</td>
</tr>
<tr>
<td>PaO2, Torr</td>
<td>313 ± 15</td>
<td>315 ± 168</td>
<td>459 ± 150</td>
<td>537 ± 54</td>
<td>573 ± 51</td>
</tr>
<tr>
<td>PaCO2, Torr</td>
<td>44.3 ± 3.1</td>
<td>43.8 ± 2.8</td>
<td>46.8 ± 2.9</td>
<td>43.0 ± 1.6</td>
<td>40.7 ± 2.4</td>
</tr>
<tr>
<td>pH</td>
<td>7.36 ± 0.07</td>
<td>7.37 ± 0.05</td>
<td>7.35 ± 0.05</td>
<td>7.37 ± 0.05</td>
<td>7.38 ± 0.06</td>
</tr>
<tr>
<td>Tb, °C</td>
<td>37.4 ± 0.5</td>
<td>37.4 ± 0.6</td>
<td>37.4 ± 0.6</td>
<td>37.2 ± 0.4</td>
<td>37.4 ± 0.9</td>
</tr>
<tr>
<td>PCV, %</td>
<td>43.6 ± 9.7</td>
<td>43.1 ± 7.5</td>
<td>40.4 ± 7.4</td>
<td>42.5 ± 6.5</td>
<td>43.2 ± 7.0</td>
</tr>
<tr>
<td>TS, g/dl</td>
<td>6.8 ± 0.6</td>
<td>6.8 ± 0.6</td>
<td>6.7 ± 0.6</td>
<td>6.6 ± 0.5</td>
<td>6.7 ± 0.5</td>
</tr>
</tbody>
</table>

Values are means ± SD; n, no. of animals. Isoflurane is 1.2 times the minimum alveolar concentration. DR, dorsal recumbency; LR, lateral recumbency; SR, sternal recumbency; HD, head down; HL, head level; HU, head up; MAP, mean arterial pressure; MAPcw, estimated MAP at the circle of Willis; ICP, intracranial pressure; CPP, cerebral perfusion pressure; CVP, central venous pressure; HR, heart rate; RR, respiratory rate; PaO2, arterial PO2; PaCO2, arterial PCO2; pH, arterial pH; Tb, body temperature; PCV, packed cell volume; TS, total solids in serum.
Instead, paired t-tests were used to determine significance for a variable between two positions. To protect against false rejection of the null hypothesis caused by increased numbers of tests, differences were considered significant only at $P \leq 0.01$. Because ICP was hypothesized to be inversely correlated with head elevation within a given body position, single-tailed t-tests were used between comparisons of DR-HD vs. LR and SR-HL vs. SR-HU.

RESULTS

Cardiorespiratory responses. Hemodynamic and blood-gas responses are summarized in Table 1; significant group comparisons observed by using paired t-tests are listed in Table 2. MAP was significantly higher in SR than in LR; heart rate tended also to be higher in SR, with an average increase of 4.6 ± 3.5 beats/min in SR-HU compared with LR. When corrected for changes in hydrostatic pressure, MAP$_{CW}$ was highest during DR-HD and SR-HL and lowest during SR-HU. In addition, MAP was significantly increased in SR-HL compared with LR, despite identical head elevations. No significant changes in CVP were observed among any positions.

Significant differences in Pa$_O_2$ were also seen for several body positions (Table 2), despite an inspired O$_2$ fraction of 94 ± 4% for all measurements. Oxygenation was greatest in SR and poorest in DR; significant mean differences in Pa$_O_2$ between these positions ranged from 259 to 286 Torr. Although controlled ventilation maintained normocapnia, differences in Pa$_CO_2$ between SR-HU and the lateral and dorsal body positions nonetheless approached significant levels (Table 2), although the greatest absolute differences (3.4–6.3 Torr) were relatively modest and probably contributed only a small physiological effect.

ICP and CPP. Individual ICP values ranged from −21 mmHg in SR-HU to +40.3 mmHg in DR-HD. Statistically significant differences (or differences approaching statistical significance) were seen in ICP among all body positions, with the exception of SR-HL vs. LR (Table 2). However, only statistically significant differences in CPP were seen between SR and LR, due primarily to group differences in MAP$_{CW}$, not ICP (Fig. 1).

Statistical testing. Missing data arose from two sources. First, additional body and head positions were added to the study design after the first experiment, for which measurements were, therefore, unavailable. Second, inadequate muscle relaxation present in one horse during SR precluded measurements in the SR-HL position.

A large number of t-tests were performed to avoid estimation of missing data, and $x$ was set at 0.01 to minimize incorrect rejection of null hypotheses (no difference between positions). Since power was sacrificed for these comparisons, tests designated as “approaching statistical significance” ($0.01 < P \leq 0.05$) necessitate cautious interpretation.

DISCUSSION

In isoflurane-anesthetized horses, ICP changes in accordance with hydrostatic pressure gradients brought about by changes in head position, i.e., positive hydrostatic gradients caused by a dependent head position result in increased ICP, and negative hydrostatic gradients caused by an elevated head position result in decreased ICP. However, equidistant elevation or depression of the head with respect to the thoracic inlet produces dissimilar magnitudes of ICP alteration in different body positions. A 20-cm lowering of the head from DR-HL to DR-HD produced a mean ICP change of +3.3 mmHg (4.5 cmH$_2$O), corresponding to an average increase of 0.16 mmHg (0.22 cmH$_2$O) per centimeter head depression. A 65-cm raising of the head from SR-HL to

Fig. 1. Bar graph of mean arterial pressure at the circle of Willis (MAP$_{CW}$) (height of open bar) and mean intracranial pressure (ICP) (height of shaded bar) for horses in 5 body and head positions. Cerebral perfusion pressure is equal to the length of the central vertical line (MAP$_{CW}$–ICP). DR, dorsal recumbency; LR, lateral recumbency; SR, sternal recumbency; HD, head down; HL, head level; HU, head up.

Table 2. Mean positional differences for pairwise comparisons

<table>
<thead>
<tr>
<th>Comparison</th>
<th>MAP, mmHg</th>
<th>ICP, mmHg</th>
<th>CPP, mmHg</th>
<th>CVP, mmHg</th>
<th>Pa$_O_2$, Torr</th>
<th>Pa$_CO_2$, Torr</th>
<th>Degrees of Freedom</th>
</tr>
</thead>
<tbody>
<tr>
<td>DR-HD vs. DR-HL</td>
<td>NS</td>
<td>3.3±1.7$^+$</td>
<td>NS</td>
<td>NS</td>
<td>−286±71$^+$</td>
<td>−260±102$^+$</td>
<td>4</td>
</tr>
<tr>
<td>DR-HD vs. SR-HL</td>
<td>NS</td>
<td>19.6±10.2$^+$</td>
<td>NS</td>
<td>NS</td>
<td>−260±102$^+$</td>
<td>3.6±2.2$^+$</td>
<td>3</td>
</tr>
<tr>
<td>DR-HD vs. SR-HU</td>
<td>NS</td>
<td>50.0±4.5$^+$</td>
<td>NS</td>
<td>−280±137$^+$</td>
<td>3.4±2.3$^+$</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>DR-HD vs. LR</td>
<td>NS</td>
<td>13.2±7.3$^+$</td>
<td>NS</td>
<td>−270±155$^+$</td>
<td>NS</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>DR-HL vs. SR-HL</td>
<td>NS</td>
<td>14.8±9.9$^+$</td>
<td>NS</td>
<td>−280±137$^+$</td>
<td>NS</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>DR-HL vs. SR-HU</td>
<td>NS</td>
<td>46.7±4.8$^+$</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>SR-HL vs. SR-HU</td>
<td>NS</td>
<td>29.2±11.2$^+$</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>SR-HL vs. SR-HU</td>
<td>NS</td>
<td>31.9±13.1$^+$</td>
<td>NS</td>
<td>38.7±15.3$^+$</td>
<td>NS</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>SR-HL vs. LR</td>
<td>NS</td>
<td>33.9±17.1$^+$</td>
<td>−36.9±8.5$^+$</td>
<td>23.0±10.5$^+$</td>
<td>NS</td>
<td>−6.3±3.7$^+$</td>
<td>4</td>
</tr>
</tbody>
</table>

Values are means ± SD. Pairwise comparisons are shown as x vs. y, calculated as x − y. *One-tailed test. †Significant difference, $P \leq 0.01$. ‡Approaching statistical significance, $P \leq 0.05$. NS, differences were not significant.
SR-HU produced a mean ICP change of −29.2 mmHg (−39.7 cmH2O), corresponding to an average ICP increase of 0.45 mmHg (0.61 cmH2O) per centimeter head elevation. Assuming a linear relationship between head position and ICP change, there exists a threefold greater effect of head elevation on lowering ICP in SR than the effect of head depression on increasing ICP in DR. In addition, significant differences between DR-HL vs. LR and DR-HL vs. SR-HL suggest that increases in ICP associated with DR are, at least in part, independent of head position. Instead, these changes may be related to changes in abdominal pressure or organ displacement caused by DR, producing possible cranial displacement of the diaphragm, increased thoracic pressure, and external compression of the vena cava (3).

Although unaffected by DR and LR, CPP was significantly increased during SR, principally as a consequence of markedly increased MAP. This hemodynamic change probably occurred less from a need to increase CPP than as a sequel of SR itself, which is associated with an increased risk of postanesthetic myopathies (26) and presumably muscle pain. Hence, increased MAP may signify an autonomic response to a noxious stimulus. Other evidence for this interpretation includes increased heart rate for most horses during SR and insufficient muscle relaxation with purposeful movement present only during SR in one animal, despite a constant end-tidal iso-flurane dose. Additionally, blood pressures in this study for horses in LR are significantly higher than those described in the literature for horses anesthetized under similar circumstances (5). This discrepancy may also be due to increased sympathetic tone after SR, body repositioning, direct cerebral stimulation from the pressure transducer, or persistent, subconscious, postsurgical discomfort.

CVP, as measured by right atrial pressure, was similar in all body positions. Nevertheless, cerebral venous pressures would be very different if CVP were corrected for the same hydrostatic gradient as MAPCw. DR-HD would change cerebral venous pressures by +15 mmHg and tend to impede cerebral drainage and increase capillary pressure. Conversely, SR-HU would decrease cerebral venous pressures by −48 mmHg, facilitating drainage and causing the jugular vein to act as a Starling resistor (28); resulting atmospheric or subatmospheric venous pressures would, therefore, be predicted to have no differential effect on cerebral blood flow.

All animals were normoxic throughout the study. However, PaO2 was significantly higher (and with less variance) during SR and significantly lower during DR as a result of gravitational effects on pulmonary ventilation-perfusion matching (18); these findings directly confirm similar comparisons in the literature for this species (25, 26) but should not significantly influence cerebral hemodynamics or oxygen delivery in normoxic animals. Similarly, comparisons of PaCO2 that approached significance (Table 2) were only of a few Torr in magnitude and, at most, contributed only a small portion to the overall differences in ICP.

Isoflurane interferes with normal cerebrovascular autoregulation by causing dose-dependent cerebral vasodilation (1, 17, 27), which increases ICP by increasing cerebral vascular volume as a function of cerebral arterial and cerebral venous pressures. Thus, whereas head position in awake horses does not appear to influence ICP (Brosnan et al., unpublished observations), isoflurane-anesthetized horses do show profound positional effects. Consequently, body position may necessitate even greater consideration in horses anesthetized with higher end-tidal anesthetic concentrations or with concurrent intracranial disease so as to minimize risks of inadequate CPP and cerebral ischemia.

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