Induction and recovery characteristics and cardiopulmonary effects of sevoflurane and isoflurane in bald eagles

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Objective—To compare induction and recovery characteristics and cardiopulmonary effects of isoflurane and sevoflurane in bald eagles.

Animals—17 healthy adult bald eagles.

Procedures—Anesthesia was induced with isoflurane or sevoflurane delivered in oxygen via a facemask in a crossover design with 4 weeks between treatments. Eagles were intubated, allowed to breathe spontaneously, and instrumented for cardiopulmonary measurements. Time to induction, extubation, and recovery, as well as smoothness of recovery, were recorded.

Results—Administration of sevoflurane resulted in a significantly quicker recovery, compared with isoflurane. Temperature, heart rate, and respiratory rate significantly decreased over time, whereas systolic (SAP), diastolic (DAP), and mean arterial blood pressure (MAP) significantly increased over time with each treatment. Temperature, heart rate, SAP, DAP, and MAP were significantly higher with isoflurane. Blood pH significantly decreased, whereas Paco2 significantly increased over time with each treatment. Bicarbonate and total carbon dioxide concentrations significantly increased over time with each treatment; however, there was a significant time-treatment interaction. The Paco2 and arterial oxygen saturation increased over time with isoflurane and decreased over time with sevoflurane with a significant time-treatment interaction. Six eagles developed cardiac arrhythmias with isoflurane, as did 4 with sevoflurane anesthesia.

Conclusions and Clinical Relevance—Isoflurane and sevoflurane administration resulted in smooth, rapid induction of and recovery from anesthesia similar to other species. Isoflurane administration resulted in tachycardia, hypertension, and more arrhythmias, compared with sevoflurane. Sevoflurane was associated with fewer adverse effects and may be particularly beneficial in compromised bald eagles. (Am J Vet Res 2008;69:13–22)

Inhalation anesthesia is frequently used in avian patients for examination, diagnostic investigation, and surgical procedures, as well as for research and management purposes. Traditionally, isoflurane has been the agent of choice for avian anesthesia because of its rapid induction and recovery times and minimal cardiovascular adverse effects. However, raptors apparently have increased sensitivity to isoflurane anesthesia as indicated by development of cardiac arrhythmias, and bald eagles (Haliaeetus leucocephalus) are particularly sensitive. In raptors, isoflurane may cause short periods of excitement at induction and recovery, apnea, cardiac arrhythmias, and occasionally sudden death. In 1 study, isoflurane caused arrhythmias in 75% of anesthesia events in convalescent bald eagles, with second-degree atrioventricular block representing the most common type of arrhythmia. Other observed arrhythmias included third-degree atrioventricular block, sinus arrest, T-wave depression, and APC.

Sevoflurane is a volatile anesthetic agent that has potential advantages over isoflurane. Compared with some inhalation agents, sevoflurane has a low blood-

ABBREVIATIONS

- APC: Atrial premature contraction
- MAC: Minimum anesthetic concentration
- Tco2: Total carbon dioxide
- SaO2: Arterial oxygen saturation
- SAP: Systolic arterial blood pressure
- DAP: Diastolic arterial blood pressure
- MAP: Mean arterial blood pressure
- VPC: Ventricular premature contraction
gas solubility that allows for more rapid induction and recovery rates. Furthermore, sevoflurane is less irritating to the airways, as indicated by decreased breath holding, coughing, excitement, and laryngospasm in humans. Sevoflurane and isoflurane do not potentiate epinephrine-induced cardiac arrhythmias. However, isoflurane is associated with sympathoexcitatory activity at induction of anesthesia in humans, unlike sevoflurane. Sevoflurane has been evaluated in a limited number of avian species. However, sevoflurane has not been assessed in birds of prey and comparison of sevoflurane and isoflurane anesthesia in birds is scant in the literature.

Federally, bald eagles are considered threatened and are protected by their own act of Congress (Bald Eagle Protection Act of 1940). Consequently, bald eagles are a heavily managed species and are often subject to situations that require multiple anesthetic episodes for a variety of purposes, including veterinary care, captive animal and population management, and research. Because of the reported high sensitivity of raptors to isoflurane-induced adverse effects and the concern regarding high risk for cardiac arrhythmias in bald eagles anesthetized with this agent, a safer anesthetic agent for use in this species is desirable. To the authors’ knowledge, there are no reports of evaluations of sevoflurane in bald eagles. The purposes of the study reported here were to assess the safety of sevoflurane anesthesia and evaluate and compare sevoflurane and isoflurane anesthesia in captive bald eagles by evaluation of time to induction, extubation, and recovery; quality of recovery; and cardiopulmonary responses to each anesthetic agent over time.

Materials and Methods

Birds—Seventeen captive adult bald eagles (8 females and 9 males) housed in an outdoor enclosure at the American Eagle Foundation, Pigeon Forge, Tenn., participated in this study. Eagles had a mean ± SD weight of 4.32 ± 0.23 kg. Each bird was determined to be healthy on the basis of results of physical examination, hematology tests, plasma biochemistry profile, and protein electrophoresis performed 6 weeks prior to the study.

Experimental design—The study was completed in 2 sessions 4 weeks apart. Eagles were assigned to 2 groups in a crossover study. In random order, eagles were anesthetized once with isoflurane and once with sevoflurane. This project was approved by The University of Tennessee, Knoxville, Animal Care and Use Committee, and appropriate collection permits were obtained from the Tennessee Wildlife Resources Agency (Permit No. 1982) and the Department of the Interior US Fish and Wildlife Service (Permit No. MB093833-0).

Experimental study—Eagles were transferred to temporary individual housing units, and food was withheld for 18 hours prior to anesthesia. The birds were manually restrained and fitted with a leather hood. Alligator clip electrodes were placed on the skin at the leading edge of the patagium proximal to each carpus and at the cranial skin fold proximal to each stifle joint. Alcohol was placed on the skin at the site of electrode attachment to increase conductivity. A monitor was connected to the electrode leads, and a baseline ECG was recorded. The hood was removed, and anesthesia was induced via face mask attached to a Bains anesthetic circuit. Gas was delivered in oxygen at 2 L/min from a calibrated vaporizer specific for each inhalation agent at a setting of 4% for isoflurane and 7% for sevoflurane. Vaporizer settings were calculated on the basis of reported MAC in avian patients and the authors’ clinical experience with bald eagle anesthesia. When voluntary movement of the nictitating membrane was absent for 30 seconds, the birds were intubated with appropriately fitted noncuffed endotracheal tubes and placed in dorsal recumbency. A warm-air heating device was placed under the birds and maintained at 39°C. At 5 minutes after intubation, vaporizer settings were readjusted to 3.5% for isoflurane and 3% for sevoflurane, and gas was delivered in oxygen at 1.5 L/min for the remainder of the procedure. Following termination of anesthesia, birds were administered 100% oxygen via endotracheal tube for 1 minute. Birds were extubated when a swallow response was present or when they had signs of sensitivity to the endotracheal tube as indicated by coughing. Eagles were manually restrained during recovery and placed in a transportable carrier once fully conscious and able to stand unassisted.

Each anesthetic procedure lasted 40 minutes from the time of intubation. A lead II ECG was recorded for 1 minute immediately prior to induction of anesthesia (baseline), at 1-minute intervals for the first 5 minutes of anesthesia, at 5-minute intervals throughout the anesthetic session, and once during recovery. The ECGs were standardized at 1 cm = 2 mV and a chart speed of 50 mm/s. All ECG tracings were screened for arrhythmias, and abnormalities were recorded. Second-degree heart block was determined when at least 1 but less than the majority of P waves were not associated with a QRS complex. Sinus arrhythmia was determined by > 10% variation in the R-R interval, whereas sinus arrest was indicated by an R-R interval twice the length of the normal R-R interval for each individual bird. Ventricular premature contractions were determined by aberrant QRS complexes. Atrial premature contractions were determined by electrical activity (P wave) that occurred early (in the preceding beat’s QRS or T complex) and was followed by a normal-appearing early QRS complex.

The heart rate, respiratory rate, and esophageal temperature were measured at 5, 10, 15, 20, 25, 30, and 40 minutes after intubation. To monitor direct blood pressure, the ulnar artery was identified and aseptically prepared, and a 22-gauge indwelling catheter was inserted. The catheter was stabilized with tissue glue, flushed with heparinized saline (0.9% NaCl) solution, and capped. A 22-gauge needle connected the capped arterial catheter to a transducer and a pressure line filled with saline solution, which was connected to a monitor for blood pressure observation. The wing was stabilized so the catheter was at the level of the heart, and appropriate placement of the catheter was confirmed by observation of characteristic wave forms. Monitoring of direct blood pressure commenced immediately following successful placement of an arterial catheter, and recordings began at the next 5-minute time interval.
Arterial blood samples were collected for blood gas analysis at 10, 25, and 40 minutes after intubation. A 0.5-mL sample of blood was collected from the capped arterial catheter for disposal to reduce saline solution dilution. This volume was selected to adequately flush the catheter (being 10 times the fluid capacity within the cap and catheter) while ensuring safe amounts of blood were removed during the duration of the study. A 0.5-mL arterial blood sample was collected into ice-chilled syringes, transferred to an ice-chilled lithium heparin blood tube, and briefly mixed. Samples were immediately drawn back into a syringe, needles were capped with a rubber stopper, and samples were stored on ice. Arterial samples were analyzed within 15 minutes of collection by use of a blood gas analyzer for pH, PaCO₂, PaO₂, Hct, sodium concentration, potassium concentration, and ionized calcium concentration. Calculated results included HCO₃⁻ and, TC₀₂ concentrations, and SaO₂. Results were corrected for esophageal temperature.

Determination of induction and recovery characteristics—Time to induction and extubation, time to recovery, and smoothness of recovery were recorded for each anesthetic procedure. Time to induction was defined as the time from initial delivery of gaseous anesthesia until a medium level of anesthesia was achieved as determined by good muscle relaxation and absent voluntary blinking. Time to extubation was defined as the time from ceasing anesthetic gas administration until the presence of a cough, swallow reflex, or head shaking. Recovery time was defined as the time from terminating gaseous anesthesia until the bird was able to hold its head erect while unassisted. The quality of recovery was assigned a score on a scale of 1 to 3 (1 = minimal wing flapping and vocalization, 2 = wing flapping and vocalization for < 30 seconds, and 3 = wing flapping and vocalization for ≥30 seconds).

Statistical analysis—For all continuous response variables, mixed-effects repeated-measures ANOVA was used to test for main effects of treatment and time as well as their interaction. The MIXED procedure of the software program was used for the calculations. Post hoc comparisons of treatment means within each time or between treatments were performed by use of Bonferroni-corrected multiple comparisons. A value of P < 0.05 was considered significant. Model adequacy was assessed via plots of standardized residuals. Respiratory rate data were log-transformed to stabilize variances and back-transformed for presentation. For the ordered categoric responses, cross tabulations of the response categories across treatment for each time were prepared. Within the complex experimental design, the small sample size precluded calculation of inferential statistics for the categoric responses.

Results

Induction and recovery—Mean ± SE induction times for isoflurane and sevoflurane were 200.3 ± 16.5 seconds and 166.1 ± 16.5 seconds, respectively. Birds did not struggle during induction with either anesthetic agent, and no adverse reaction was elicited during intubation. Mean ± SE times to extubation for isoflurane and sevoflurane were 184.4 ± 30.3 seconds and 146.3 ± 30.1 seconds, respectively. No significant difference was detected between treatment groups for time to induction (P = 0.16) and time to extubation (P = 0.19). Mean ± SE times to recovery for isoflurane and sevoflurane were 323.7 ± 64.0 seconds and 195.1 ± 63.0 seconds, respectively. Recovery time was significantly (P = 0.02) shorter with sevoflurane, compared with isoflurane. Six of 17 eagles received a recovery score of 2 during 9 of 34 anesthesia sessions. Three eagles received a score of 3 during 2 of 3 sessions.

Figure 1—Mean ± SE heart rate of spontaneously ventilating bald eagles (n = 17) during isoflurane and sevoflurane anesthesia. *Individual values are significantly (P ≤ 0.05) different from the first measurement of the variable.

Figure 2—Geometric mean ± 95% confidence interval log respiratory rate of the bald eagles in Figure 1. See Figure 1 for key.
of 2 with both sevoflurane and isoflurane, and 3 with sevoflurane only. All remaining eagles (25/34) received a recovery score of 1.

Cardiorespiratory measurements—Mean heart rate was increased throughout isoflurane and sevoflurane anesthesia (Figure 1). Heart rate was significantly \((P = 0.01)\) higher during isoflurane anesthesia, compared with sevoflurane, and heart rate significantly \((P = 0.02)\) decreased over time with both agents. During sevoflurane anesthesia, heart rate was significantly \((P < 0.01)\) lower at 30 \((215.2 \pm 16.7\) beats/min) and 40 \((218.4 \pm 16.7\) beats/min) minutes after induction, compared with the first measurement of the variable.

The geometric mean and 95% confidence intervals for respiratory rate during isoflurane and sevoflurane anesthesia were determined (Figure 2). There was a significant \((P < 0.01)\) decrease in respiratory rate over time for each agent; however, there was no significant difference \((P = 0.24)\) between treatment groups or for time-treatment interaction \((P = 0.88)\).

Esophageal temperature was significantly \((P < 0.01)\) higher during isoflurane anesthesia (Figure 3), and there was an initial increase in body temperature in the first 5 minutes, followed by a significant \((P < 0.01)\) decrease over time for both agents. At the end of both anesthesia sessions, the mean body temperatures were mildly decreased, compared with reference limits for avian patients.\(^6\)

Placement of an arterial catheter was successful in 13 eagles during isoflurane anesthesia and 11 eagles during sevoflurane anesthesia. The SAP, DAP (Table 1), and MAP (Figure 4) were significantly \((P < 0.01)\) higher with isoflurane, compared with sevoflurane. Each variable followed a similar pattern for both anesthetic agents, with a significant \((P < 0.01)\) increase over time.

Complete blood gas analysis was performed on 11 eagles at 10 and 40 minutes after induction with isoflurane and sevoflurane and on 12 and 10 eagles at 25 minutes after induction during isoflurane and sevoflurane anesthesia, respectively (Table 2). There was no significant treatment effect for blood gas variables. Blood pH significantly \((P < 0.01)\) decreased over time accompanied by a significant \((P < 0.01)\) increase in PaCO\(_2\) (Figure 5) for each treatment group; no significant time-treatment effect was present for either variable. Blood pH remained within reference ranges for awake birds.\(^7\) There was a significant change over time for HCO\(_3^-\) \((P < 0.01)\) and TCO\(_2\) \((P < 0.01)\) concentrations as well as a significant time-treatment effect \((P = 0.03)\) for each variable. Bicarbonate and TCO\(_2\) values steadily increased throughout anesthesia with isoflurane. In contrast, HCO\(_3^-\) and TCO\(_2\) values had an initial increase followed by a mild decrease during sevoflurane anesthesia. There was a significant time-treatment effect for PaO\(_2\) \((P = 0.01;\) Figure 6) and SaO\(_2\) \((P = 0.04)\). Both PaO\(_2\) and SaO\(_2\) increased throughout anesthesia with isoflurane. During sevoflurane anesthesia, these values did not change initially yet this was followed by a marked decrease for each variable. Despite the significant time-treatment effect, time effect and treatment effect were not significantly different. No significant differences between treatment groups or over time were found with respect to Hct and sodium, potassium, and ionized calcium concentrations.

Six eagles developed arrhythmias with isoflurane and 4 eagles with sevoflurane anesthesia (Table 3). Three eagles that had arrhythmias with isoflurane also had arrhythmias during sevoflurane anesthesia.

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### Table 1—Mean ± SE direct SAP and DAP at various times in spontaneously breathing bald eagles \((n = 17)\) anesthetized with isoflurane and sevoflurane.

<table>
<thead>
<tr>
<th>Time (min)</th>
<th>Isoflurane*</th>
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<th>Sevoflurane*</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>SAP (mm Hg)†</td>
<td>DAP (mm Hg)†</td>
<td>SAP (mm Hg)†</td>
<td>DAP (mm Hg)†</td>
</tr>
<tr>
<td>5</td>
<td>183.0 ± 17.2</td>
<td>158.0 ± 16.9</td>
<td>128.8 ± 15.0</td>
<td>129.2 ± 15.2</td>
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<tr>
<td>10</td>
<td>178 ± 14.4</td>
<td>139.2 ± 14.5</td>
<td>138.1 ± 13.9</td>
<td>134.2 ± 14.3</td>
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<tr>
<td>15</td>
<td>180.9 ± 14.4</td>
<td>142.3 ± 14.5</td>
<td>138.1 ± 13.8</td>
<td>130.5 ± 14.1</td>
</tr>
<tr>
<td>20</td>
<td>206.9 ± 14.3</td>
<td>163.3 ± 14.3</td>
<td>142.7 ± 13.8</td>
<td>129.3 ± 14.1</td>
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<tr>
<td>25</td>
<td>208.4 ± 14.3</td>
<td>164.4 ± 14.2</td>
<td>147.2 ± 13.8</td>
<td>153.0 ± 14.1</td>
</tr>
<tr>
<td>30</td>
<td>204.5 ± 14.4</td>
<td>164.4 ± 14.4</td>
<td>146.3 ± 13.6</td>
<td>138.3 ± 13.9</td>
</tr>
<tr>
<td>40</td>
<td>209.3 ± 14.4</td>
<td>171.6 ± 14.4</td>
<td>163.0 ± 13.5</td>
<td>147.1 ± 13.8</td>
</tr>
</tbody>
</table>

*All values were significantly \((P < 0.01)\) different between treatment groups. †Within a column, values significantly \((P < 0.01)\) increased over time.

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The ECG recordings of 1 eagle had too much artifact to assess cardiac rhythm between 2 and 20 minutes during anesthesia with sevoflurane. Three eagles had second-degree heart block with isoflurane, 2 of which developed heart block within 10 minutes of induction that continued through recovery. Similarly, 1 of these 2 eagles developed second-degree heart block during sevoflurane anesthesia within 10 minutes of induction, which continued through recovery. Three eagles developed APCs during isoflurane anesthesia—1 prior to induction (baseline), 1 at 30 minutes after induction, and 1 during recovery. The eagle that developed APCs prior to induction with isoflurane also had multiple APCs 30 minutes after induction with sevoflurane, and this arrhythmia continued through recovery. During isoflurane anesthesia, 1 eagle had several VPCs prior to anesthesia and 1 VPC during recovery. This eagle also had a single VPC 3 minutes after induction during sevoflurane anesthesia. Sinus arrest occurred in 2 eagles during induction of anesthesia—1 with isoflurane and 1 with sevoflurane. During isoflurane anesthesia, 1 eagle developed second-degree heart block and APC simultaneously at 30 minutes after induction. In addition, 1 eagle developed second-degree heart block, VPC, and sinus arrhythmia during isoflurane anesthesia, with each arrhythmia recorded at different times. Multiple arrhythmias were not observed in any of the eagles during sevoflurane anesthesia.

**Discussion**

Isoflurane and sevoflurane resulted in a smooth, rapid induction to and a relatively smooth recovery from anesthesia in adult bald eagles, which is consistent with previous reports\(^\text{9,10,18,19}\) in birds. Induction time was more rapid with sevoflurane, but this difference was not significant. Following sevoflurane anesthesia in eagles, recovery time was significantly shorter and some birds had an excitatory response as indicated by uncoordinated wing flapping during recovery; however, this excitatory response was minimal overall. Quandt and Greenacre\(^\text{8}\) found no significant difference in recovery time between sevoflurane and isoflurane in psittacine birds; however, birds seemed to become alert sooner and were less ataxic with sevoflurane. In the present study, the increased frequency of activity observed in eagles during recovery from sevoflurane versus isoflurane may be attributed to the shortened recovery time; yet, a more rapid recovery may be desirable following extensive anesthetic periods or in debilitated eagles. A more rapid induction and recovery with sevoflurane are consistent with its lower partition coefficient.\(^\text{8}\) To the authors’ knowledge, this is the first assessment of induction and recovery characteristics of sevoflurane in a bird of prey species.

In this study, tachycardia was present at the beginning of all anesthetic sessions as indicated by comparison with reported\(^\text{10,18}\) baseline values in spontaneously ventilating chickens (173 ± 37 beats/min and 190 ± 17 beats/min, respectively) and the European common buzzard (Buteo buteo; mean, 110 beats/min).\(^\text{19}\) This tachycardia was probably stress induced and caused by manual restraint during induction. With sevoflurane, tachycardia appeared to resolve over time and approached reported values for heart rate in awake birds of comparable size.\(^\text{21}\) Furthermore, heart rate was significantly lower with sevoflurane than with isoflurane, which is consistent with 1 report\(^\text{22}\) in human patients. There is evidence that sevoflurane stabilizes heart rate in humans and pigs\(^\text{23}\) as well as cats.\(^\text{24}\) Alternatively, inhalation anesthesia can depress heart rate in birds.\(^\text{19}\) In contrast, the findings of the present study were inconsistent with the non significant, dose-dependent increase in heart rate detected in spontaneously ventilating chickens anesthetized

<table>
<thead>
<tr>
<th>Variable</th>
<th>Time after isoflurane induction (min)</th>
<th>Time after sevoflurane induction (min)</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>10 (n = 11)</td>
<td>25 (n = 12)</td>
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<tr>
<td>pH</td>
<td>7.42 ± 0.01</td>
<td>7.33 ± 0.01</td>
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<tr>
<td>Tco, (mM)</td>
<td>24.3 ± 0.6</td>
<td>26.5 ± 0.6</td>
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<tr>
<td>HCO(_3) (mmol/L)</td>
<td>23.2 ± 0.5</td>
<td>25.2 ± 0.5</td>
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<td>Hct (%)</td>
<td>39.7 ± 0.8</td>
<td>39.3 ± 0.8</td>
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<td>Na(^+) (mM)</td>
<td>151.3 ± 1.0</td>
<td>152.3 ± 1.0</td>
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<td>K(^+) (mM)</td>
<td>4.5 ± 0.2</td>
<td>4.2 ± 0.2</td>
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<tr>
<td>iCa(^+) (mM)</td>
<td>1.3 ± 0.0</td>
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The number in parentheses represents the number of eagles assessed. iCa\(^+\) = Ionized calcium.

![Figure 4—Mean ± SE direct MAP of the bald eagles in Figure 1.](image-url)
with sevoflurane.\textsuperscript{25} Additionally, spontaneously ventilating chickens\textsuperscript{9} and cranes\textsuperscript{12} had higher heart rates than those undergoing controlled ventilation with 2 MAC of sevoflurane and isoflurane, respectively.

In contrast with sevoflurane, tachycardia was detected in bald eagles throughout isoflurane anesthesia and was consistent with sinus tachycardia reported in ducks anesthetized with isoflurane.\textsuperscript{16} Yet this is inconsistent with European common buzzards that had a significantly lower heart rate with isoflurane, compared with awake values.\textsuperscript{20} Isoflurane acts directly on the myocardium, resulting in an increase in heart rate\textsuperscript{26} and thus predisposing the myocardium to ischemic events.\textsuperscript{22} In contrast to similar cardiovascular effects reported with isoflurane and sevoflurane in mammals, isoflurane appears to induce tachycardia in bald eagles because other causes for tachycardia, including pain, pyrexia, anaphylactic reactions, hypoxemia, hypokalemia, and anemia,\textsuperscript{27} were not detected in this study. In mammals, hypercapnia may result in increased heart rate; however, its effect on the heart rate of anesthetized birds is unknown.\textsuperscript{10}

Direct arterial blood pressure values have not been reported for awake bald eagles. Preanesthetic direct blood pressure values would have been valuable in this study but were not determined as this would have added an additional handling session and stress to the eagles. Consequently, no comparison of direct arterial blood pressure values can be made between awake and anesthetized eagles. In 1 study,\textsuperscript{4} mean \( \pm \) SD indirect MAP of conscious bald eagles was 123.5 \( \pm \) 61.89 mm Hg and the MAP decreased with time during isoflurane anesthesia. In contrast, bald eagles anesthetized with isoflurane in the present study were hypertensive, compared with eagles of the aforementioned study, as indicated by > 20% change\textsuperscript{22} between mean MAP values.

Table 3—Arrhythmias (values indicate number of affected birds) in the bald eagles in Table 1.

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*Arrhythmia occurred during mask induction.
— = No affected birds. Pre = Preinduction. Rec = Recovery. 2° HB = Second—degree heart block. SA = Sinus arrhythmia. SArr = Sinus arrest.
were hypertensive, compared with other avian species undergoing isoflurane anesthesia.

Isoflurane and sevoflurane cause a decrease in MAP in controlled and spontaneously ventilated avian patients.13 19 Naganobu et al10 revealed a decrease in MAP in chickens anesthetized with sevoflurane; however, this decrease was dose dependent during controlled ventilation but not in spontaneously ventilating birds. In the present study, it is unlikely that spontaneous ventilation was responsible for the difference in blood pressures between treatment groups because all eagles were subjected to the same experimental protocol. Although a light plane of anesthesia may cause increased blood pressure, all eagles appeared to be at a similar depth of anesthesia. Thus, plane of anesthesia was an unlikely cause for higher arterial blood pressure in bald eagles anesthetized with isoflurane compared with sevoflurane. Hypercarbia is a potential cause of hypertension during inhalation anesthesia.16 In the present study, the eagles became hypercapnic over time with both agents with no significant difference between treatments, suggesting that hypercarbia was not the cause for hypertension in the eagles anesthetized with isoflurane. Other causes of hypertension, including pain and fever,27 were not present in eagles during this study. Furthermore, mean SAP, DAP, and MAP were significantly higher with isoflurane than with sevoflurane, suggesting a relatively hypertensive state. Consequently, results of the present study suggest that isoflurane administered at vaporizer settings of 3.5% for maintenance anesthesia induces hypertension in spontaneously ventilating bald eagles.

Inhalational anesthetics cause a dose-dependent respiratory depression as indicated by an increase in PaO2 in all species, and birds may be particularly sensitive to this effect. Avian lungs possess unique CO2-sensitive intrapulmonary chemoreceptors that are sensitive to changes in CO2 but not hypoxia.28 Ludders et al4 suggested that birds may have increased sensitivity to inhalation anesthesia because of the effects of anesthetic agents on these chemoreceptors, resulting in greater respiratory depression in birds than mammals. In the present study, isoflurane and sevoflurane resulted in development of substantial respiratory depression over time in spontaneously ventilating eagles as indicated by an increase in Pco2, and with spontaneously ventilating chickens,10 cranes,12 and human volunteers38 administered sevoflurane, isoflurane, or both, respectively. Furthermore, eagles developed respiratory acidosis with both agents as indicated by increased Pco2 values10,11,13 associated with a significant decrease in pH. Similarly, spontaneously ventilating cranes12 and ducks13 anesthetized with isoflurane at 2 and 1.5 MAC, respectively, developed respiratory acidosis. In contrast, Pco2 values were maintained within reference ranges in avian patients undergoing controlled ventilation during isoflurane and sevoflurane anesthesia.10,12,25 The respiratory depression accompanied by respiratory acidosis in the bald eagles reported here supports recommendations for intermittent positive pressure ventilation in avian patients during inhalation anesthesia.3,29

Despite respiratory depression, the eagles remained in a state of adequate oxygenation, as indicated by increased PaO2 concentrations. Partial pressure of O2 increased with isoflurane, whereas it initially remained steady with sevoflurane and then decreased. Despite these differences, PaO2 values were comparable between isoflurane and sevoflurane treatments and remained greater than reference ranges for awake birds.37,31 Overall, PaO2 values in eagles were lower than in healthy dogs and cats administered inhalant anesthetics delivered in 100% O2.32 This may be attributable to the unique anatomic features of the avian respiratory system in which only 10% of the respiratory tract volume (10 to 20 mL/kg) undergoes gaseous exchange, compared with 96% of the respiratory tract volume (45 mL/kg) in the mammalian lung.3 Another cause could be increased vagal tone as the avian lung has substantial vagal and sympathetic innervations. In particular, the entrance to the parabronchi is surrounded by smooth muscle which contracts when the vagus nerve is stimulated.33 This result in narrowing of the parabronchi, the site for gaseous exchange. Partial pressure of O2 in bald eagles anesthetized with both gaseous agents was lower than reported values in other avian species during isoflurane anesthesia, including African grey parrots receiving intermittent positive-pressure ventilation1 and spontaneously breathing pigeons30 and emus.31 The reason for differences between avian species is not known, but this was not considered clinically important since all eagles remained in a state of adequate oxygenation.

The normal avian body temperature range is 40° to 44.4°C.31,34 During anesthesia, supplemental heat is recommended for avian patients because of a substantial decrease in body temperature over time.1 In the present study, a forced-air warming blanket delivering a constant temperature of 39°C was used during each anesthetic session. Despite a supplemental heat source, the body temperature of the bald eagles significantly decreased over time and decreased to less than the reported reference limit with both anesthetic agents. In this study, the mean body temperature of the eagles during isoflurane anesthesia was similar to previously reported temperature ranges in bald eagles1 and sandhill cranes13 anesthetized with isoflurane. In 1 study,4 mean cloacal temperature in bald eagles anesthetized with isoflurane over 2 anesthesia sessions ranged from 40.36 ± 0.45°C to 41.2 ± 0.39°C. In contrast, the body temperature of the eagles during sevoflurane anesthesia was significantly lower, compared with isoflurane. A low body temperature has been associated with bradycardia in birds.3 This association was not observed in the bald eagles with a subnormal temperature possibly because the decrease in body temperature was only slightly less than reported reference limits. An esophageal probe was selected for its accuracy in monitoring core body temperature of birds.3 Occasionally, digestive fluid was identified in the esophagus of the eagles at the end of anesthesia despite withholding food for at least 18 hours. It should be noted that inaccurate readings secondary to regurgitation may occur with esophageal probes.

The MAC for isoflurane and sevoflurane has been determined in a limited number of avian species. Mean MAC (± SD) for isoflurane in chickens and ducks is 1.34 ± 0.14% and 1.3 ± 0.23%, respectively12,13 whereas the MAC for sevoflurane in chickens is 2.21 ± 0.32%.25
These values are consistent with MACs reported in mammals and support the hypothesis that MAC appears to remain relatively constant across taxonomic groups for inhalation anesthetics. The present study, we used previously determined MAC values for other avian species combined with the authors' clinical experience to predict vaporizer settings. Vaporizer settings corresponded to 3.1 MAC and 3.2 MAC during induction of anesthesia with isoflurane and sevoflurane, respectively. Vaporizer settings corresponded to 2.7 MAC and 2.3 MAC during maintenance of anesthesia with isoflurane and sevoflurane, respectively. Despite having the vaporizer settings > 2 MAC for birds, some eagles remained at a light plane of anesthesia as indicated by occasional gross movements caused by stimulation during anesthesia with each agent. Spontaneous ventilation is the most likely cause of the light plane of anesthesia observed in some birds despite high vaporizer settings.

Monitoring end-tidal anesthetic concentrations is the ideal means of determining the amount of inhaled anesthetic in an animal. We did not monitor end-tidal anesthetic concentration in the present study; however, we did record the vaporizer setting, and because a nonrebreathing system was used to deliver the inhaled anesthetic, the inspired concentration of inhaled anesthetic was essentially the same as the vaporizer setting. Although an equipotent dose of anesthetic agents was not administered to the 2 groups, all eagles subjectively appeared to remain at a similar depth of anesthesia.

The sympathetic and parasympathetic branches of the autonomic nervous system are responsible for neural control of the heart. Parasympathetic control of the heart is provided via the vagus nerve, and increased vagal tone can result in several changes in heart rhythm, including sinus bradycardia, first-degree heart block, second-degree heart block, sinus arrest, and sinus arrhythmia. One eagle developed sinus arrhythmia prior to second-degree heart block with isoflurane, suggesting increased vagal tone as the cause of arrhythmias in this bird. Additionally, second-degree heart block occurred in 3 eagles during isoflurane anesthesia and 1 eagle during sevoflurane anesthesia. Gentle ocular pressure, which inadvertently may occur during mask induction, can lead to a reflex increase in vagal tone. In this study, 2 eagles developed sinus arrest during mask induction, 1 with isoflurane and 1 with sevoflurane. Sinus arrest resolved following removal of the mask and intubation. Although slightly more eagles had vagus-associated arrhythmias during isoflurane anesthesia (n = 4), compared with sevoflurane anesthesia (2), a causal relationship between the inhalation anesthetic agent and control over vagal tone could not be determined.

Second-degree heart block was the arrhythmia most frequently observed in this study but occurred at a low frequency, as did sinus arrhythmia and sinus arrest. According to Lumeij and Ritchie, sinus arrest is a normal physiologic occurrence in birds and second-degree heart block can occur in a small percentage of clinically normal birds. This would suggest that observations of arrhythmias in birds at a low frequency should be expected and is consistent with the findings of the present study. Previous studies have detected similar arrhythmias in birds during inhalation anesthesia at a much higher frequency. In convalescent and recovered bald eagles anesthetized with isoflurane, second-degree heart block (18/24) was the most common arrhythmia, followed by sinoatrial block (8/24) and sinus arrest (5/24). In another study, arrhythmias were observed in 63.3% of free-living birds (n = 79) anesthetized with isoflurane, with sinus arrhythmia being the most common (96%), followed by sinus arrest (8%; some birds experienced more than 1 arrhythmia). The low frequency of arrhythmias in bald eagles in the present study was likely observed because clinically normal adult bald eagles habituated to frequent handling may be less prone to arrhythmias during anesthesia, compared with eagles with physiologic or capture-related stress.

Atrial premature contractions are usually associated with structural cardiac abnormalities; metabolic; systemic; or inflammatory disease; and drug-induced toxicosis in dogs, but they are occasionally detected in clinically normal dogs. Atrial premature contractions occurred in more eagles with isoflurane anesthesia (n = 3) than with sevoflurane anesthesia (1). This arrhythmia occurred in low numbers during this study and was consistent with previous reports in eagles and other free-living birds anesthetized with isoflurane. The importance of the APCs could not be determined in this group of eagles because other means of assessing heart disease in birds such as echocardiography and histologic examination were not performed; thus, underlying heart disease could not be ruled out. However, none of the eagles had any clinical signs or hematologic, plasma serum biochemical, or protein electrophoresis results consistent with cardiac disease or other infectious or inflammatory diseases at least 1 year prior to, during, and 1 year after the study.

Ventricular premature contractions are often associated with primary or secondary cardiac diseases in dogs but are occasionally detected in clinically normal dogs. In birds, VPC has been associated with hypokalemia, thiamine deficiency, vitamin E deficiency, Newcastle disease, avian influenza viruses, and lead and digoxin toxicosis. In addition, VPC has been associated with inhalation anesthetic agents in birds, in particular halothane and isoflurane associated with hypercapnia. In the present study, 1 eagle had VPCs prior to induction and during recovery with isoflurane, yet no VPCs were observed during anesthesia. Partial pressure of CO₂ was not available during induction for the affected eagle, but hypercarbia was present immediately prior to recovery in this bird. Presumably, hypercapnia was absent prior to induction of anesthesia and highest at the end of each anesthetic session. Thus, the timing of the arrhythmia suggested that stress was the most likely cause of the VPCs because it is unlikely that the eagle had other potential causes of VPCs, as judged on the basis of clinical history, physical examination, and laboratory results obtained prior to and during anesthesia.

In dogs and cats isoflurane controls VPCs by increasing the myocardium's threshold to epinephrine. Sevoflurane appears to have a similar, if not better, effect of inhibiting VPCs in dogs, compared with isoflurane. The effect of these anesthetic agents on the frequency of VPCs in bald eagles is unknown. In 1 study, ECG of domestic fowl during isoflurane anesthesia (n = 2,200)
revealed runs of VPCs (n = 15); some of the fowl died and had evidence of chronic heart disease at necropsy. The authors believed isoflurane was not associated with the arrhythmias because the severity and frequency of arrhythmic episodes were increased in conscious birds, compared with those anesthetized. This arrhythmia-sparing effect of isoflurane in birds has also been suggested by Goelz et al.18 In our study, VPCs were not observed in the single affected eagle during isoflurane anesthesia despite hypercarbia but were present during recovery. This observation supports the hypothesis that isoflurane may have a sparing effect on the heart with respect to VPCs in bald eagles; however, causality cannot be proven because only 1 bird had VPCs associated with isoflurane anesthesia. Interestingly, the same eagle had VPCs 3 minutes after induction with sevoflurane anesthesia.

A previous study4 in convalescing and recovered bald eagles anesthetized with isoflurane found that most arrhythmias occurred at induction or recovery of anesthesia. Studies monitoring ECGs in healthy adult raptors while awake, compared with those during isoflurane anesthesia, are limited in the literature. One study20 recorded ECGs in conscious and isoflurane-anesthetized common buzzards during echocardiography, but presence or absence of arrhythmias was not discussed. Electrocardiography of conscious peregrine falcons (Falco peregrinus brookii) revealed normal sinus rhythm,45 yet no comparison was made with anesthetized individuals. Further evaluation of ECGs in awake and anesthetized birds is necessary to support or refute the hypothesis of isoflurane’s sparing effects on the myocardium.

Normal sinus rhythm was observed throughout anesthesia in 11 of 17 eagles anesthetized with isoflurane. Normal sinus rhythm has been observed in buzzards,11,20 sandhill cranes,12 and ducks28 anesthetized with isoflurane. In addition, 13 of 17 eagles had normal sinus rhythm throughout sevoflurane anesthesia. Similarly, chickens25,24 and adult psittacine birds of different species7 anesthetized with sevoflurane did not develop any ventricular arrhythmias.

Isoflurane and sevoflurane resulted in a smooth, rapid induction to and recovery from anesthesia in captive adult bald eagles. Similar cardiovascular changes were observed during anesthesia with each agent, although slightly more clinically important and frequent cardiac arrhythmias occurred with isoflurane. Sevoflurane anesthesia was associated with fewer adverse effects overall, suggesting that sevoflurane may be preferable to isoflurane lor use in bald eagles.

References