Introduction

The most critical function of the cardiovascular system is to circulate blood continuously, ensuring the adequate delivery of oxygen and survival of cells and tissues. The body can survive deprivation of food and water far longer than it can survive deprivation of oxygen and lack of perfusion; lack of oxygen delivery can trigger the complicated cascade that leads to temporary, permanent, or irreversible cell death. As such, the simplest definition of cardiovascular disease is the decreased ability of this system to ensure adequate oxygen delivery for day-to-day survival.

Nearly all anesthetic drugs compromise cardiovascular function via a single or multiple mechanism(s) and can severely compromise oxygen delivery in patients with underlying cardiac disease. Cardiovascular goals during anesthesia include maintenance of oxygen delivery and homeostasis when using drugs that knowingly disturb the system. However, this goal becomes complicated in patients with underlying cardiovascular disease and increasingly more difficult when severe pathology is present. In patients with significant cardiovascular disease, the optimization of oxygen delivery requires a complete understanding of the mechanisms underlying the pathology, as well as the anesthetic drugs, patient support, and monitoring tools available. The most difficult challenge when faced with these patients is how to balance the pathophysiology of disease against the effects of anesthetic drugs and to subsequently individualize an anesthetic plan that minimizes cardiovascular compromise.

It is difficult to predict all possible combinations of patient signalment and temperament, cardiovascular and comorbid conditions, clinicopathologic abnormalities, surgical procedures, and their effects on anesthetic drug choices. Thus, studies have tended to focus more on describing the specific cardiac disease or cardiac effects of specific anesthetics and less on their combinations. This approach leaves the difficult task of knowing how to choose the appropriate anesthetic plan for an individual patient. The goal of this chapter is to provide an overview of cardiovascular physiology and pathophysiology; anesthetic agents; and cardiovascular patient evaluation, monitoring, and support during anesthesia to help the clinician prepare anesthetic plans for patients with mild to significant cardiovascular disease.

Cardiovascular physiology

Tissue perfusion and oxygen delivery

The mathematical definition of oxygen delivery \((\text{DO}_2)\) is the product of oxygen content \((\text{CaO}_2, \text{ml O}_2 \text{ dl}^{-1} \text{ blood})\) and cardiac output \((\text{CO}, \text{ l min}^{-1}; \text{Figure 1.1})\).

Perfusion and the ability to deliver oxygen suffer either if the ability of the heart to eject blood \((\text{CO})\) is compromised or if the ability of the blood to carry oxygen \((\text{CaO}_2)\) is reduced. Although decreases in \(\text{CaO}_2\) significantly affect tissue oxygenation, the focus of this chapter is on treating reductions in \(\text{CO}\) associated with cardiac disease.

\[
\text{Oxygen delivery} = \frac{\text{O}_2 \text{ delivered min}^{-1}}{\text{liters ejected/min}} \times \frac{\text{ml O}_2 \text{ carried l}^{-1}}{\text{blood}}
\]

\(\text{DO}_2\) \quad \text{“CO”} \quad \text{“CaO}_2\)
Blood pressure and cardiac output
It is critical to monitor blood pressure (BP) during anesthesia and is our best, yet indirect, clinical indicator of perfusion. BP helps determine how anesthesia affects the patients’ ability to perfuse their tissues and, as such, is used as a tool to treat perfusion abnormalities. However, BP is not a component of the mathematical definition of oxygen delivery: \( DO_2 = CO \times CaO_2 \). It is useful to assess BP in an attempt to estimate changes in CO, as CO is rarely measured in nonresearch patients.

Systolic arterial pressure (SAP) is the peak pressure measured in the artery or arteriole during one cardiac cycle and is due to a number of variables, including stroke volume (SV, volume ejected during one ventricular contraction), velocity of left ventricular ejection, arterial resistance, and the viscosity of blood. Diastolic arterial pressure (DAP) is the lowest arterial pressure measured during the cycle and is affected by blood viscosity, arterial compliance, and length of the cardiac cycle. Mean arterial pressure (MAP) is not the arithmetic mean pressure in the vessel and is always a calculated number. Various formulae exist to calculate MAP as follows: (1) \( MAP = DAP + \frac{1}{3} \times (SAP - DAP) \) or (2) \( MAP = (SAP + (2 \times DAP))/3 \). In regards to perfusion, the most important of these values is MAP, as the time during the cardiac cycle spent at SAP is very short, whereas the time spent at MAP is much longer (Figure 1.2).

Mean arterial pressure and autoregulation
Autoregulation is the automatic adjustment of blood flow through a tissue regardless of the MAP driving blood through the tissue (Figure 1.3). In other words, autoregulation is the unconscious adjustment of arterial and arteriolar smooth muscle tone to maintain a constant blood flow through a tissue across a wide range of pressures. Classically, this is thought to occur between MAPs of \( \sim 60 - 160 \) mmHg and is due to adaptive metabolic, myogenic, and neurogenic feedback mechanisms. Outside of this interval, tissue or organ blood flow is substantially altered, potentially resulting in reduced or nonuniform perfusion patterns.

Hypotension
MAPs <60 mmHg (or SAP <90 mmHg) have historically been considered the minimum recommended pressures in small animals associated with adequate tissue oxygen delivery. However, a MAP of \( \sim 60 \) mmHg may not actually reflect adequate perfusion for a number of reasons. Firstly, studies investigating autoregulation are routinely performed in nonanesthetized patients. Neurogenic mechanisms for autoregulation depend on sympathetic nervous system (SNS) input. Anesthetic agents depress both the conscious and unconscious (autonomic) nervous systems. Since the SNS tone is substantially reduced during

Figure 1.2 Diagram of arterial pulse waveform. Mathematically, mean arterial pressure is \( 1/3 \) the difference between systolic arterial pressure and diastolic arterial pressure, added to the diastolic arterial pressure. Mean arterial pressure is considered the pressure of perfusion, as more time in the cardiac cycle is spent closer to mean arterial pressure as compared to systolic arterial pressure. Total cycle length is estimated at 400 ms for illustration and determined by the heart rate and other cardiovascular variables.
Chapter 1. Cardiovascular disease

Autoregulation

Zone of autoregulation

Perfusion is pressure dependent

Blood flow

Mean arterial pressure

60 70 100 160

Buffer zone

Figure 1.3 Principles of autoregulation. Between mean arterial pressures (MAPs) of ~60 and 160 mmHg, blood flow through a tissue capillary bed is held constant by autoregulatory mechanisms. At MAP > ~160 mmHg and at MAP < ~60 mmHg, autoregulation of blood flow is lost and blood flow through capillary beds becomes pressure dependent; tissues are either overperfused or underperfused.

Figure 1.4 Determinants of mean arterial blood pressure. Mean arterial blood pressure (MAP) is the product of cardiac output (CO), the volume of blood ejected by the heart per minute, and systemic vascular resistance (SVR), the degree of vasodilation (decreased SVR) or vasoconstriction (increased SVR). Note that MAP is not a component of oxygen delivery. Cardiac output is the product of heart rate (HR) and stroke volume (SV), the volume of blood ejected from the heart per cardiac cycle. Stroke volume is determined by the volume of blood returning to the heart during diastole (preload), the resistance to ejection of blood during systole (afterload), and the strength of cardiac muscle contraction (contractility).

Relationship between mean arterial pressure (MAP) and cardiac output (CO)

When considering the relationship of measured BP to the definition of oxygen delivery, one must understand the components that derive a measured BP:\[^4\] MAP is the product of CO (l min^{-1}) and SVR (dynes s^{-1} cm^{-5}). SVR is considered the degree of vasodilation (which reduces SVR) or vasoconstriction (which increases SVR) present in the systemic circulation. CO is the product of heart rate (HR, beats per minute) and SV (milliliter ejected per heart beat). SV is determined by preload (the venous return during diastole preloading the ventricle before contraction/ejection), afterload (the resistance that ventricular contraction must overcome in order to eject blood), and contractility (the force of contraction of ventricular muscle, independent of preload and afterload; Figure 1.4).
Increases in SVR, SV, preload, and contractility tend to increase BP, whereas increases in afterload tend to decrease SV, CO, and MAP. As MAP is a mathematical product, one cannot definitively determine if a decrease or increase in MAP is due to a decrease or increase in CO or SVR, as CO or SVR are not routinely measured in clinical patients. Choosing which mechanism for hypotension or hypertension is driving the change in pressure for a given patient requires understanding the effects of anesthetic drugs, autonomic physiology, and underlying pathophysiology, among many others.

The four mechanisms based on this algorithm are vasodilation, bradycardia, decreases in cardiac preload, and a decrease in myocardial contractility (Figure 1.4). These mechanisms of hypotension each have a variety of causes (Figures 1.5–1.8) and treatments (Figure 1.9).

For example, vasodilation can be treated either with (1) fluid boluses (crystalloids or colloids) to expand vascular volume to “fill” the vasodilated vasculature or with (2) administration of vasoconstricting agents to “offset” the vasodilation (phenylephrine, vasopressin, norepinephrine, etc.) or a positive inotrope that has vasoconstrictive properties (e.g. dopamine). Bradycardia can be treated with anticholinergics for sinus bradycardia or second-degree atrioventricular (AV) block or with other antiarrhythmics directed at specific bradyarrhythmias. Decreases in cardiac filling can be treated with blood volume expansion (crystalloid or colloid boluses) or with reversal or removal of...

**Table: Causes of vasodilation**

- Propofol
- Acepromazine
- Inhalant anesthetics
- Hypothermia
- Cardiac drugs
  - Nitroprusside
  - Nitroglycerine
  - Pimobendan
  - Hydralazine
  - ACE Inhibitors
  - Amlodipine
- Sepsis
- Anaphylaxis
- Hypercapnia

**Figure 1.5 Causes of bradycardia.** Example causes of decreased heart rate either via disease, complications of a procedure (e.g. ocular or vagal stimulation), or via drug side effects. Note that this list can be used not only to treat a cause of bradycardia, but also to predict potential bradycardia from patient comorbidities or procedures for management before or during anesthesia.

**Table: Causes of decreased preload**

- Low total body water (geriatric)
- Dehydration (vomiting, diarrhea)
- 3rd spacing (effusions, ascites, GI fluid)
- Hemorrhage
- Hypovolemia
- Vascular occlusion
- Vascular compression/obstruction
- Positive pressure ventilation
- Vasodilation

**Figure 1.6 Causes of vasodilation.** Example causes of decreased systemic vascular resistance, either via disease, complications of a procedure (e.g. septic shock or anaphylaxis), or via drug side effects. Similar to Figure 1.5, this list can be used not only to treat a cause of vasodilation, but also to predict potential vasodilation from patient comorbidities or diseases for management before or during anesthesia.

**Figure 1.7 Causes of decreased preload.** Example causes of decreased venous return (i.e. preload), either via disease or via complications from drug side effects.
Causes of decreased or poor contractility

- Neonates/juveniles/pediatrics
- Dilated cardiomyopathy
  - Secondary cardiomyopathies
- Isoflurane (dose-dependent)
- Propofol
- Hypocalcemia
- Acidosis
- Beta-receptor blocking agents
- Calcium channel blockers

Figure 1.8 Causes of decreased contractility. Example causes of decreased contractility (or inotropy) via either disease, complications of a disease, or drug side effects. Note that this list can be used not only to treat a cause of decreased contractility, but also to predict potential negative inotropy from patient comorbidities or anesthetics for management before or during anesthesia.

Obstructions or compression of the cranial and caudal vena cava. Lastly, decreases in myocardial contractility from any cause can be treated either by reducing or removing the cause or with positive inotropes that improve contractility. As inhalant anesthetics are moderately to severely depressant on myocardial contractility (depending on dose), reducing the inhaled anesthetic dose (or requirement) of a patient can dramatically improve contractility and improve hypotension.

It is critical to understand that these mechanism(s) and cause(s) exist not only in the anesthetized patient, but also in the patient with preexisting disease or abnormal physiology (e.g. pregnancy, neonates, and geriatrics), and this approach can be used not only in the anesthetized patient, but also in planning ahead for hypotension and other complications under anesthesia.

Preanesthetic patient assessment

The presence of underlying cardiac disease necessitates a more extensive patient evaluation compared to noncardiac patients. 11, 12 For example, patient history should include previous cardiovascular diagnoses, medications, and any recent changes in medication dosages. Historical radiographs, electrocardiography (ECG), or Holter monitor evaluation, BP, and echocardiogram findings should be available. Patients with severe disease should be evaluated within 1–2 weeks of a planned anesthetic procedure.

Although a complete physical examination (PE) should be performed before and on the day of anesthesia, particular attention must be paid to the cardiovascular and respiratory systems. The localization and characterization of heart murmurs, changes in lung sounds, increases in respiratory rate and effort, poor color and refill of mucous membranes, presence

<table>
<thead>
<tr>
<th>Mechanism of hypotension</th>
<th>Treatment(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Vasodilation</td>
<td>1a. Fluid volume</td>
</tr>
<tr>
<td></td>
<td>1b. Vasoconstrictors or “pressors”</td>
</tr>
<tr>
<td>2. Bradycardia</td>
<td>2a. Anticholinergics</td>
</tr>
<tr>
<td></td>
<td>2b. Antiarrhythmics</td>
</tr>
<tr>
<td>3. Decreased preload</td>
<td>3. Volume bolus, decrease ventilation, relieve obstruction/compression</td>
</tr>
<tr>
<td>4. Decreased contractility</td>
<td>4a. Positive inotropes</td>
</tr>
<tr>
<td></td>
<td>4b. Reduce inspired inhalant levels</td>
</tr>
</tbody>
</table>

Figure 1.9 Strategies for Management of Hypotension. Suggested treatment options for each mechanism are presented. Vasodilation can be treated with either volume resuscitation or vasoconstrictive agents. Bradycardia can be treated with anticholinergic or antiarrhythmic agents. Decreased preload can be treated with volume boluses or correction of the inciting cause of the loss of preload (e.g. obstruction to venous return). Decreased contractility can be treated with either minimizing the inciting cause (e.g. inhaled anesthetics) or with positive inotropic drugs (e.g. dopamine, dobutamine, etc.).
of jugular pulsations, and pulse irregularities or pulse deficits are obvious indicators of potential heart disease or changes in the patient’s cardiovascular status.

A minimum database for cardiac disease should include assessments of organ function with a blood chemistry panel, electrolytes, and a complete blood count. Patients with cardiac disease should have some combination of preanesthetic ECG, BP, thoracic radiographs, and echocardiogram depending on the type of cardiac disease. Ideally, the entire workup should be completed for patients presenting with a cardiac murmur or arrhythmia and previously unrecognized cardiac disease.

**Functional classification of cardiac disease**

Previous texts have established a functional classification of cardiac disease on the basis of clinical signs in an effort to help the clinician recognize which patients may have a higher risk of anesthetic complications and for whom anesthesia should be avoided until the patient has stabilized. If the presenting complaint necessitates anesthesia, this classification alerts the clinician to the high risk nature of such patients for owner counseling, preanesthesia preparation, requirements for intensive patient monitoring, and patient support.

**Classification I** comprises all nonclinical patients with preexisting cardiac disease and can be anesthetized with no preanesthetic stabilization. **Classification II** includes patients who have preexisting cardiac disease with mild to moderate clinical signs of disease at rest or with exercise. These patients require significant stabilization with medications and/or hospitalization before anesthesia can be considered. If anesthesia is required for a life-saving procedure, immediate stabilization with parenteral medications before anesthesia is required. Aggressive and invasive monitoring is necessary due to their fragile nature. **Classification III** includes patients with ongoing, fulminant heart failure. Anesthesia is contraindicated until the patient can be stabilized. If anesthesia cannot be avoided due to a life-saving procedure, they carry the highest risk of anesthetic complications, including severe debilitation, morbidity, and mortality.

The American Society of Anesthesiologists (ASA) patient status classification scheme has been adopted by The American College of Veterinary Anesthesia and Analgesia (ACVAA; Table 1.1). The ASA patient status value is not intended to be a risk assessment; however, the assignment of a patient status implies only the presence or absence of disease and that the clinician has evaluated the health status of the patient. The ASA physical status classification has limitations and can be seen as overly vague. However, the ASA does not (and presumably will not, as these definitions were accepted in 1963) expand on these limited definitions. Therefore, assignment of a particular patient to cardiac disease must be determined by the individual clinician (Table 1.1). Some authors have suggested

<table>
<thead>
<tr>
<th>Category</th>
<th>Physical status</th>
<th>Clinical examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Normal healthy patients</td>
<td>No detectable disease; patients presenting with ovariohysterectomy or castration</td>
</tr>
<tr>
<td>II</td>
<td>Patients with mild systemic disease</td>
<td>Skin tumor, fracture without shock, uncomplicated hernia, cryptorchidectomy, localized infection, or compensated cardiac disease</td>
</tr>
<tr>
<td>III</td>
<td>Patients with severe systemic disease</td>
<td>Fever, dehydration, anemia, cachexia, or moderate hypovolemia</td>
</tr>
<tr>
<td>IV</td>
<td>Patients with severe systemic disease that is a constant threat to life</td>
<td>Uremia, toxemia, severe dehydration and hypovolemia, anemia, cardiac decompensation, emaciation, or high fever</td>
</tr>
<tr>
<td>V</td>
<td>Morbiund patients who are not expected to survive 24 h without operation</td>
<td>Extreme shock, dehydration, terminal malignancy or infection, severe trauma</td>
</tr>
</tbody>
</table>

Table 1.1 American Society of Anesthesiologists (ASA) physical status.

Patient physical status adapted from the American Society of Anesthesiologists (ASA) physical status classification. According to the ASA guidelines, “There is no additional information that will help you further define these categories.” Clinical examples have been suggested by some authors, however, patient classification is highly variable and must be determined by the individual clinician.
classic types of patients who may be categorized into a particular physical status to help guide clinicians in the determination of ASA physical status.\textsuperscript{13}

**Sedation versus general anesthesia**

Sedation is defined as “a state characterized by central depression accompanied by drowsiness. The patient is generally unaware of his or her surroundings but is responsive to painful manipulation.”\textsuperscript{14} General anesthesia is defined as “drug-induced unconsciousness that is characterized by controlled but reversible depression of the central nervous system (CNS) and analgesia. In this state, the patient is not aroused by noxious stimulation. Sensory, motor, and autonomic reflexes are attenuated.”\textsuperscript{14} Surgical anesthesia is defined as “the state/plane of general anesthesia that provides unconsciousness, muscular relaxation, and analgesia sufficient for painless surgery.”\textsuperscript{14} The choice between whether to simply sedate a patient for a procedure or to use general anesthesia is important to consider. The degree of CNS depression that accompanies general anesthesia also depresses autonomic reflexes; the effects of which may be avoided if sedation is an acceptable alternative for the planned procedure. Systemic sedation that is appropriate for the patient’s temperament and underlying disease in combination with locoregional analgesia may be sufficient for surgical analgesia in some cases.\textsuperscript{15–17}

Although sedation may appear to be a universally safer option due to the avoidance of CNS/autonomic depression, sedatives such as alpha-2 agonists and phenothiazines may be absolutely contraindicated with some types of cardiac disease.\textsuperscript{18,19} Moreover, the degree of cardiovascular depression may be difficult to treat (particularly in the case of the alpha-2 adrenergic agonists) without reversal of the sedative with an antagonist reversal agent. In some cases, however, sedation may be preferred. However, general anesthesia with cardiovascular-sparing protocols and appropriate patient monitoring and support may be the safer option.

There is no single ideal anesthetic agent or anesthetic protocol for all cardiovascular disease; no one plan that will work for all patients and all procedures. All anesthetic plans should be individualized for the patient’s heart disease and coexisting disease. Optimizing the plan requires a complete understanding of anesthetic drug effects and side effects, as well as pathophysiology of disease, so as to combine the two for optimal outcome.

**Anesthetic and analgesic agents**

**Premedications**

Premedication is an extremely important step in the process of anesthetizing patients because it provides sedation, analgesia, and a reduction in induction and maintenance drug doses.\textsuperscript{2} As the induction and maintenance agents frequently are associated with severely depressant cardiovascular effects (albeit drug and dose-dependent in most cases), a large step toward cardiovascular stability can be provided with good to very good sedation with appropriate premedication.

**Opioids**

Opioids are a mainstay of premedication, induction, and maintenance of anesthesia in patients with cardiac disease, as they have minimal cardiovascular effects.\textsuperscript{20–23} Bradycardia is the major consequence of opioid use, as opioids have minimal to no effects on cardiac contractility or vascular tone.\textsuperscript{24,25} Bradycardia can be controlled with treatment or concomitant premedication with an anticholinergic (such as atropine or glycopyrrolate). Differences among the large number of opioids can cause confusion in choosing the most appropriate drug in this class. As a general rule, opioids will produce better sedation in the very young, old, or compromised patient as compared to a normally healthy adult patient. This rule is especially important consider in debilitated patients with cardiac disease.

**Morphine**

Morphine is considered the basis for comparison of all other opioids. Morphine is a full mu-opioid receptor agonist and provides very good sedation, often perceived as the best sedating choice in this class of drugs. It is also the most likely drug to induce vomiting.\textsuperscript{26} It is absorbed rapidly when given intramuscularly,\textsuperscript{27} and its duration is ∼4–6 h. Intravenous (IV) administration is not recommended due to the risk of histamine release.\textsuperscript{28} Morphine can, however, be delivered by low dose constant rate infusion and provides significant reductions in inhaled maintenance anesthetic requirements.
Hydromorphone/oxymorphone

Hydromorphone and oxymorphone have very similar profiles in small animals. Both are full mu-opioid agonists and provide excellent analgesia. They are moderately sedating opioids and are less likely to induce vomiting compared to morphine. Hydromorphone (as well as morphine) may cause panting in clinical canine patients, which may be undesirable for sedated procedures. Hydromorphone has also been reported to cause postoperative hyperthermia in cats at standard clinical doses; however, the clinical relevance of this is unclear.

Fentanyl

Fentanyl is a synthetic full mu-opioid agonist that is 80–100 times more potent than morphine, implying that an equally effective dose is 80–100 times less than morphine. Owing to its short duration of action (~20–30 min after bolus administration), fentanyl is most useful for IV premedication, induction, or delivery by constant rate infusion. Fentanyl is minimally sedating and is extremely unlikely to induce vomiting. It is very well suited for use as a sole anesthetic induction agent at high doses or as part of a multidrug induction protocol.

Butorphanol

Butorphanol is a mixed opioid agonist–antagonist; it is an agonist at the kappa-opioid receptor and an antagonist at the mu-opioid receptor. Therefore, it is only indicated for mild to weakly moderate pain, as it has analgesic effects only at the kappa receptor and is a very poor analgesic for moderate to severe pain. Although it has a relatively short duration of action (~45–90 min), it can be sedative in small animals and thus used for conscious procedures either as a sole IV sedative or in combination with other more potent sedatives, depending on the requirements. Bradycardia is less likely to occur after butorphanol administration than with full mu-opioid agonists. It is very unlikely to cause vomiting and demonstrates a ceiling effect in which no further sedation or analgesia is seen beyond 0.8 mg kg$^{-1}$.

Buprenorphine

Buprenorphine is unique among the common opioids in that it is a partial mu-opioid receptor agonist. Buprenorphine has an extremely high affinity for the mu-opioid receptor, such that it outcompetes other opioids for receptor binding, but cannot evoke a full mu-opioid response. Therefore, it is not equally efficacious compared to full mu-opioid agonists. It also demonstrates a ceiling effect in that doses above 0.04 mg kg$^{-1}$ do not provide additional analgesia or sedation. Owing to receptor binding, buprenorphine is poorly reversible to irreversible with opioid antagonists. It is very unlikely to cause bradycardia and vomiting and is a relatively poor sedative.

Phenothiazines

Acepromazine is a common premedication and is an excellent tranquilizer in small animals. However, it is a potent alpha-1 adrenergic receptor antagonist and will lead to peripheral vasodilation and hypotension and so must be used with caution in patients with cardiac disease. Patients with stable, nonclinical disease may be able to compensate for the vasodilatory effects. However, it is prudent to avoid acepromazine in patients with moderate to severe cardiac disease. Hypotension may lead to a compensatory increase in HR, which can increase myocardial oxygen consumption. Acepromazine will protect the myocardium from epinephrine and barbiturate-induced arrhythmias. However, this benefit must be weighed against the hypotensive effects.

Anticholinergics

Atropine and glycopyrrolate are parasympatholytic anticholinergic agents used to increase HR associated with vagal-mediated sinus bradycardia and AV block. Atropine has a faster onset time (~1–2 min IV), shorter duration of action (~20–30 min IV), and is more likely to incite tachyarrhythmias. Glycopyrrolate has a longer onset time (~2–4 min IV), longer duration of action (~1 h IV), and may be less likely to cause tachyarrhythmias. Low doses of atropine and glycopyrrolate can initially precipitate second-degree AV block (see the following sections), which may require additional doses of anticholinergic for treatment.

Benzodiazepines

Benzodiazepines (diazepam and midazolam) are good choices for sedation in patients with cardiac disease. They have minimal to no effects on HR, contractility, or vasomotor tone and do not lead to hypotension across a wide range of doses (0.5–2.5 mg kg$^{-1}$ IV). Although respiratory rate decreases, arterial blood gas values do not change appreciably. The major
disadvantage of benzodiazepines is that they are inconsistent sedatives in dogs\textsuperscript{44,45} and may be poor sedatives in cats. For example, IV premedication doses can lead to dysphoria, excitement, ataxia, arousal, and, potentially, violent aggression.\textsuperscript{44} Combinations of butorphanol and midazolam fail to provide sedation in healthy cats.\textsuperscript{45} Although benzodiazepines decrease inhaled anesthetic requirements, this benefit can be achieved when they are combined with induction agents during the induction protocol as opposed to risking excitement when used as premedicants.\textsuperscript{46,47}

**Alpha-2 adrenergic receptor agonists**

Alpha-2 adrenergic receptor agonists (dexmedetomidine, medetomidine, xylazine, etc.) are usually contraindicated in patients with cardiac disease. Alpha-2 agonists cause intense peripheral vasoconstriction and decrease sympathetic outflow from the CNS. The severe increase in SVR leads to a marked increase in BP, a significant increase in myocardial afterload, and a baroreceptor-mediated reflex bradycardia. Some patients may demonstrate a period of vasodilation and arterial hypotension after the initial hypertension. This is commonly seen with xylazine in horses but appears to be less common with longer acting agents such as dexmedetomidine.\textsuperscript{48,49} The initial baroreceptor-mediated bradycardia is exacerbated by a decrease in centrally mediated descending sympathetic tone. Alpha-2 adrenergic agonists can also produce AV block and ventricular escape cardiac rhythms. At sedative doses, these mechanisms will decrease CO by \( \sim 50–60\% \); dexmedetomidine at \( \geq 5\) mg kg\(^{-1}\) IV will decrease CO by 50–60\%,\textsuperscript{50} and medetomidine at 20 mcg kg\(^{-1}\) IV will decrease CO by at least 60\%.\textsuperscript{31} The increase in afterload from vasoconstriction, increase in left atrial pressure from centralization of blood volume, and decrease in CO are all mechanisms that can be detrimental to the function of a heart with underlying disease. Although alpha-2 adrenergic agonists are extremely reliable sedatives, the cardiovascular side effects are so profound that the depth of sedation may be better sacrificed in the interest of cardiovascular safety.

**Induction agents**

**Propofol**

The main advantage of propofol is a rapid onset (\( \sim 15–20\) s) and short duration of action (\( \sim 6–10\) min of anesthesia) from an IV bolus that allows intubation.\textsuperscript{52} Its main mechanism of action\textsuperscript{53} is stimulation of the gamma aminobutyric acid (GABA, the main inhibitory neurotransmitter in the CNS) receptor away from the binding site for other anesthetics such as thiopental.\textsuperscript{54} Recoveries from propofol administration are extremely smooth. However, propofol is a significant dose-dependent vasodilator\textsuperscript{55} and can precipitate significant hypotension at moderate to doses. While patients with mild cardiac disease may tolerate hypotension associated with propofol, those with more severe disease or in whom a decrease in SVR will worsen cardiac function should be cautiously induced with propofol.

**Dissociative anesthetics**

Dissociative anesthetics such as ketamine and tiletamine produce anesthesia by interrupting neuronal transmission, thus “dissociating” the centers responsible for consciousness and unconsciousness from the peripheral ascending inputs. The cardiovascular effects of dissociative anesthetics result from stimulation of the SNS, increasing HR, contractility and MAP, with little change in SVR.\textsuperscript{56} This leads to an increase in myocardial work and myocardial oxygen demand that is compensated for by increased CO and coronary blood flow.\textsuperscript{57} The increase in oxygen demand in patients with cardiac disease may worsen cardiac function or arrhythmias. Thus, ketamine is contraindicated in hypertrophic cardiomyopathy (HCM) and is frequently avoided in any patient with other forms of cardiomyopathy and valvular cardiac disease (see the following section) or in those with severe systemic illness.\textsuperscript{58}

**Etomidate**

Etomidate is a nonopioid, nonbarbiturate sedative hypnotic drug that works similar to propofol and barbiturates in that it enhances inhibitory GABA effects.\textsuperscript{59} Etomidate has the distinct advantage of having minimal to no cardiovascular depression because it does not significantly change HR, contractility, afterload, or venous return. However, it has several drawbacks. Etomidate has a very high osmolarity (\( \sim 4800\) mOsm l\(^{-1}\)) and can lead to osmolar shifting, causing possible phlebitis, pain at the injection site, red blood cell crenation, and potential hemolysis, as well as adrenocortical suppression.\textsuperscript{60} Etomidate causes a reliable but relatively slow transition to unconsciousness when compared to propofol. Etomidate has poor muscle relaxation and
can stimulate myoclonus and so should be given with a benzodiazepine or fentanyl to facilitate a smooth induction period.\textsuperscript{61}

**High dose opioids**

High dose, full mu-agonist opioids such as fentanyl can be extremely effective in producing general anesthesia with uncomplicated placement of an endotracheal tube. High dose opioids have the disadvantage of moderate to severe respiratory depression and bradycardia; however, both are easily controlled with intubation and anticholinergics, respectively. Unfortunately, transition to unconsciousness with fentanyl appears somewhat less reliable and slower compared to propofol\textsuperscript{62} or etomidate. Patients who are bright and energetic or are stimulated during the induction process by sound, touch, or pain may attempt to “override” the induction process, leading to poorer quality induction. In these cases, a rescue induction agent (typically propofol for speed of onset, but etomidate is an alternative option) can help push such a patient into unconsciousness. Quiet, dimly lit environments with little stimuli are ideal for fentanyl inductions, and fentanyl inductions usually work best in debilitated, older animals. Fentanyl should be given with a benzodiazepine for improved muscle relaxation.

**Anesthetic maintenance**

**Inhaled anesthetics**

Inhaled anesthetics are the most commonly chosen drugs for maintenance of anesthesia. Although injectable protocols for maintenance of anesthesia exist, referred to as total intravenous anesthesia (TIVA) protocols, inhaled anesthetics provide a number of unique advantages. Their pharmacokinetic properties allow for careful titration of and rapid changes in the anesthetic depth. The use of inhaled anesthetics requires the use of an anesthetic vaporizer that requires a carrier gas flow (nearly always 100% oxygen), which supports maximal arterial blood oxygenation. The need for an anesthesia machine requires endotracheal intubation, which allows for more accurate monitoring of ventilation. In addition, ventilation can also be supplemented and/or supported easily with this equipment. The ability to monitor expired gases such as carbon dioxide or exhaled anesthetic concentrations allows for more robust patient monitoring and support. Unfortunately, inhaled anesthetics depress cardiovascular function, leading to dose-dependent CO and BP depression.\textsuperscript{63} This is due to a moderate to severe dose-dependent reduction in myocardial contractility (e.g. negative inotropy) and subsequent decreases in SV and CO.\textsuperscript{63–66} Isoflurane also decreases SVR, resulting in vasodilation, which can incite or predispose to hypotension. Generally, these cardiovascular side effects are managed either by minimizing the dose administered or by counteracting the side effects with interventions aimed at providing cardiovascular support. Many strategies are available to allow reductions (“MAC reduction”) in inhaled anesthetic drug requirements (MAC, the Minimum Alveolar Concentration of inhaled anesthetic required to produce lack of response to a supra-maximal noxious stimulus applied to a patient 50% of the time) and include use of premedications, induction agents, bolus or infusion-dose analgesics or sedatives, and local/regional anesthesia techniques. The hypotensive effects of inhaled anesthetic agents can be treated by a variety of mechanisms, including optimizing HR and rhythm, judicious use of IV fluids (if not contraindicated by cardiovascular disease), and directly increasing contractility (to oppose the inhaled agents effects) with positive inotropic drugs (Figure 1.9).

**Anesthetic adjuncts**

One major goal of adjunctive techniques or interventions is to increase cardiovascular stability and maximize CO and BP. In practice, this can be generally summarized as applying a technique that has fewer negative cardiovascular side effects as compared to patient management without that particular technique. As an example, fentanyl infusions have been shown to reduce the requirement for enfurane by as much as 65%\textsuperscript{67} and of isoflurane by ~50%\textsuperscript{68} at 0.8 mcg kg\textsuperscript{-1} min\textsuperscript{-1} and 0.3 mcg kg\textsuperscript{-1} min\textsuperscript{-1}, respectively. As the primary cardiovascular effect of opioid infusions is bradycardia, which is easily corrected with anticholinergics, these infusions allow for decreased inspired concentrations of inhalant anesthetics, therefore reducing their cardiovascular compromise. This is presumed to be safer by providing improved cardiovascular stability than using higher doses of inhalants alone. Other anesthetic adjunctive techniques, including nonopioid analgesic constant rate infusions (lidocaine and ketamine) and local and regional anesthesia (epidurals, peripheral nerve blocks, and local anesthetics), are aimed at reducing the requirement of maintenance anesthetics in the interest of cardiovascular stability.
Local and regional analgesia

Local anesthetics have the distinct advantage of blocking peripheral nerve function as compared to other analgesic drug classes (opioids and nonsteroidal anti-inflammatory drugs) that modulate the ascending nociceptive stimuli. If nociceptive stimuli are completely prevented from reaching higher centers, then, theoretically, a patient would not require general anesthesia despite painful surgery or procedures. Although this may not be practical for most procedures, it reminds us that local anesthetics are a powerful tool in preventing pain perception or ascending nociceptive information. For patients under general anesthesia, local or regional anesthesia/analgesia can dramatically reduce systemic and inhaled anesthetic drug requirements. As local anesthetics have minimal cardiovascular compromise at appropriate doses, the reduction in systemic and inhaled anesthetic drug levels can minimize or prevent the cardiovascular depressant effects of these anesthetics, leading to a more stable patient. Numerous studies have shown a significant reduction in inhaled anesthetic requirements due to application of regional anesthesia techniques, including the infraorbital nerve block, and methadone epidurals in dogs and morphine/buprenorphine epidurals in cats as some examples. However, the use of local anesthetic administration can result in toxicity. For example, the dose of IV lidocaine at which canine patients will develop neurologic signs of toxicity (i.e. convulsions) is ~22 mg kg\(^{-1}\). Bupivacaine has a much lower therapeutic index in that cardiotoxicity and neurotoxicity can be seen at doses between 4.3 and 5.0 mg kg\(^{-1}\) IV.

Systemic analgesic infusions

Much like local and regional techniques, systemically delivered analgesic infusions have the significant potential for reducing inhaled anesthetic drug doses and responsiveness to painful stimuli. Provided that the cardiovascular side effects of the infusion(s) are not more detrimental than the inhaled anesthetic, the reduction in inhaled anesthetic dose can lead to a significant reduction in their negative consequences, such as negative inotropy, vasodilation, and respiratory depression, thus improving cardiovascular performance. As mentioned previously, IV opioid infusions are particularly beneficial in reducing inhaled anesthetic requirements (Tables 1.2 and 1.3) and are extremely safe cardiovascular infusions, as their primary side effect is bradycardia, easily treatable with anticholinergics. In horses anesthetized with sevoflurane, an IV lidocaine bolus of 1.3 mg kg\(^{-1}\) followed by a constant rate infusion of 50 mcg kg\(^{-1}\) min\(^{-1}\) reduced sevoflurane MAC by 27%. IV lidocaine infusions have been studied in dogs repeatedly for their benefits in reducing both isoflurane and sevoflurane inhaled anesthetic concentrations. Lidocaine at 50 mcg kg\(^{-1}\) min\(^{-1}\) reduced isoflurane MAC by 29% and sevoflurane MAC by 22.6% in dogs (Tables 1.2 and 1.3). In another study, at 50 and 200 mcg kg\(^{-1}\) min\(^{-1}\), no changes in cardiovascular parameters due to lidocaine infusion(s) were identified, and inhalant MAC was reduced by 15% and 37%, respectively.

Inotropes and vasopressors

Terminology and definitions confuse these classifications of drugs not only because the term vasopressor is used to refer to both drug categories, but also because of overlapping drug effects. Inotropes or positive inotropes are drugs that increase myocardial contractility by actions on the beta-1 adrenergic receptors and are used to improve SV, CO, and BP. By way of their actions on the beta-1 receptor, these drugs also tend to increase HR, although this is not a positive inotropic effect by the strictest definition. This would be a positive chronotropic effect. Regardless, these drugs are typically referred to by their positive effects on myocardial contractility. Vasopressor is the term applied to drugs that increase SVR via alpha-1 adrenergic or other receptor-mediated vasoconstriction, which subsequently increases BP. Although some drugs are uniquely suited to a single category, an inotrope or a vasopressor, many pharmacologic agents affect multiple receptor subtypes or have varying effects on the basis of dose, and their use in the spectrum of cardiovascular disease is difficult to generalize (Table 1.4).

Dopamine and dobutamine

Dopamine and dobutamine are some of the most commonly applied positive inotropic drugs during veterinary anesthesia. As inhaled anesthetic agents cause dose-dependent suppression of myocardial contractility and decrease SVR, these drugs are highly efficacious for the management of inhaled anesthetic-mediated hypotension.

Dopamine is the immediate precursor to norepinephrine and has dose-dependent positive inotropic
Table 1.2  MAC-reducing effects of common infusions in dogs.

<table>
<thead>
<tr>
<th>Study</th>
<th>Loading dose (mg kg⁻¹)</th>
<th>Infusion dose (mcg kg⁻¹ min⁻¹)</th>
<th>Inhalant</th>
<th>MAC (%)</th>
<th>MAC reduction</th>
<th>MAC-reduction percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Fentanyl</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ueyama 2009¹</td>
<td>0.005</td>
<td>0.15</td>
<td>Isoflurane</td>
<td>1.42 ± 0.08</td>
<td>0.93 ± 0.04</td>
<td>−35%</td>
</tr>
<tr>
<td>Hellyer 2001⁴</td>
<td>0.01</td>
<td>0.3</td>
<td>Isoflurane</td>
<td>1.8 ± 0.21</td>
<td>0.85 ± 0.14</td>
<td>−53%</td>
</tr>
<tr>
<td><strong>Remifentanil</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Michelsen 1996⁷</td>
<td>None</td>
<td>1.0</td>
<td>Enflurane</td>
<td>2.1 ± 0.2</td>
<td>NR</td>
<td>−63 ± 10.4%</td>
</tr>
<tr>
<td>Allweiler 2007⁷</td>
<td>None</td>
<td>0.1</td>
<td>Isoflurane</td>
<td>1.28 ± 0.13</td>
<td>0.78 ± 0.17</td>
<td>−40%</td>
</tr>
<tr>
<td>Monteiro 2010⁷⁷</td>
<td>None</td>
<td>0.15</td>
<td>Isoflurane</td>
<td>1.28 ± 0.13</td>
<td>0.65 ± 0.16</td>
<td>−50%</td>
</tr>
<tr>
<td></td>
<td>None</td>
<td>0.3</td>
<td>Isoflurane</td>
<td>1.24 ± 0.18</td>
<td>NR</td>
<td>−43 ± 10%</td>
</tr>
<tr>
<td></td>
<td>None</td>
<td>0.6</td>
<td>Isoflurane</td>
<td>1.24 ± 0.18</td>
<td>NR</td>
<td>−59 ± 10%</td>
</tr>
<tr>
<td></td>
<td>None</td>
<td>0.9</td>
<td>Isoflurane</td>
<td>1.24 ± 0.18</td>
<td>NR</td>
<td>−66 ± 9%</td>
</tr>
<tr>
<td></td>
<td>None</td>
<td>0.25</td>
<td>Isoflurane</td>
<td>1.24 ± 0.18</td>
<td>NR</td>
<td>−50%</td>
</tr>
<tr>
<td></td>
<td>None</td>
<td>0.3</td>
<td>Isoflurane</td>
<td>1.24 ± 0.18</td>
<td>NR</td>
<td>−59 ± 10%</td>
</tr>
<tr>
<td></td>
<td>None</td>
<td>0.6</td>
<td>Isoflurane</td>
<td>1.24 ± 0.18</td>
<td>NR</td>
<td>−66 ± 9%</td>
</tr>
<tr>
<td></td>
<td>None</td>
<td>0.9</td>
<td>Isoflurane</td>
<td>1.24 ± 0.18</td>
<td>NR</td>
<td>−71 ± 9%</td>
</tr>
<tr>
<td><strong>Ketamine</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Muir 2003⁷⁸</td>
<td>None</td>
<td>10</td>
<td>Isoflurane</td>
<td>1.38 ± 0.08</td>
<td>1.03 ± 0.07</td>
<td>−25%</td>
</tr>
<tr>
<td>Queiroz-Castro 2006⁹</td>
<td>1.0</td>
<td>25</td>
<td>Isoflurane</td>
<td>1.06 ± 0.02</td>
<td>0.73 ± 0.04</td>
<td>−28.7 ± 3.7%</td>
</tr>
<tr>
<td>Doherty 2007⁹⁴</td>
<td>1.5</td>
<td>50</td>
<td>Isoflurane</td>
<td>1.11 ± 0.05</td>
<td>0.56 ± 0.04</td>
<td>−49.6%</td>
</tr>
<tr>
<td>Love 2011⁸¹</td>
<td>0.5</td>
<td>6.25</td>
<td>Sevoflurane</td>
<td>2.62 ± 0.21</td>
<td>2.61 ± 0.22</td>
<td>−0.4 ± 4%</td>
</tr>
<tr>
<td></td>
<td>1.0</td>
<td>12.5</td>
<td>Sevoflurane</td>
<td>2.62 ± 0.21</td>
<td>2.06 ± 0.22</td>
<td>−22 ± 4%</td>
</tr>
<tr>
<td></td>
<td>2.0</td>
<td>25</td>
<td>Sevoflurane</td>
<td>2.91 ± 0.21</td>
<td>2.64 ± 0.22</td>
<td>−12 ± 4%</td>
</tr>
<tr>
<td></td>
<td>3.0</td>
<td>50</td>
<td>Sevoflurane</td>
<td>2.91 ± 0.21</td>
<td>2.44 ± 0.22</td>
<td>−18 ± 4%</td>
</tr>
<tr>
<td>Wilson 2008⁸²</td>
<td>3.0</td>
<td>50</td>
<td>Sevoflurane</td>
<td>1.9 ± 0.2</td>
<td>1.1 ± 0.1</td>
<td>−40 ± 3.5%</td>
</tr>
<tr>
<td></td>
<td>3.0</td>
<td>100</td>
<td>Sevoflurane</td>
<td>1.7 ± 0.2</td>
<td>0.9 ± 0.1</td>
<td>−44.7 ± 3.5%</td>
</tr>
<tr>
<td><strong>Lidocaine</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Muir 2003⁷⁸</td>
<td>None</td>
<td>50</td>
<td>Isoflurane</td>
<td>1.38 ± 0.08</td>
<td>0.97 ± 0.04</td>
<td>−29%</td>
</tr>
<tr>
<td>Doherty 2007⁹⁴</td>
<td>2.5</td>
<td>100</td>
<td>Isoflurane</td>
<td>1.20 ± 0.04</td>
<td>0.98 ± 0.06</td>
<td>−18.3%</td>
</tr>
<tr>
<td>Matsubara 2009⁹³</td>
<td>2.0</td>
<td>50</td>
<td>Sevoflurane</td>
<td>2.30 ± 0.19</td>
<td>1.95 ± 0.23</td>
<td>−15%</td>
</tr>
<tr>
<td></td>
<td>2.0</td>
<td>200</td>
<td>Sevoflurane</td>
<td>2.30 ± 0.19</td>
<td>1.45 ± 0.21</td>
<td>−37%</td>
</tr>
<tr>
<td>Wilson 2008⁸²</td>
<td>2.0</td>
<td>50</td>
<td>Sevoflurane</td>
<td>2.0 ± 0.2</td>
<td>1.6 ± 0.1</td>
<td>−22.6 ± 3.6%</td>
</tr>
<tr>
<td></td>
<td>2.0</td>
<td>100</td>
<td>Sevoflurane</td>
<td>1.8 ± 0.2</td>
<td>1.3 ± 0.1</td>
<td>−29 ± 3.5%</td>
</tr>
<tr>
<td></td>
<td>2.0</td>
<td>200</td>
<td>Sevoflurane</td>
<td>2.0 ± 0.2</td>
<td>1.1 ± 0.1</td>
<td>−39.6 ± 3.5%</td>
</tr>
<tr>
<td>Valverde 2004⁹⁴</td>
<td>2.0</td>
<td>50</td>
<td>Isoflurane</td>
<td>1.34 ± 0.11</td>
<td>1.09 ± 0.13</td>
<td>−18.7%</td>
</tr>
<tr>
<td></td>
<td>2.0</td>
<td>200</td>
<td>Isoflurane</td>
<td>1.34 ± 0.11</td>
<td>0.76 ± 0.1</td>
<td>−43.3%</td>
</tr>
</tbody>
</table>

Studies performed in goats.

Study evaluated MAC-BAR, the physiologic response to stimulus rather than evaluating for purposeful movement.

effects. The infusion dose of dopamine for beta-1 adrenergic-mediated increases in myocardial contractility, and HR is 5–10 mcg kg⁻¹ min⁻¹. The recommended dose for improvement of CO is 7 mcg kg⁻¹ min⁻¹.⁸⁹ Dopamine actions are unique, as doses above 10 mcg kg⁻¹ min⁻¹ likely stimulate alpha-1 receptors, leading to an increase in SVR. Although this can also be beneficial for BP, it must be noted that this increase in myocardial afterload may, in fact, worsen cardiovascular performance and may be contraindicated in patients with specific cardiovascular diseases such as dilated cardiomyopathy (DCM), HCM, and regurgitant valvular disease. Specific comments regarding positive inotropes and vasopressors are included in the sections of this chapter for each type of heart disease.

Dobutamine is a nonspecific beta-adrenergic agonist, activating both beta-1 and beta-2 receptors and will increase both HR and contractility similar to the beta-1 effects of dopamine. The general recommended dose for dobutamine to achieve beta-1 effects is 1–5 mcg kg⁻¹ min⁻¹. However, it is critically important to understand that dobutamine is also a beta-2 agonist and will induce a decrease in SVR, leading to beta-2-mediated vasodilation. Research has shown that
Table 1.3  MAC-reducing effects of common infusions in cats.

<table>
<thead>
<tr>
<th>Study</th>
<th>Drug</th>
<th>Loading dose (mg kg(^{-1}))</th>
<th>Infusion dose (mcg kg(^{-1}) min(^{-1}))</th>
<th>Inhalant</th>
<th>MAC (%)</th>
<th>MAC reduction percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brosnan 2009(^{66})</td>
<td>Remifentanil</td>
<td>none</td>
<td>0.0625–16</td>
<td>Isoflurane</td>
<td>1.94 ± 0.8</td>
<td>None</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.125</td>
<td>Isoflurane</td>
<td></td>
<td>None</td>
</tr>
<tr>
<td>Ferreira 2009(^{66})</td>
<td>Remifentanil</td>
<td>0.25</td>
<td>Isoflurane 1.66 ± 0.08</td>
<td>Isoflurane</td>
<td>1.27 ± 0.13</td>
<td>−23 ± 7.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.5</td>
<td>Isoflurane 1.66 ± 0.08</td>
<td>Isoflurane</td>
<td>1.16 ± 0.17</td>
<td>−29.8 ± 8.3</td>
</tr>
<tr>
<td>Pascoe 2007(^{67})</td>
<td>Ketamine</td>
<td>2.0</td>
<td>Isoflurane 1.51 ± 0.23</td>
<td>Isoflurane</td>
<td>0.84 ± 0.33</td>
<td>−45 ± 17</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.0</td>
<td>Isoflurane 1.51 ± 0.23</td>
<td>Isoflurane</td>
<td>0.57 ± 0.35</td>
<td>−63 ± 18</td>
</tr>
<tr>
<td></td>
<td></td>
<td>16.0</td>
<td>Isoflurane 1.51 ± 0.23</td>
<td>Isoflurane</td>
<td>0.41 ± 0.35</td>
<td>−75 ± 17</td>
</tr>
</tbody>
</table>

Table 1.4  Inotropes and vasopressors.

<table>
<thead>
<tr>
<th>Drug</th>
<th>Alpha-1</th>
<th>Alpha-2</th>
<th>Beta-1</th>
<th>Beta-2</th>
<th>Dopamine</th>
<th>Vasopressin</th>
<th>Dose</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effect</td>
<td>Vasoconstriction</td>
<td>Vasoconstriction</td>
<td>Inotropic</td>
<td>Vasodilation</td>
<td>Bronchodilation</td>
<td>D1 receptor</td>
<td>Vasoconstriction</td>
</tr>
<tr>
<td>Dopamine</td>
<td>+++ High dose</td>
<td>+</td>
<td>+++ Low dose</td>
<td>+ Low dose</td>
<td>+++</td>
<td>–</td>
<td>Inf: Low 5–10 mcg kg(^{-1}) min(^{-1})</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Inf: High 10–20 mcg kg(^{-1}) min(^{-1})</td>
</tr>
<tr>
<td>Dobutamine</td>
<td>–</td>
<td>–</td>
<td>+++</td>
<td>++</td>
<td>–</td>
<td>–</td>
<td>Inf: 1–10 mcg kg(^{-1}) min(^{-1})</td>
</tr>
<tr>
<td>Epinephrine</td>
<td>+++</td>
<td>+++</td>
<td>++</td>
<td>++</td>
<td>–</td>
<td>–</td>
<td>Bolus: 0.01–0.1 mg kg(^{-1}) IV Inf: 0.01–1.0 mcg kg(^{-1}) min(^{-1})</td>
</tr>
<tr>
<td>Ephedrine</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>–</td>
<td>–</td>
<td>Bolus: 0.03–0.1 mg kg(^{-1}) IV</td>
</tr>
<tr>
<td>Isoproteronol</td>
<td>–</td>
<td>–</td>
<td>+++</td>
<td>+++</td>
<td>–</td>
<td>–</td>
<td>Inf: 0.01–0.1 mcg kg(^{-1}) min(^{-1})</td>
</tr>
<tr>
<td>Norepinephrine</td>
<td>+++</td>
<td>–</td>
<td>++</td>
<td>+++</td>
<td>–</td>
<td>–</td>
<td>Inf: 0.05–2.0 mcg kg(^{-1}) min(^{-1})</td>
</tr>
<tr>
<td>Phenylephrine</td>
<td>+++</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>B: 1–5 mcg kg(^{-1}) IV Inf: 0.5–3 mcg kg(^{-1}) min(^{-1})</td>
</tr>
<tr>
<td>Vasopressin</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>Bolus: 0.1–0.6 units kg(^{-1}) IV Inf: 1–4 mU kg(^{-1}) min(^{-1}) (dogs)</td>
</tr>
</tbody>
</table>
the increase in HR and contractility may be offset by the vasodilation, and no change in BP may occur.89

**Epinephrine**

Epinephrine is a potent alpha- and beta-adrenergic agonist leading to intense peripheral vasoconstriction and increases in HR and contractility, respectively. It dramatically increases myocardial oxygen demand and is highly arrhythmogenic. It is not possible to discriminate effects (i.e. beta effects without alpha effects) with epinephrine and is therefore a poor choice for an inotropic agent, particularly due to the increase in oxygen demand and potential for arrhythmias. Epinephrine should be limited to use for cardiopulmonary cerebral resuscitation (CPCR).

**Ephedrine**

Ephedrine is similar to an alpha- and beta-adrenergic receptor agonist. However, its effects appear weaker at these receptors. Ephedrine is one of the few inotropic/vasopressive agents that can be delivered by bolus injection, rather than by infusion, as the half-life for activity is longer than most other drugs in this category. Ephedrine bolus leads to increases in BP, cardiac index, and oxygen delivery in dogs anesthetized with isoflurane.90 Onset time is very rapid, and the duration of the increase in BP is shorter than that of the increase in CO. As such, it is useful for short-term treatment of hypotension.

**Vasopressin**

Vasopressin is the hormone arginine vasopressin (antidiuretic hormone, ADH) and acts as a vasopressor because it increases SVR and has no effect on HR or myocardial contractility. However, it is unique, as it does not affect adrenergic receptors but works through the vasopressin-1 receptor located on peripheral vasculature. Actions at the vasopressin-2 receptor are responsible for the renal effects.91 Since it is not a catecholamine, it is not arrhythmogenic, a significant advantage over other drugs in this group. Vasopressin has been shown to be comparable to phenylephrine for the treatment of hypotension in an endotoxic shock model.92 Although intentionally titrated vasoconstriction can be an important strategy for treatment of refractory hypotension, high levels of SVR may potentially decrease CO and oxygen delivery, particularly in patients with heart disease for which increases in afterload can be severely detrimental such as with DCM.

**Phenylephrine and norepinephrine**

Phenylephrine and norepinephrine function as vasopressors. Phenylephrine is a pure alpha-1 adrenergic agonist that leads to dose-dependent vasoconstriction and carries the benefits and drawbacks of pure vasoconstrictors as described previously. Norepinephrine has both alpha-1 and beta-adrenergic effects, although in practice, the vasoconstrictive effects predominate, as the beta-2 and beta-1 effects are variable and typically overwhelmed by the alpha response.

**Patient monitoring and support**

**Fluid therapy**

As decreases in cardiovascular function and CO are inevitable effects of anesthetics, fluid therapy is recommended to maintain perfusion despite cardiovascular depression. Patients who present with compensated heart disease with no overt clinical signs may tolerate typical rates of IV fluids (balanced electrolyte solutions) during anesthesia, usually in the range of 5–10 ml kg\(^{-1}\) h\(^{-1}\). Patients with evidence of non-compensated cardiovascular disease are often at risk for failure due to poor cardiac function or the cascade of neurohormonal mechanisms that lead to an increase in circulating blood volume such as activation of the renin–aldosterone–angiotensin system (RAAS) and increased secretion of ADH. Patients with a history of heart failure and/or chronic volume overload (mitral, tricuspid, and aortic valve insufficiency, left to right shunts including patent ductus arteriosus [PDA], and ventricular septal defects [VSD]) may be less likely to tolerate high fluid rates during surgery, and so lower fluid rates should be used in these patients. Usually, 3–5 ml kg\(^{-1}\) h\(^{-1}\) is sufficient to meet maintenance metabolic needs but not increase blood volume and risk precipitating heart failure. Furosemide may be used for its’ diuretic effects if the patient receives an excessive amount of IV crystalloid solution. The administration of synthetic colloids (i.e. hetastarch, pentastarch, dextran, and hemoglobin glutamer-200) is often avoided in patients with cardiac disease, as colloids can expand plasma volume for significantly longer periods and are more difficult to treat/reverse with diuretics.
**Patient preoxygenation**

Most anesthetic premedications and induction agents are respiratory depressants; the most significant of which are the opioids, propofol, and inhaled anesthetic agents. Ketamine is considered a mild respiratory depressant\(^93\) as is etomidate.\(^94\) The onset of respiratory depression can be very rapid, which can result in patient desaturation and cyanosis. The alveolar partial pressure of oxygen (PAO\(_2\)) is predicted by the alveolar gas equation (Table 1.5).

The following equations are examples of differing conditions during normoxia

\[
\text{PAO}_2 = \text{FIO}_2 (\text{Patm} - \text{PH}_2\text{O}) - \text{PaCO}_2 / 0.8 \quad (1.1)
\]

\[
\text{PAO}_2 = 0.21(760 - 47) - 40/0.8 = 99.7 \text{ mmHg} \quad (1.2)
\]

\[
\text{PAO}_2 = 0.21(760 - 47) - 60/0.8 = 74.7 \text{ mmHg} \quad (1.3)
\]

and hypoxemia

\[
\text{PAO}_2 = 0.40(760 - 47) - 40/0.8 = 235.2 \text{ mmHg} \quad (1.4)
\]

\[
\text{PAO}_2 = 0.40(760 - 47) - 60/0.8 = 210.2 \text{ mmHg} \quad (1.5)
\]

where FIO\(_2\) refers to the inspired fraction of oxygen, Patm is the atmospheric pressure, PH\(_2\)O is the partial pressure of water vapor, and PaCO\(_2\) is the arterial partial pressure of carbon dioxide. In animals that are ventilating normally with a normal PaCO\(_2\) of 40 mmHg (Table 1.5, Equation 1.2), the PAO\(_2\) is ~100 mmHg. This pressure represents the alveolar pressure of oxygen able to diffuse down the oxygen concentration gradient into pulmonary arterial blood.

As patients hypoventilate, PaCO\(_2\) increases which decreases the alveolar partial pressure of oxygen (PAO\(_2\)) and can result in clinical hypoxemia when PAO\(_2\) is less than 80 mmHg. (Table 1.5, Equation 1.3). When providing supplemental oxygen via a tight-fitting facemask (estimated to be a FIO\(_2\) of ~40%), PAO\(_2\) is subsequently increased (Table 1.5, Equation 1.4), which can blunt the effects of hypoxemia due to hypoventilation (Table 1.5, Equation 1.5). Thus, preoxygenation can be a critical component of maintaining a high PAO\(_2\) and arterial partial pressure of oxygen (PaO\(_2\)) subsequent to anesthetic-related respiratory depression from premedication through the induction process. The general recommendation is to provide oxygen via a tight-fitting facemask for a minimum of 3 min before induction of anesthesia.\(^96\) This can be easily performed as monitoring equipment (ECG, noninvasive BP, capnometry) is placed before induction of anesthesia.

**Blood pressure (BP)**

BP is the most reliable clinical indicator of perfusion, despite the disadvantage that it is not a clear indicator of CO. BP is a standard monitoring tool for all anesthetized patients and has been the standard of care in humans for decades. The ACVAA Guidelines on Small Animal

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**Table 1.5** Alveolar to arterial pressure gradient calculations.

<table>
<thead>
<tr>
<th>ETCO(_2)</th>
<th>30</th>
<th>40</th>
<th>60</th>
<th>80</th>
</tr>
</thead>
<tbody>
<tr>
<td>21</td>
<td>112.2</td>
<td>101.0</td>
<td>99.7</td>
<td>89.9</td>
</tr>
<tr>
<td>30</td>
<td>176.4</td>
<td>158.8</td>
<td>163.9</td>
<td>147.5</td>
</tr>
<tr>
<td>40</td>
<td>247.7</td>
<td>222.9</td>
<td>235.2</td>
<td>211.7</td>
</tr>
<tr>
<td>100</td>
<td>675.5</td>
<td>608.0</td>
<td>663.0</td>
<td>596.7</td>
</tr>
</tbody>
</table>

Alveolar partial pressure of oxygen is calculated using the alveolar gas equation: \(\text{PAO}_2 = \text{FIO}_2 (\text{Patm} - \text{PH}_2\text{O}) - \text{PaCO}_2 / 0.8\). \text{PAO}_2 is the alveolar partial pressure of oxygen. FIO\(_2\) is the fraction of inspired oxygen. Patm is atmospheric barometric pressure specific to the elevation at or above sea level. PH\(_2\)O is the vapor pressure of water, which varies by patient temperature but is generally assumed to be ~47 mmHg. PaCO\(_2\) is the patient’s current arterial partial pressure of carbon dioxide. PaCO\(_2\) divided by 0.8 is the respiratory quotient, which is the ratio of CO\(_2\) molecules produced for O\(_2\) molecules consumed by the body. The normal alveolar to arterial gradient is <10–15% \(^95\) in room air and the PaO\(_2\) values calculated in Table 1.5 assume a 10% difference between alveolar and arterial partial pressures. PaO\(_2\) is a measured variable with arterial blood gases; the numbers in the above table are calculated as expected normal values on the basis of FIO\(_2\) and PaCO\(_2\) and measurement at sea level (Patm = 760 mmHg). Refer to equations for values 1.2–1.5 in the body of the text.
Patient Monitoring recommends measurement of BP as part of basic patient care during anesthesia.

Methods of arterial BP monitoring include both noninvasive and invasive techniques. Noninvasive methods include automated oscillometric BP monitors and manual Doppler BP monitoring. Invasive (direct) BP monitoring involves the placement of a catheter into a peripheral artery with connection to a fluid-filled pressure transducer system. All of the techniques have both advantages and disadvantages regarding the ease of placement, frequency and speed of measurement, invasive nature, and technical skill required for measurement and accuracy of measurement.

Invasive BP monitoring is the gold standard with which all other forms of BP measurement are compared. Direct monitoring is the most accurate BP measurement and offers additional benefits of being a continuous, second-to-second monitor for SAP, DAP, and MAP. Acute changes in the patient’s hemodynamic status can be appreciated rapidly, and alterations in the arterial pressure waveform can also provide information about patient status. The placement of an indwelling arterial catheter also allows for sampling of arterial blood for arterial blood gas analysis. Invasive BP monitoring has significant drawbacks, including the skill in placing arterial catheters in potentially hypotensive, unstable patients, the requirement for a multiparameter patient monitor with the capability of connecting to a fluid filled transducer system, the understanding of what causes error in the transducer system, and troubleshooting of the system. There is the risk of hemorrhage and reduced perfusion to tissues distal to the catheterization site. Despite these complexities, invasive pressure management is a mainstay of advanced cardiovascular monitoring.

Noninvasive pressure monitoring includes both automated oscillometric monitoring devices and Doppler ultrasound BP monitoring. Oscillometric monitoring devices use the principle of oscillometry to determine BP. An automated cuff is inflated above SAP, occluding arterial blood flow. As cuff pressure is reduced, the arterial pulse begins to generate oscillations in the arterial wall that are transmitted to the cuff. These oscillations increase and then decrease in amplitude as cuff pressure is reduced, and eventually the oscillations are eliminated as blood flow becomes laminar. Although technology and calculation algorithms vary between oscillometric devices, generally, the onset of oscillations is considered SAP, maximal oscillation amplitude MAP, and the cessation of oscillations DAP. Oscillometry carries the advantage of automation and ease of use. However, oscillometric devices are fraught with error, including inappropriate cuff size. The cuff should be ∼40% of limb circumference; overlarge cuffs lead to inappropriately low readings, and inappropriately small ones lead to falsely elevated measurements. Other issues with oscillometric devices include motion artifacts and interference from high HRs or potentially cardiac arrhythmias. Studies comparing the accuracy of oscillometric BP cuffs to direct BPs found limited agreement with MAP and DAP in anesthetized dogs: “67% and 95% of readings were within 10 and 20 mmHg of invasive pressure values, respectively.” Another study found poor correlation such that a 25-mmHg bias was identified between invasive and oscillometric pressure in anesthetized cats. Oscillometric BP devices also carry the disadvantages of slow performance compared to continuous arterial catheters.

Doppler BP devices use a BP cuff that is manually inflated over SAP. A Doppler crystal is placed over a peripheral artery, and blood flow is audibly demonstrated with appropriate Doppler sound. Inflation of the cuff occludes flow, and the Doppler signal is lost. As the cuff is manually deflated, blood flow begins to pass through the cuff and is again audible via the Doppler crystal. This is generally interpreted as the peak pressure or SAP. Doppler BPs can be checked manually more frequently than oscillometric devices, carry more confidence for the user in that the user can hear blood flow, provide an audible signal to the anesthetist that there is a blood flow (a comforting sound for many anesthetists), and are simple to use. A Doppler crystal placed over a peripheral artery provides the anesthetist with an audible signal for blood flow, which can be a strong comfort for those moments the anesthetist’s attention cannot be on the patient or patient monitor. The placement of Doppler crystal also allows for a second assessment of BP should an arterial catheter fail. Disadvantages of Doppler crystals include that they are somewhat fragile, require more skill for placement to obtain an audible signal, and show inability to accurately predict SAP. For example, multiple studies have evaluated the assessment of SAP with Doppler noninvasive measurement compared to invasive BPs. In cats, poor agreement was found between invasive SAP and Doppler BPs, such that the Doppler underestimated SAP by ~14 mmHg.
to ~25 mmHg.\textsuperscript{98,99} Doppler BP measurement was not recommended when accuracy is desired. However, in rabbits, direct SAP was found to have good agreement with Doppler BP.\textsuperscript{107}

**Electrocardiography (ECG)**

ECG monitoring allows analysis of the cardiac rhythm. Understanding the components of the cardiac rhythm and how it relates to mechanical function of the heart allows the anesthetist to analyze the rhythm for changes that would indicate abnormalities. These abnormalities might imply that there is asynchrony in mechanical function of the heart and further correction may improve mechanical function, CO, and perfusion. Although ECG monitoring does not "prove the patient is alive," as there can be dissociation between the electrical and mechanical activity (termed pulseless electrical activity, PEA), it is nevertheless a basic requirement of patient monitoring during anesthesia.

**Pulse oximetry**

Saturation of hemoglobin in arterial blood is an important component of the CaO\textsubscript{2} equation. As the vast majority of oxygen is carried in the hemoglobin molecule, the degree to which hemoglobin is saturated with oxygenated blood is a critical variable in oxygen delivery. The pulse oximeter is a simple tool that measures the oxygen saturation of arterial blood (SpO\textsubscript{2}). Hemoglobin saturation of ~90% is correlated with a PaO\textsubscript{2} of ~60 mmHg, well into the hypoxic range. Therefore, a hemoglobin saturation of >93–94% is required to ensure normoxia. Many variables can interfere with the ability of the pulse oximeter to provide an accurate arterial saturation (Table 1.6).\textsuperscript{110}

<table>
<thead>
<tr>
<th>Table 1.6 Pulse oximetry: sources of error\textsuperscript{138–140}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motion artifact</td>
</tr>
<tr>
<td>Thickness of tissue</td>
</tr>
<tr>
<td>Tissue hypoperfusion/hypotension</td>
</tr>
<tr>
<td>Vasocstriction</td>
</tr>
<tr>
<td>Hypothermia</td>
</tr>
<tr>
<td>Tissue pigment</td>
</tr>
<tr>
<td>Met-hemoglobinemia (tends to 85% when Met-Hgb ~30%)</td>
</tr>
<tr>
<td>Carboxy-hemoglobinemia (tends toward 90%)</td>
</tr>
<tr>
<td>Intravenous dye injections (indocyanine green, methylene blue)</td>
</tr>
<tr>
<td>Ambient light at 660, 920 nm wavelength(s)</td>
</tr>
<tr>
<td>Severe anemia (hemoglobin &lt; 5 g d\textsuperscript{−1})</td>
</tr>
</tbody>
</table>

**Core body temperature**

Hypothermia has varying effects on the basis of the degree of body temperature loss.\textsuperscript{5} Essentially, all patients will become hypothermic to some degree due to the effects of premedication and induction of anesthesia, unless active heat support is provided. Causes of hypothermia include, but are not limited to, opioid, phenothiazine and alpha-2 adrenergic-mediated changes in thermoregulation, high surface area to body mass ratio, high cold-compressed oxygen flow rates, open body cavities, cold surfaces, room temperature IV fluids, cold scrub solutions, and body cavity lavage (especially orogastric lavage with fluids below body temperature). Mechanisms for heat loss include evaporation, conduction, and convection and heat loss from respiration and radiant heat loss.\textsuperscript{111} Anesthetized patients also have decreased heat production due to central depression and inability to shiver in response to hypothermia. It is far easier to prevent than it is to treat hypothermia, as the peripheral vasoconstrictive effects of hypothermia make external rewarming difficult and inefficient. Consideration of the aforementioned variables for an individual patient or procedure will help the anesthetist generate a robust heat loss prevention or rewarming plan.

The physiologic effects of hypothermia vary with severity and include catecholamine release, decreased cerebral metabolic rate of oxygen consumption and intracranial pressure, and altered electroencephalogram and arterial blood gas results.\textsuperscript{112,113} At moderate levels, hypothermia decreases inhalant requirements, reduces concentrations of inhalant required to produce apnea, decreases CO and BP, and increases SVR. In addition, moderate hypothermia results in bradycardia, prolonged clotting times, decreased drug metabolism, prolonged nerve conduction and muscle contraction, and a left shift of the oxygen–hemoglobin dissociation curve (which favors hemoglobin loading).\textsuperscript{114} With these profound physiologic changes, it is clear that body temperature should be controlled in any anesthetized patient and especially in one who may have preexisting cardiovascular compromise, as they may lack the reserves to compensate.

**Capnometry and ventilation**

Capnometry is the assessment of exhaled carbon dioxide as an indicator of ventilatory adequacy. Capnometry refers to the measurement of end-exhalation (end-tidal)
CO₂; a capnograph provides a visual waveform display of the measurement of CO₂ over time. However, the term capnography is often used to imply all of these components. Hypoventilation is defined by an increase in the PaCO₂ with a subsequent increase in end-tidal CO₂ levels. Hypoventilation leads to respiratory acidosis and should be avoided in patients with cardiac disease, as ideal cardiac function occurs at normal blood pH; acute respiratory acidosis has been shown to increase HR and CO but decrease myocardial contractility and SVR. Hypercapnia increases catecholamine release and can result in tachyarrhythmias from the combination of acidosis, electrolyte changes due to acidosis, and carbon dioxide-mediated increases in catecholamine release. It is possible to roughly estimate the change in pH on the basis of the increase in PaCO₂; for every 10–20 mmHg increase in PaCO₂, arterial pH will decrease by ∼0.1 pH unit.

Assisted or controlled ventilation can be helpful in maintaining normoventilation, to optimize oxygenation (SpO₂ or PaO₂) and improve inhaled anesthetic depth. Mechanical ventilation can be provided either with a controlled mechanical ventilator or with intermittent assisted manual ventilation (“bagging”). It is nearly impossible to provide the same consistency, tidal volume, respiratory rate, peak inspiratory pressure, and duration of inspiration with manual ventilation as compared to mechanical ventilation, and the use of mechanical ventilators is strongly recommended to maintain this consistency and allow the anesthetist to attend to other tasks.

However, mechanical ventilation can and very often will decrease BP by one of three mechanisms. Firstly, tidal volume via mechanical ventilation is very likely to be larger than that of a spontaneously taken breath. Therefore, mechanical ventilation represents an increase in anesthetic delivery via a larger number of isoflurane molecules being delivered with a larger tidal volume. Inhaled anesthetics subsequently cause dose-dependent decreases in BP, mediated by decreases in myocardial contractility and SVR. Secondly, increases in intrathoracic pressure during positive pressure ventilation decrease venous return (i.e. preload), leading to reduced SV, CO, and BP. The effects on CO are more pronounced with more frequent respiratory rates, longer inspiratory phase duration, and larger tidal volumes. Lastly, high PaCO₂ can increase sympathetic tone and improve BP, an effect that is reduced when patients are ventilated to a normal or even low end-tidal CO₂.

**Arterial blood gases**

Arterial blood gas analysis is a useful direct measurement of PaO₂ and PaCO₂ to evaluate pulmonary function and quality of ventilation. Serial monitoring of arterial blood gases can allow the anesthetist to better direct adjustments in ventilation to maintain oxygenation and normal carbon dioxide levels. The availability of arterial catheters allows for continuous invasive pressure monitoring, as well as serial blood sampling for clinical pathology. Normal values for arterial blood gas values are presented in Table 1.5.

**Central venous pressure (CVP)**

Central venous pressure (CVP) is the intraluminal pressure measured in the intrathoracic vena cava immediately outside the right atrium. CVP is the difference in pressure between the atmosphere and IV at this location. It is often used as an indicator of right ventricular preload and overall patient intravascular volume status, as well as in assessment of right heart function and critical patient care monitoring. However, right ventricular preload is truly defined by the difference between the intracardiac (i.e. right ventricular) and extracardiac transmural pressure gradient. A variety of factors can reduce preload but lead to an increase in measured CVP, which may lead the clinician to erroneously interpret an increase in preload. These include changes in intrathoracic pressure (changes in stage of ventilation, pleural effusion, and abdominal hypertension) and blood volume or cardiac arrhythmias. Decreases in right ventricular compliance also can increase CVP as end-diastolic filling pressures can be elevated with a "stiff" ventricle, pericardial disease, or pericardial tamponade. Ultimately, CVP represents the balance between volume return to the heart and cardiac function. There are many excellent, in-depth published reviews of CVP monitoring. Although CVP monitoring requires a complete understanding of these variables and the ability to trend values over time, it can be a valuable tool in monitoring patients under anesthesia in select cases.
Chapter 1. Cardiovascular disease

Anesthetic and pharmacologic recommendations for specific cardiac diseases

Valvular heart disease

Introduction

Valvular heart disease accounts for over 50% of congenital heart disease in dogs; chronic AV valvular disease is the most common cardiac disease in dogs, whereas mitral valve insufficiency is in the top three causes of cardiac disease in cats. The prevalence of valvular disease in small animals necessitates a complete understanding of these comorbidities and how they affect and dictate the perianesthetic plan.

Preanesthetic evaluation

A common misconception is that most heart murmurs do not definitively require complete cardiac evaluation before anesthesia is planned and that all patients with heart disease must be managed similarly when anesthetized. As with any anesthetic patient, patients with underlying cardiac disease should be evaluated with a complete history (detailing both the long- and short-term changes in underlying disease), PE, and minimum database of bloodwork/urinalysis relevant for their signalment. In addition, patients with cardiac disease should be evaluated with thoracic radiographs, ECG, BP, and ECG, which are aimed at not only documenting presence of disease, but also assessing the severity of disease and possible response to previous treatments. As one of the main goals of perianesthetic management is maintenance of homeostasis, especially perfusion and oxygen delivery, preanesthetic cardiac evaluation should include assessments for cardiac pump function.

Degenerative mitral valve disease (dMVD)

Incidence and pathophysiology

Degenerative mitral valve disease (dMVD) is the most common cardiac disease in dogs, found in as much as 30% of the geriatric canine population. dMVD can also be referred to as myxomatous mitral valve degeneration, endocardiosis, degenerative valvular disease, and myxomatous degeneration; all these terms describe the same constellation of pathophysiologic and clinical signs. dMVD is grossly seen as an idiopathic development of nodular irregularities on the free edge of mitral valve leaflets. These nodules consist of deposition of mucopolysaccharides in the layers of the valve leaflet, which can increase in size and number over time. Pathophysiology of dMVD may also include distortion of the chordae tendineae such that they lengthen and/or thicken. When valve changes are severe, this leads to curling of the valve leaflet and subsequent AV valve incompetence. The valve may degenerate to the point at which valve leaflets can prolapse into the left atrium. When valvular changes are sufficient that leaflets do not oppose one another during ventricular systole, regurgitant flow of blood into the left atrium results. Mitral valve regurgitation may be trivial or severe, and volume of regurgitation is dictated by the size of the space between the valve leaflets, the pressure gradient between ventricle and atria, and the duration of systole. Mitral regurgitation leads to a volume overload on the left atrium, as pulmonary venous return is complemented by regurgitant flow. CO suffers as regurgitant flow increases, and the body compensates with renal, neurohormonal, and cardiac remodeling (left ventricular eccentric hypertrophy). High atrial pressures due to volume overload lead to atrial dilation, as well as increases in pulmonary vein pressures and congestion of pulmonary venous flow, which will eventually lead to pulmonary edema. Congestive heart failure (CHF) is the end result of chronic volume overload to the left atrium and pulmonary veins with eventual failure of adaptive mechanisms.

Physical examination findings

Dogs may present with lethargy, cough, exercise intolerance, weight loss, respiratory difficulty, or collapse. Patients may also present with other complaints, and a murmur may be auscultated in a patient with no previous history of cardiac disease. It is these patients who often require a more cautious approach to evaluation and anesthesia planning, a lack of clinical signs may provide a false sense of security with regards to potential anesthetic complications. The classic heart murmur for dMVD is a holosystolic murmur, loudest over the left apex of the heart. The intensity of the murmur tends to be consistent over the duration of
systole, with no increase or decrease in the loudness of the murmur. Often, the second heart sound is inaudible. The intensity of the murmur is not correlated with the severity of regurgitant flow, but in general, louder murmurs indicate worse regurgitation. Pro-lapse of the mitral valve may result in a midsystolic click.

Anesthetic management

Anesthetic management can cover the spectrum from patients with fully compensated, nonclinical disease to those at high risk for heart failure. No consensus statements exist regarding the management of either end of this spectrum. Patients with stable, compensated disease with no left atrial enlargement and no clinical signs of pulmonary edema or heart failure generally do not require intensive management. As a portion of left ventricular ejection regurgitates into the left atrium, CO is compromised, and the patient with dMVD is thought to compensate for this with increases in HR. Normal to high normal HRs are recommended for any particular signalment. Therefore, it is optimal to consider anticholinergics in the anesthesia plan, particularly if opioids are to be administered. Opioids are considered to be extremely safe as part of an anesthesia plan for a patient with dMVD, as the cardiovascular effects are primarily limited to bradycardia, which is easily treated or prevented with the use of anticholinergic agents. Hypothermia should be avoided by using supplemental heat support to avoid hypothermia-related bradycardia. Stable patients should tolerate inductions with ketamine and diazepam/midazolam. Alternatively, they should tolerate the dose-dependent vasodilation with propofol induction; however, the dose of propofol should be minimized using preanesthetic sedatives and/or combining propofol with benzodiazepines and/or opioids during induction. The severe negative inotropic effects and mild to moderate vasodilation associated with inhaled anesthetics can be minimized by additional use of local, regional, or systemic sedatives and analgesics. Opioids are well suited for this purpose. Alpha-2 adrenergic agonists are contraindicated due to the severe increase in afterload and the potential for increased regurgitant flow, as well as severe decreases in HR and CO.

Unstable patients, such as those at significant risk for onset of heart failure or a previous history of heart failure, those with arrhythmias, or those with preexisting cardiovascular compromise must be handled with extreme caution. Preinduction stabilization of heart failure, hypotension, and arrhythmias must be attempted. Complete cardiac evaluation (PE, thoracic radiographs, ECG, BP, and echocardiogram) is optimal. Anesthetic management includes all efforts made to minimize or mitigate the cardiovascular compromise due to inhaled anesthetics and reliance on balanced anesthesia. As stated previously, alpha-2 adrenergic agonists are contraindicated. Sedation with opioids and benzodiazepines is recommended, as they have minimal effects on cardiovascular function; opioid-mediated bradycardia can be minimized or prevented with anticholinergics. Although optimal sedation is ideal, oftentimes, good sedation has to be sacrificed in the name of cardiovascular stability, as induction of anesthesia is approached. Midazolam followed quickly by etomidate is a good induction choice because they have minimal to no cardiovascular side effects. Fentanyl and midazolam may also be used for induction, provided opioid-associated bradycardias (and respiratory depression) are controlled and the patient is sufficiently sedated beforehand or is quite compromised. Alternatively, some patients may require induction with propofol despite the risk of dose-dependent vasodilation and hypotension. In these situations, reducing the dose of propofol with preinduction sedation and/or combining propofol with one (i.e. midazolam) or two (i.e. midazolam/fentanyl) additional induction drugs can minimize propofol doses. Inhaled anesthetic dose should similarly be minimized with additional local, regional, or systemic analgesics and sedatives. Monitoring in patients with severe mitral valve disease should include either Doppler noninvasive BPs or invasive BP monitoring.

Mitral valve stenosis (MVS)

Incidence and pathophysiology

Mitral valve stenosis (MVS) is a rare finding in dogs, with only 12 reported cases in a 10-year period in one reference. Stenotic lesions may involve the valve annulus, leaflets, chordae tendineae, or papillary muscles and present as a valvular or supravalvular lesion. The heart murmur associated with MVS is a mid-diastolic low frequency murmur and possibly a split S2. The stenotic lesion creates a pressure gradient across the valve and leads to an increase in left atrial pressure, which is transmitted to the pulmonary vasculature and can lead to pulmonary edema with
severe stenosis. Diagnosis of MVS may be made only when a patient presents with left heart failure and the defect is identified with echocardiography. The treatment for MVS is frequently medical, as surgical options are extremely high risk and should only be considered when all alternatives have been exhausted. The goal of medical intervention is to manage signs of left-sided heart failure and to decrease left atrial pressure and signs of left heart failure with diuretics and angiotensin-converting enzyme (ACE) inhibitors. Sodium restriction is recommended in humans and small animals. Additional treatment may be required for supraventricular arrhythmias such as atrial fibrillation or supraventricular tachycardia (SVT).

Anesthetic management

Anesthetic management of these patients largely depends on the severity of clinical presentation. The anesthetic goal is to prevent any situation wherein CO is significantly impaired or they are put at risk of development of pulmonary edema. With MVS, CO can be decreased by multiple mechanisms. For example, as MVS worsens in severity, ventricular filling depends increasingly on diastolic filling time and right atrial pressure. Tachycardia or tachyarrhythmias will decrease diastolic filling time and worsen ventricular filling and subsequently CO. Loss of association between atrial depolarization or the atrial kick boosting end-diastolic volume (10–30% of end diastolic volume) and ventricular contraction/ejection will worsen CO. Therefore, arrhythmias affecting AV coordination should be treated rapidly in these cases. Atrial fibrillation and SVTs can develop, while anesthetized and the ECG should be evaluated before and through induction of anesthesia. Acute vasodilation and decreases in atrial preload may worsen ventricular filling, as the normal response to acute hypotension is tachycardia. Lastly, the pressure overload to the pulmonary vasculature from MVS can precipitate pulmonary edema. Avoidance of increases in blood volume that has the potential for precipitating CHF is strongly recommended.

Patients with mild MVS can likely be managed with any anesthetic plan with the exception of ketamine and tiletamine. Both dissociative agents will increase catecholamine release, which increases sympathetic tone, leading to tachycardia and increases in myocardial contractility. If diastolic filling time decreases significantly, CO can drop precipitously. Similarly, tachycardia from patient stress, anxiety, and pain can decrease CO. Good preanesthetic sedation is optimal to prevent tachycardia. Opioids and benzodiazepines are attractive options, as they do not significantly decrease HR, contractility, or vascular tone. While some opioids are good sedatives, benzodiazepines are inconsistent sedatives in small animals and can precipitate mild dysphoria or excitement in dogs and undesirable behavioral changes including potentially aggression in cats. Anticholinergic agents are controversial in that they can precipitate tachycardia. However, anticholinergics can be indicated if there is a preexisting bradycardia or second-degree AV block. Patients with mild disease can likely tolerate the vasodilation associated with propofol for induction, but combination with an opioid (propofol-fentanyl) or benzodiazepine (propofol-midazolam) is recommended to reduce the total dose of propofol. If patients have severe disease with significant cardiovascular compromise, anesthetic induction can be achieved with etomidate or fentanyl in combination with a benzodiazepine. Monitoring of patients with MVS also depends on their degree of disease and anticipated complications. Patients with mild disease can likely be monitored as for any patient. Patients with advanced disease may require invasive BP monitoring, arterial blood gas assessment to evaluate pulmonary function, and CVPs. Patients with severe disease may warrant referral to specialty centers for consultations with veterinary cardiologists and anesthesiologists for management.

Tricuspid valve stenosis (TVS)

Incidence and pathophysiology

Tricuspid valve stenosis (TVS) as an independent finding is rare in small animals, and tricuspid valve incompetence is far more often due to tricuspid valve dysplasia or is the result of underlying cardiac disease. Similar to MVS, it may result from abnormalities of the annulus, valve leaflets, or papillary muscles. Labradors or breeds at risk for AV valve disease such as Newfoundlands and Bull terriers may be at higher risk.

Anesthetic management

Should TVS be identified as an isolated finding, recommendations for anesthetic management are the same as MVS. Given the rarity of isolated TVS, other causes for tricuspid valve incompetence must be investigated in patients who have suspicion of tricuspid valve disease.
Aortic stenosis (AS)
Incidence and pathophysiology
Aortic stenosis (AS) is the most common congenital cardiac disease of large breed dogs such as Boxers, Great Danes, Rottweilers, Golden Retrievers, German Shepherds, English Bulldogs, and Bouvier des Flandres and has been described as heritable in Newfoundlands. Subvalvular aortic stenosis (SAS) can be due to valvular, supravalvular, and subvalvular lesions; however, SAS is the most common finding in dogs representing more than 95% of lesions identified. The site of SAS is the left ventricular outflow tract (LVOT), which comprises the membranous and muscular portions of the basilar interventricular septum, the craniolateral left ventricular free wall, and the anterior mitral valve leaflet.

AS can be described as fixed or dynamic. Fixed SAS is due to an anatomic abnormality creating the stenotic lesion; the severity of the obstruction does not change with rate or velocity of flow through the area. Fixed SAS has been graded in cadavers depending on the anatomic findings. For example, grade 1 has minor changes (endothelial nodules) in the subaortic endocardial surface, grade 2 has a narrow fibrous band around part of the LVOT, and grade 3 has a complete band of tissue surrounding the entire LVOT. Dynamic SAS is an obstruction in the LVOT that changes on the basis of the rate of flow through the subaortic outflow tract. Increases in HR or cardiac contractility lead to a decrease in intraluminal pressure (on the basis of the Bernoulli principle) and an increase in the degree of LVOT obstruction (LVOTO). Dynamic SAS is most commonly identified in HCM and can be referred to as hypertrophic obstructive cardiomyopathy (HOCM).

The principal hemodynamic consequence of outflow tract obstruction is an increase in resistance to systolic ejection of blood from the ventricle, thereby decreasing flow through the outflow tract, increasing pressure across the stenosis, or both. Left ventricular pressure is increased and results in compensatory concentric hypertrophy to maintain left ventricular output. The ejection of blood through the stenotic area results in turbulence of blood during systole and a resultant systolic murmur, typically described as an ejection murmur that increases and then decreases (crescendo-decrescendo) through systole. SAS and LVOTO along with the left ventricular hypertrophy typically do not lead to left-sided heart failure. However, left ventricular hypertrophy, a decrease in capillary density, and increased wall tension predispose to myocardial ischemia. Patients who develop this pathophysiology are at risk for syncope, ventricular arrhythmias, and sudden death, although it is unclear which of these is the definitive cause of death. Another possible explanation for sudden death is exercise-induced increases in left ventricular pressure (in addition to pathologically high resting left ventricular pressure) and activation of ventricular mechanoreceptors that lead to vasodilation and bradycardia; the Bezold-Jarisch reflex. Damage to aortic valve leaflets from high velocity regurgitant jet flow can predispose the valves to bacterial endocarditis associated with bacterial shower from surgical or dental procedures or from concurrent noncardiac infectious causing bacteremia. Prophylactic antibiotics are recommended for all anesthetized procedures to minimize the risk of endocarditis.

Anesthetic management
Anesthetic management in patients with SAS can become very complicated and requires intensive monitoring and antiarrhythmic treatments to maintain normal ventricular filling and optimal CO. Patients should remain in a normal sinus rhythm without sinus tachycardia or bradycardia, and one should be prepared to treat ventricular ectopy or atrial fibrillation. For example, left ventricular CO is dependent on the organization of atrial and ventricular contraction. Thus, AV blocks or atrial fibrillation will lead to loss of the atrial kick and reduction of left ventricular end-diastolic volume. Sinus tachycardia prevents diastolic filling time and should be avoided. Sinus bradycardia leads to poor CO and hypotension, subsequently leading to poor coronary and myocardial perfusion in a thickened left ventricle. Thus, HR should be kept in the normal range to prevent decreased tissue perfusion. Ventricular premature complexes (VPCs) cause contraction before complete ventricular filling and lead to a decrease in CO. Prompt treatment of ventricular ectopy is important, as the presence of ventricular rhythms can be a risk factor for sudden death.

Premedication in patients with moderate to severe AS should provide adequate sedation/analgesia to prevent anxiety, pain, or stress-related tachyarrhythmias. Anticholinergic agents are indicated to prevent bradycardia and AV blocks. The administration of Acepromazine is controversial due to long acting vasodilation but may be tolerated in the minimally affected patient if anxiety is
present and tranquilization is required. Anesthetic drugs contraindicated in AS include dissociative anesthetics (ketamine and tiletamine) and alpha-2 adrenergic agonists (xylazine, medetomidine, and dexmedetomidine). High dose anticholinergic agents are controversial in that it is difficult to predict the maximum HR a patient may develop in response to a typical dose of anticholinergic. It is worth considering titrating lower doses of anticholinergic agents for patients developing sinus bradycardia and assessing the response to low doses, rather than risk-inducing tachyarrhythmias with standard or high doses of atropine or glycopyrrolate. Induction of anesthesia can be accomplished with propofol, etomidate, or opioid-benzodiazepine combinations.

Pulmonic stenosis (PS)
Incidence and pathophysiology
Pulmonic stenosis (PS) is rarely identified in cats, but is the third most common cardiac defect identified in dogs. PS is the most common abnormality, with supravalvular and subvalvular stenosis being less common. PS is commonly identified as a sole lesion in dogs, but can be identified in combination with other cardiac abnormalities such as Tetralogy of Fallot (TOF). It is heritable in Beagles and Keeshonds, and a variety of breeds have increased risk for PS, including English bulldogs, Cocker Spaniels, Mastiffs, Samoyeds and Miniature Schnauzers, Chihuahuas, and Chow Chows.

Pulmonic stenosis is due to variable congenital deformations and fusion of pulmonic valve leaflets. The degree of anatomical change and severity of pulmonary outflow tract obstruction are graded as either grade 1 with minimal to mild fusion and trivial to mild outflow obstruction or grade 2 that has moderate to severe valve deformation and fusion, with severe outflow obstruction. Severe obstruction leads to poststenotic main pulmonary artery dilation in response to the turbulent blood flow downstream from the affected valve. The primary pathophysiologic hemodynamic effect of PS is an increase in resistance to right ventricular systolic ejection, leading to increased right ventricular pressure. This pressure overload leads to concentric hypertrophy of the right ventricle as a compensatory response, thereby returning right ventricular output to normal or near-normal. The degree of pressure overload is related to the pressure gradient across the pulmonic valve and is correlated with the severity of disease.

Right ventricular hypertrophy decreases right ventricular compliance, reduces ventricular filling, and leads to an increase in right atrial pressure. This mechanism also underlies the tricuspid regurgitation in patients with tricuspid dysplasia (whether preexisting or as a result of change in right ventricular size), which can result in right heart failure, jugular distension/pulsations, ascites, and pleural effusion.

Anesthetic management
Definitive anesthetic recommendations for mild PS are lacking, but patients with clinically insignificant PS can likely be anesthetized with any technique. IV crystalloid administration during anesthesia should be limited (2–5 ml kg$^{-1}$ h$^{-1}$), and synthetic colloids should be avoided, as volume overload and right heart failure could be a concern, particularly in patients with concurrent tricuspid dysplasia. Patients with severe PS should be treated cautiously, and anesthetic management should be designed to minimize cardiovascular depression. Alpha-2 adrenergic agonists are contraindicated due to the significant increase in right atrial pressure. Acepromazine is controversial due to the long lasting, irreversible vasodilation, hypotension, and reduced right atrial preload. However, opioids for patient analgesia and sedation, as well as anticholinergics to prevent or treat opioid-associated bradycardia are recommended. Induction agents that preserve cardiac function and CO are preferred; combinations of etomidate or fentanyl with benzodiazepines have minimal cardiovascular depression, provided patients do not become bradycardic. Dissociative anesthetics are controversial and may be contraindicated in severe PS due to increases in SVR. Inhaled anesthetic doses should be minimized by opioid infusions to minimize vasodilation and significant decreases in contractility. Local and regional anesthetic techniques should be employed to reduce systemic and inhaled anesthetic requirements. Monitoring should consist of standard ECG, \text{SpO}_2, temperature, and capnography, as well as invasive BP management to allow observation in minute-to-minute changes in patient status.

Congenital cardiac disease
Congenital cardiac defects can be grouped according to their pathophysiologic mechanisms. The most common examples include those with left-to-right shunting.
of blood and volume overload (PDA and VSD), pressure overload (PS and SAS), and those which present for cyanosis (TOF, PDA, and VSD with shunt reversal [right-to-left]).

**Patent ductus arteriosus (PDA)**

**Incidence and pathophysiology**

PDA is one of the most common congenital abnormalities identified in dogs but is rare in cats. Predisposed breeds include the Chihuahua, Bichon Frise, Collie, Cocker Spaniel, Keeshond, Maltese, Miniature Poodle, Pomeranian, and Yorkshire terrier, among others. The defect is genetic in the Miniature Poodle. The ductus arteriosus is a fetal structure that allows shunting of blood (80–90% of total flow) from the pulmonary artery to the aorta necessary to avoid blood flow through the high vascular resistance of the fetal lungs. Increases in oxygen tension in the ductus with neonatal ventilation should lead to constriction of the ductus and closure within the first week of life. A PDA is the persistence of this fetal structure in the neonatal and juvenile patient. Morphology of a PDA can vary from a diverticular, funnel-shaped structure to a cylindrical tube between the pulmonary artery and vena cava. Blood flow for a left-to-right shunt is determined by the diameter in the shunt and the pressure gradient between the aorta and pulmonary artery.

Left-to-right shunting of blood occurs continuously in patients with PDA throughout the cardiac cycle because of higher systemic BP, as compared to pulmonary BP and is a function of relative resistances in the aorta as compared to pulmonary vascular resistance. This leads to constant volume overload of the left ventricle as shunt flow is added to normal pulmonary venous return. The volume overload leads to atrial and ventricular dilation and ventricular hypertrophy. When pulmonary vascular resistance increases and exceeds SVR, shunt flow will reverse and become right-to-left, leading to clinical cyanosis, as shunt flow does not circulate through the lungs.

**Anesthetic management**

Owing to the risk of shunt reversal, cyanosis, development of heart failure, arrhythmias, and other complications, it is recommended that patients with PDA be anesthetized by individuals intimately familiar with the pathophysiology of disease and the surgical/interventional procedures required to ligate/occlude PDA shunts; evaluation and treatment by veterinary specialists trained to safely handle these patients are strongly recommended.

Anesthetic factors to consider are primarily directed at the patients’ age and size. Neonatal or juvenile physiology leads to a variety of unique pharmacokinetic and pharmacodynamic alterations. For example, the cardiovascular system has lower myocardial contractile mass, low cardiac reserve, and high cardiac index; CO is HR-dependent primarily due to poor vasomotor control. The ability to increase contractility or vasoconstrict may be reduced, and treatments aimed at increasing contractility or providing vasoconstriction may be reduced or ineffective. The respiratory system is very compliant with high elastic forces, leading to increased airway resistance. Respiratory rates and minute ventilation are greater than in the adult. The hepatic and renal systems are immature, and drug effects may be pronounced or prolonged in these patients. Young patients have high body weight to surface area ratios and will lose body heat rapidly. Thus, heat support is critical in these patients. High body water content may lead to lower than adult packed cell volume (PCV) and albumin levels. Blood glucose regulation may be impaired; patient fasting should be shorter than adults, and supplemental dextrose may be warranted.

Patient size may present special challenges because they are usually quite small at presentation. Placement of monitoring equipment may be difficult, and the ability to access the patient during surgery may be limited. Venous access may be challenging, and access tubing should be confirmed and clearly labeled if the patient cannot be clearly visualized. Anticipated surgical or procedural complications can include hemorrhage, as well as complications from thoracotomy (pain, hypoventilation, hypoxia, ventilation/perfusion imbalance, etc.). Interventional catheterization carries the risk of hemorrhage, migration of the occlusive device into the pulmonary artery, and failure to occlude the PDA with conversion to thoracotomy.

Anesthetic drug selection is generally dictated by the unique neonatal/juvenile physiology; short acting, reversible drugs are recommended. For example, a combination of opioids, benzodiazepines, and anticholinergics is frequently used for sedation, analgesia, and HR support. Examples for premedication may
include hydromorphone, oxymorphone, methadone or morphine with or without atropine. In very young patients, additional sedation may be achieved with midazolam or diazepam. Anticholinergics are recommended, as CO is HR dependent and bradycardia can lead to significant hypotension. Acepromazine is not recommended, as juvenile patients are relatively more vasodilated than adults, have difficulties in increasing cardiac contractility and SVR, and diastolic runoff through the PDA leads to very low DAPs. Induction agents including ketamine, etomidate, and fentanyl/benzodiazepine are recommended. Propofol is not recommended as a primary induction agent because of the dose-dependent vasodilation. The requirement of maintenance agent can be reduced by concurrent infusions of opioids and/or lidocaine. Arterial pressure monitoring is recommended, although Doppler BP measurement is a reasonable alternative, given the difficulty of arterial catheter placement in these patients. Regional anesthesia including intercostal or intrapleural nerve blocks can be considered as a part of a balanced analgesic plan for patients undergoing thoracotomy. Intercostal nerve blocks are performed by intercostal intramuscular injection of local anesthetic along the caudal margin of the ribs, dorsal to the length of the incision, and two to three intercostal spaces cranial and caudal to the incision location for lateral thoracotomy. Total dose of lidocaine or bupivacaine is recommended to not exceed 2 mg kg\(^{-1}\), as the highest plasma concentration of local anesthetics is seen after intercostal nerve blocks, suggesting significant drug uptake from intercostal injection. Intrathecal analgesia can also be obtained by direct intrathecal infiltration of local anesthetic, again, not exceeding the 2 mg kg\(^{-1}\) maximum dose. Typically, bupivacaine is chosen for these regional techniques for the longer duration of action compared to lidocaine. Supplemental dextrose at 1.25–2.5% in maintenance IV fluids can be considered, and glucose monitoring is recommended. Additional complications of hemorrhage, arrhythmias, hypothermia, and others are treated as needed.

**Tetralogy of Fallot (TOF)**

**Incidence and pathophysiology**

TOF is a common congenital anatomic malformation, which can cause cyanosis. Predispensed breeds include the English bulldog, Keeshond, Miniature Poodle, and Schnauzer, as well as other breeds and cats. TOF is a combination of four anatomic derangements as follows: (1) VSD, (2) dextroversion with an overriding aorta, (3) PS, and (4) right ventricular hypertrophy due to obstruction in the right ventricular outflow tract (RVOT). Hemodynamic alterations are dependent on the degree of shunt through the VSD and the consequences of the PS. If PS is mild and resistance to RVOT flow is mild, then right ventricular pressures should be lower than left ventricular pressures and flow should be left-to-right. If PS is severe and represents significant outflow obstruction, then elevated right ventricular pressures can shunt blood right-to-left and lead to clinical cyanosis. Clinical cyanosis results in erythropoietin release and secondary polycythemia. Polycythemia (PCV >70–75%) can lead to increased blood viscosity and poor perfusion because of sludging of blood flow. Patients may seizure because of polycythemia.

**Anesthetic management**

The primary consideration for anesthesia in a patient with TOF is maintenance of normal systemic BPs to prevent reduction in left ventricular pressure. Decreases in left ventricular pressure can lead to shunt reversal (i.e. right-to-left) if right ventricular pressures are higher than left ventricular pressures. Right ventricular desaturated blood can subsequently enter the systemic circulation, resulting in cyanosis and decreased oxygen delivery. Premedication, induction, and maintenance anesthetic agents should be selected to prevent systemic hypotension as much as possible. Avoiding or minimizing doses of propofol (vasodilation) and inhaled anesthetics (negative inotrope and mild vasodilator) is recommended. Opioids are a mainstay of anesthetic management used to reduce inhaled anesthetic requirements. BP should be supported and hypotension rapidly treated to prevent further right-to-left shunting; this may include positive inotropic agents such as dopamine or dobutamine or vasopressors such as phenylephrine or norepinephrine. Invasive arterial pressure monitoring is recommended for patients with significant cyanosis or right-to-left shunting for both gold-standard monitoring of systemic BP and arterial blood gas sampling in the event of desaturation. Preoxygenation and postoxygenation are strongly recommended.
Ventricular septal defect (VSD)

Incidence and pathophysiology

VSD represent failures of complete development of the membranous or muscular interventricular septum. They are more likely seen in Keeshond and English Bulldogs but have been identified in a large number of breeds. The incidence in cats is unknown, but the prevalence in dogs and cats is low. VSDs can vary in size and pathophysiology, and clinical presentation depends on the degree and direction of shunting. Simple VSDs show left-to-right shunting in both phases of the cardiac cycle, and volume of flow is dependent on the shunt diameter. Small-to-medium size defects exhibit resistance to flow across the VSD, which typically minimizes the increase in right ventricular volume and does not result in increases in pulmonary circulation or pulmonary pressures. Large VSDs that do not cause resistance to flow across the VSD lead to pulmonary overcirculation and pulmonary hypertension (PHT). PHT can then increase right ventricular pressure and, if higher than left ventricular pressure, may lead to right-to-left shunting and clinical cyanosis. Increased pulmonary flow leading to increased left ventricular preload can lead to left ventricular hypertrophy and pulmonary edema because of the inability of the left ventricle to eject the increased pulmonary venous return.

Anesthetic management

Similar to TOF, anesthetic management is directed at preventing right-to-left shunting by maintenance of systemic BP. Anesthetic plans should be designed to minimally impact BP, and rapid support for hypotension should be available with positive inotropic agents (dopamine and dobutamine) or vasopressors (phenylephrine and norepinephrine) if needed. Monitoring and interventions for patients are similar to those for TOF.

Abnormalities of cardiac conduction and cardiac rhythm

The importance of a normal cardiac rhythm cannot be overstated. The essential function of the cardiovascular system is to provide tissues with oxygen and nutrients while removing the waste products of metabolism. More than any other, the one essential micronutrient that the body cannot survive without is oxygen. As previously discussed, oxygen delivery is the product of CO (l min$^{-1}$) and CaO$_2$ (ml O$_2$ 100 ml blood$^{-1}$). CaO$_2$ is the sum of oxygen bound by saturated hemoglobin and the PaO$_2$. CO is the product of HR and SV (milliliters blood ejected per heart beat). In order to maximize CO and optimize oxygen delivery, the contraction and relaxation of the heart must be sufficiently coordinated to allow diastolic ventricular filling and systolic ejection of blood. Cardiac arrhythmias, by definition, are disorganizations of the coordinated electrophysiologic and mechanical function of the heart and can rapidly lead to life-threatening reductions in CO and perfusion. Identification and treatment of arrhythmias are critical components of the management of patients before and during anesthetic events, as well as into the recovery period.

The behavior of electrical impulses and of the cardiac rhythm is largely determined by the shape of the action potential. The ECG is the electrical representation of the summation of all cardiac vectors measured in standard Lead I, II, or III configurations at the limb electrodes placed on the patient, graphed in voltage versus time. Changes in the shape of the cardiac action potential or ECG are determined by shifts of ions, particularly sodium, potassium, and calcium across the cardiac myocyte cell membrane. The movement of ions is determined by cell surface receptors and the electrochemical gradients of these ions across the membrane and is extensively reviewed elsewhere.

Electrophysiology of the conduction system

The cardiac action potential is described in four phases, labeled as Phase 0 through 4 during the progression of the cardiac cycle (Figure 1.10). Phase 4 represents the resting phase and is described by the resting membrane potential (RMP), the voltage measured across the myocyte cell membrane during the unstimulated state. RMP varies by the type of myocyte; specialized myocytes such as the sinoatrial (SA) nodal cells (Figure 1.10) and AV nodal cells have a different RMP as compared to a nonspecialized working cardiac myocyte.

The transmembrane RMP measured in the generic cardiac myocyte is −90 mV but can vary from −50 to −90 mV depending on the type of cardiac myocyte. In Phase 4, the cell membrane is relatively permeable to potassium (inwardly rectifying potassium current, IK1) and impermeable to sodium and calcium; therefore, the RMP is determined mostly by potassium as it moves out
Figure 1.10 Example myocardial action potentials. Representative membrane potential tracings of a ventricular myocyte (top) and SA nodal myocyte (bottom). Phase 4: resting membrane potential. Phase 0: rapid depolarization. Phase 1: initial repolarization. Phase 2: plateau phase. Phase 3: repolarization.

of the cell along the electrical and chemical gradients. The term “resting state” is somewhat misleading, as the RMP is also an active process due to the action of the basolateral sodium/potassium/ATPase pump, which actively moves sodium out of the cell against the concentration gradient.

Phase 0 is characterized by the depolarization of the myocyte cell membrane due to the rapid influx of sodium through rapidly opening voltage-gated sodium channels, down the electrochemical and concentration gradients such that the transmembrane potential reaches a positive value of $\sim +30$ mV. The reversal in polarity to positive in cell membrane potential opens the L-type calcium channels, allowing the onset of inward conductance of calcium that becomes important through Phase 2. The slope of Phase 0 represents the speed of depolarization of a single myocyte, and as conduction of the action potential through one myocyte dictates conduction to adjacent myocytes and spread of the action potential, the slope of Phase 0 determines conduction velocity through the heart. Pathologic states that slow sodium influx during Phase 0 reduce the speed of conduction of single myocytes and through the heart and can be the origin of cardiac arrhythmias or reentry circuits.

Phase 1 results from the return of the RMP toward neutral due to the inactivation of Phase 0 voltage-gated sodium currents, the onset of inward movement of calcium through L-type calcium channels, as well as transient inwardly rectifying potassium channels via voltage-gated potassium channels (IK-to).

Phase 2 is the sustained depolarization of the cardiac myocyte termed “the plateau phase,” which is a unique feature in electrically excitable tissues. The plateau is the balance of the inward movement of calcium via L-type calcium channels and the outward movement of potassium through a sodium/potassium exchanger current.

Phase 3 is the final repolarization of the cardiac myocyte and is primarily due to the increase in outward potassium conductance across the cell membrane via multiple slow, rapid, and delayed rectifier currents. At the same time, conductance of sodium and calcium decreases, allowing overall net movement of positive charge out of the cell and re-establishment of RMP at $\sim -50$ to $-90$ mV. Another mechanism of arrhythmia generation is the reduction in overall potassium outward movement during Phase 3 in the failing heart, leading to events such as early afterdepolarizations.

After the end of Phase 3, the cardiac myocyte enters a refractory period, wherein further stimulation cannot result in the generation of an action potential. The refractory period allows the heart to relax during diastole and the ventricles to reach an appropriate end-diastolic volume such that when the refractory period ends and the heart is again able to contract, a normal volume of blood is ejected and SV/CO is maintained. The refractory period prevents cardiac tetany and depolarization of one myocyte from the adjacent. This appropriately propagates the action potential in one direction, rather than allowing the passage of an action potential between two adjacent myocytes. The duration of the refractory period is roughly that of the action potential, such that the myocyte cannot be restimulated until the end of Phase 3. The refractory period can be divided into an (early) absolute refractory period, wherein no degree of stimulation can lead to depolarization, and a (later) relative refractory period, wherein a higher than normal stimulus has the potential to depolarize the myocyte.

**Mechanisms eliciting cardiac arrhythmias**

Cardiac arrhythmias can be classified on the basis of the electrophysiologic mechanism underlying the
generation of the abnormal rhythm. These mechanisms include disorders of impulse generation and impulse conduction and combined disorders. Specific arrhythmias of these classes are separated into sinus, supraventricular, and ventricular origin arrhythmias (Table 1.7).

Table 1.7 Classification of cardiac arrhythmias by mechanism.

<table>
<thead>
<tr>
<th>Normal sinus impulse formation</th>
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<tbody>
<tr>
<td>• Normal sinus rhythm</td>
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<tr>
<td>• Sinus arrhythmia</td>
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<tr>
<td>• Wandering sinus pacemaker</td>
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<tr>
<td>Disturbances of sinus impulse formation</td>
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<td>• Sinus arrest</td>
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<td>• Sinus bradycardia</td>
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<td>• Sinus tachycardia</td>
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<tr>
<td>Disturbances of supraventricular impulse formation</td>
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<tr>
<td>• Atrial premature complexes</td>
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<tr>
<td>• Atrial tachycardia</td>
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<tr>
<td>• Atrial flutter</td>
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<tr>
<td>• Atrial fibrillation</td>
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<tr>
<td>• Atrioventricular junctional rhythm</td>
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<tr>
<td>Disturbances of ventricular impulse formation</td>
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<td>• Ventricular premature complexes</td>
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<td>• Ventricular tachycardia</td>
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<td>• Ventricular asystole</td>
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<tr>
<td>• Ventricular fibrillation</td>
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<tr>
<td>Disturbances of impulse conduction</td>
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<tr>
<td>• Sinoatrial block</td>
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<tr>
<td>• Persistent atrial standstill (‘silent’ atrium)</td>
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<tr>
<td>• Atrial standstill (hyperkalemia)</td>
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<tr>
<td>• Ventricular pre-excitation</td>
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<tr>
<td>• First-degree AV block</td>
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<tr>
<td>• Second-degree AV block</td>
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<tr>
<td>• Complete AV block (third degree)</td>
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<tr>
<td>• Bundle branch blocks</td>
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<tr>
<td>Disturbances of both impulse formation and impulse conduction</td>
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<tr>
<td>• Sick sinus syndrome</td>
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<tr>
<td>• Ventricular pre-excitation and the Wolff-Parkinson-White (WPW) syndrome</td>
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<tr>
<td>• Atrial premature complexes with aberrant ventricular conduction</td>
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<tr>
<td>Escape rhythms</td>
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<td>• Junctional escape rhythms</td>
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<tr>
<td>• Ventricular escape rhythms (dioventricular rhythm)</td>
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Normal sinus impulse formation
The normal ECG waveform is generated from the coordinated conduction of the action potential from the SA node across the atria to the AV node, through the AV node to the Bundle of His, and into the ventricular Purkinje system. The conduction is subsequently carried rapidly through the ventricles, leading to coordinated muscular contraction of the ventricles. Repolarization of the ventricular myocardium is the terminal event of a single ECG complex.

Atrial depolarization is seen as the P wave. P wave amplitude and duration can vary with changes in body position relative to electrode position, vagal tone, and with arrhythmias or cardiac disease. Conduction of the action potential through the AV node is represented by the P–R interval. Shortened P–R intervals can be due to accessory atrial pathways increasing rate of atrial conduction. Prolongation of the P–R interval is the classic finding for first-degree AV block. Atrial repolarization occurs during ventricular depolarization and is not seen on the ECG waveform. The QRS complex is formed from ventricular depolarization (ventricular septum, left and right ventricular free walls; Figure 1.11). The S–T segment is the time between the end of ventricular depolarization and beginning of ventricular repolarization. Both S–T segment elevation and depression can be abnormal findings; elevation can be due to myocardial hypoxia, pericardial effusion or digoxin toxicity (cats), and S–T segment depression due to hypoxia, hyper/hypokalemia, infarction, or digoxin.
Figure 1.12 Einthoven’s triangle. Einthoven’s triangle illustrates the vectors of electrical measurements through the heart on the basis of lead selection. The physics of electrical potential measurement states that the highest amplitude measurement occurs when the vector of measurement is parallel to that of electrical potentials. Electrical potentials that are perpendicular to the vector of measurement have a measured amplitude of zero. Myocardial potentials that are oblique to the vector of measurement have an amplitude between these extremes. A Lead II ECG shows the highest amplitude tracings as Lead II parallels electrical potentials from SA to AV node and through the His-Purkinje system to the ventricular myocardium. As the normal left ventricular myocardium has more mass than the right ventricular myocardium, it has a larger sum of electrical activity/potentials, and the overall direction of electrical potentials is from SA to AV node to the left ventricle. For this reason, Lead II is the most common ECG tracing used during general anesthesia. Source: Cardiac image courtesy of D. Altman, www.ECGguru.com.

Ventricular repolarization occurs after the QRS complex and is represented by the T wave.

Evaluation of the ECG rhythm
Clinical evaluation of the ECG during anesthesia is typically performed in a Lead II arrangement. Each lead arrangement has a positive and negative electrode, described by Einthoven’s triangle (Figure 1.12). The principal cardiac vector during normal sinus rhythm is from the SA node to the left ventricular free wall. Lead II ECG (negative right arm to positive left leg) measures parallel to this vector, typically resulting in the largest amplitude ECG waveform.

Evaluation of the ECG for arrhythmias requires a systematic approach to ensure arriving at an accurate diagnosis, and it is a common mistake to interpret the ECG and diagnose an arrhythmia with an “at-a-glance” approach. The following variables should be evaluated to identify ECG abnormalities.

Heart rate (HR)
HR will be averaged by the patient monitor over a specific duration of time, typically 6–10 s. Although this may be sufficient for some arrhythmias, manual calculation of the HR, whether an average over time or a calculated instantaneous rate (HR between two consecutive complexes), is recommended as a patient monitor can incorrectly calculate HR with irregular rhythms. HR allows classification of tachyarrhythmias and bradyarrhythmias, which are species dependent.

P–QRS relationship
The anesthetist must ensure that there is a QRS present for every P wave and a P wave for every QRS complex. P waves not followed by a QRS are typical of second and third-degree AV block. In small animals, the P wave has a positive deflection. Rounded P waves indicate an abnormality in the SA node, and P waves of different or variable morphology may represent ectopic atrial
contractions. Absence of P waves is seen with hyperkalemia, atrial standstill, atrial fibrillation, or P waves lost within a dissociated QRS complex (third-degree AV block). Inverted P waves (negative in Lead II) indicate that the P wave origin is near the AV node and travel toward the Lead II negative electrode (right arm).

Rhythm regularity is assessed by measuring the R–R interval between two successive QRS complexes, most easily accomplished with calipers. A regular rhythm is one in which the R–R interval is consistent. Regular rhythms with a consistent R–R interval include normal sinus rhythm, sinus tachycardia, sinus bradycardia, SVT, and ventricular tachycardia. Irregularity can be described as “regularly irregular” where there is irregularity with a pattern (AV blocks, sinus arrhythmias, and wandering pacemakers) or as “irregularly irregular” where there is no pattern to the rhythm (e.g. atrial fibrillation). Usually, the faster the rhythm, the more difficult it is to detect regularity or irregularity. Printing ECG strips at faster paper speeds (e.g. 50 mm s⁻¹) can assist in unmasking irregularity if difficult to determine compared to slower paper speeds (12.5 or 25 mm s⁻¹).

QRS morphology

Morphology of the QRS complex can aid in identification of supraventricular or ventricular origin waveforms. Ventricular origin ectopic complexes rarely conduct through the Purkinje system, and therefore the wave of depolarization must spread cell to cell. Cell-to-cell conduction is far slower (∼1 ms⁻¹) compared to conduction rates of the Purkinje system (∼100 ms⁻¹), and therefore the ECG trace of an ectopic ventricular complex is wide and bizarre. Narrow complex QRS morphology is consistent with supraventricular origin complexes that pass through the AV node and spread via the Purkinje fibers and lead to extremely rapid (and therefore narrow) QRS complexes.

Periodicity

Periodicity is the frequency of an arrhythmia and is described as either a sustained, incessant abnormality or nonsustained, paroxysmal rhythm. The term paroxysm is often reserved for an arrhythmia that converts from totally normal to totally abnormal between two QRS complexes, for example, the sudden, acute paroxysm of SVT or ventricular tachycardia.

Specific arrhythmias

Sinus arrhythmia

Sinus arrhythmia is the most commonly seen regularly irregular sinus rhythm during the respiratory cycle, wherein HR increases with inspiration and decreases with expiration. This is due to changes in underlying vagal tone through the respiratory cycle and the effect of changing vagal tone on HR. It is common in the canine but is abnormal in the feline. If required, treatment is directed at increasing sympathetic tone or normalizing HR if bradycardic. Owing to the effects of premedication and induction agents and subsequent effects on parasympathetic tone, sinus arrhythmia can be a normal finding while anesthetized.

Wandering sinus pacemaker

A wandering pacemaker is a sinus rhythm with variation in the origin of the P wave within the SA node and is likely due to the effects of variable vagal tone to the SA node. It is seen as a cyclic variation in P wave configuration in the midst of a normal sinus rhythm. The P wave may occasionally be isoelectric and therefore undetected on the ECG trace.

Sinus arrest

Sinus arrest is the failure of the SA node to produce a depolarization and subsequent PQRS complex due to severely depressed automaticity of the SA node. For a diagnosis of sinus arrest to be made, the R–R interval of the period of arrest must be a minimum of twice the R–R interval of the underlying sinus rhythm. However, pauses of 5–12 s are not impossible and can be terminated by an escape ventricular complex, junctional escape complex, or sinus complex. Sinus arrest can result in clinical signs of weakness or syncope. Possible causes of sinus arrest include carotid sinus or ocular stimulation, SA nodal fibrosis, drug effects (digoxin, beta-blockers), or hyperexcitability of the vagus nerve (“vagotonia”) with intrathoracic or cervical mass manipulation. Treatment of sinus arrest can include termination of the stimulating cause and attempts at anticholinergic therapy; however, if severe, mechanical pacemaker implantation may be required.

Sinus bradycardia

Sinus bradycardia is a normal sinus rhythm of lower than normal expected rate. Assessment of normal HR varies with species and breeds. It may be a normal
finding in a very calm, athletic, or sleeping patient but can also be a consequence of drug therapy (opioids, alpha-2 adrenergic agonists, propofol, beta-blockers, calcium channel blockers, and digoxin), pathophysiologic (hypothyroidism and hyperthermia), or a result of cardiac disease (sick sinus syndrome) or elevations in vagal tone. Treatment for sinus bradycardia is recommended if there are signs of reduced perfusion, CO, or BP. If no contraindications exist, a bradycardic animal that is hypotensive should have the HR increased with anticholinergic therapy to improve CO and BP before other treatments to improve BP are attempted.

**Sinus tachycardia**

Sinus tachycardia is a sinus rhythm in excess of the normal range, typically HR >160 beats per minute in dogs and >200–220 beats per minute in cats. It can be a normal physiologic response to pain, stress, or anxiety, due to drug overdoses of anticholinergics, catecholamines, their derivatives (positive inotropes such as dopamine and dobutamine), or thyroid over-supplementation. Pathologic sinus tachycardia can be seen with pain, hyperthyroidism, fever, shock, CHF, and early stages of hypoxia (hypoxic, ischemic, hypemic, and/or histotoxic). Treatment of sinus tachycardia before or during anesthesia requires ruling out possible causes of tachycardia and treating as needed. Light planes of anesthesia have been associated with sudden onsets of tachycardia and are due to increases in catecholamines as the patient mounts a physiologic response to noxious stimuli. Improvement of depth of anesthesia or administration of analgesics typically resolves tachycardia because of this etiology. Rarely, beta-blockers may be required to treat a pathologic sinus tachycardia; however, identification and treatment of underlying causes should be the focus of treatment.

**Atrial premature complexes (APCs)**

Atrial premature complexes (APCs) are ectopic foci of depolarization in the atria, which lead to premature atrial contractions. APCs are often seen in dogs and cats, and are typically associated with increased ventricular rates. Treatment of APCs may include the use of beta-blockers or calcium channel blockers. If APCs are frequent, further diagnostic evaluation may be necessary to identify any underlying cardiac disease.

**Atrial flutter**

Atrial flutter is a tachyarrhythmia (HR >300 beats per minute) in which P waves are replaced by a “saw-tooth pattern” of atrial depolarization, referred to as a flutter or “f” waves. Conduction of these flutter waves to the ventricles is variable, so that there may be a 4:1 ratio of atrial f waves to ventricular complexes or a 1:1 ratio that is difficult to differentiate from atrial tachycardia. Causes of atrial flutter are the same as those for other atrial tachyarrhythmias, particularly those causing atrial enlargement. Reentry rhythms can underlie atrial flutter, as can feline restrictive or HCM and ruptured chordae tendineae. Treatment of atrial flutter is not well described in veterinary medicine but is aimed at slowing ventricular rate. Options include diltiazem or digoxin administration, direct current cardioversion, or precordial thump in an emergency situation.

**Atrial fibrillation**

Atrial fibrillation is a common rhythm in dogs and tends to be a sustained rhythm, although paroxysms have been described. It is the classic “irregularly irregular” rhythm noted on auscultation, pulse palpation, or ECG analysis. There is complete loss of P waves, replaced by a chaotic isoelectric line of fibrillatory waves and irregular R–R intervals. It is characterized mechanically by complete lack of coordinated atrial activity. Loss of all atrial coordination prevents the atrial kick in most if not all cardiac cycles and leads to significantly reduced CO when combined with the high ventricular rates. Atrial fibrillation is often the rhythm associated with DCM of large breed dogs, severe atrial enlargement of any cause, and cases with severe mitral regurgitation;
“lone” atrial fibrillation is seen in giant breed dogs that have atrial fibrillation but no structural cardiac disease. Treatment of atrial fibrillation focuses on medical therapy for rate control and includes digoxin, beta blockers, and calcium channel blockers. Slowing of ventricular rate is important to prevent the development of heart failure and as a means to extend diastolic filling time and improve CO. However, long-term conversion from atrial fibrillation to a sinus rhythm is often not possible with severe underlying cardiac disease. In cases with minimal underlying structural cardiac disease (typically those with lone atrial fibrillation and atrial enlargement only), cardioversion to a sinus rhythm may be considered. The decision to attempt cardioversion (medically or with electric cardioversion) is controversial, and there are no clear criteria for attempting cardioversion.

Atrioventricular junctional tachycardia
AV junctional tachycardia is due to the presence of an ectopic focus of depolarization in the AV node. Intrinsic automaticity rate of the AV node is 40–60 beats per minute. Therefore, an AV nodal tachycardia has only to be faster than this rate to be termed a tachycardia. The mechanism underlying this rhythm is most commonly a reentry circuit. As the depolarization occurs in the AV node, the ventricular portion of the complex tends to be narrow. A noted variation in this rhythm is the presence of inverted P waves that can be seen before, during, or after the QRS complex. It may not be possible to distinguish this rhythm from an atrial tachycardia at very high HRs, so the term SVT can be used to identify either rhythm. Treatment is aimed at breaking the reentry circuit with a calcium channel blocker (e.g. diltiazem) to reduce calcium entry into the myocyte and therefore reduce HR.

Ventricular premature complexes (VPCs)
VPCs are due to ectopic foci of depolarization located in the ventricular myocardium. They occur before the next expected QRS complex on the basis of the underlying R–R interval. Depolarization spreads cell to cell, and a wide QRS complex results. Unifocal VPCs are individual wide QRS complexes with the same morphology, indicating they come from the same focus of depolarization. Multifocal VPCs have differing morphology and can be positive with different morphology, negative with different morphology, or both. Couplets (two consecutive wide complexes) and triplets are terms used to describe multiple VPCs occurring consecutively. A rhythm of alternating VPCs and sinus-origin beats is referred to as ventricular bigeminy. There is often a compensatory pause after the VPC, due to the refractory period of the VPC. When the VPC does not affect the R–R interval of the underlying sinus rhythm, it is referred to as an “interpolated VPC.” R-on-T phenomenon occurs when the VPC occurs on the T wave of the previous sinus beat and can predispose to development of ventricular fibrillation (VFib).

The first-line treatment of VPCs is a class 1b antiarrhythmic such as IV lidocaine. Recommended IV doses range from 1 to 2 mg kg⁻¹ in dogs or 0.25 to 1.0 mg kg⁻¹ (up to 4 mg) for cats. Oral sotalol has also been recommended in cats but is not an option during anesthesia. Other therapies for ventricular arrhythmias have largely been unproven in the cat. Mexilitine is an alternative for long-term management, as it is only available as an oral preparation. Class 1b antiarrhythmic drugs are believed to shorten the refractory period and terminate reentry rhythms by this mechanism. Triggers for treatment include multifocal VPCs (as more of the heart is presumed to be diseased/affected, and degradation to a worsening rhythm likely), runs of couplets/triplets/ventricular tachycardia, R-on-T phenomenon, or any ventricular rhythm that has hemodynamic consequences.

Causes of VPCs include hypoxia, cardiac disease (myocarditis, arrhythmogenic right ventricular cardiomyopathy, neoplasia, trauma, and structural cardiac disease), splenic/hepatic neoplasia, gastric dilatation volvulus syndrome, acidosis, pain, and catecholamine or sympathomimetic therapy. Treatment of VPCs and ventricular rhythms must include evaluation, monitoring, and treatment of these mechanisms in addition to treatment for the arrhythmia itself.

Ventricular tachycardia
Ventricular tachycardia is defined as a ventricular rhythm in excess of 160–180 beats per minute in dogs, whether paroxysmal or sustained. Idioventricular rhythm is the ventricular escape rhythm seen with loss of supraventricular input such as in complete (third degree) AV block, typically a pulse rate of 40–60 min⁻¹ in dogs and 60–80 min⁻¹ in cats. The most appropriate term for complete ventricular rhythm with rates between 60 and 160 min⁻¹ (in dogs) is an accelerated
idioventricular rhythm; a ventricular rhythm that is not quite tachycardic. The major hemodynamic difference between accelerated idioventricular rhythm and ventricular tachycardia is the decrease in diastolic filling time as HR increases past 160–180 beats per minute, as well as the decrease in CO that results. Causes of ventricular tachycardia are the same as for VPCs, and the same considerations apply for treatment.

**Ventricular fibrillation**
VFib is a chaotic organization of coarsely wandering electrical potentials of variable duration and amplitude with no PQRST organization. It is a nonperfusing rhythm, creating no mechanical activity in the heart, and CO is near zero. VFib is a terminal rhythm and can be the end result of severe ventricular tachycardia or severe systemic or cardiac disease, the result of general anesthetics or cardiac surgery. The only treatment with a reasonable chance of converting VFib to a perfusing rhythm is electrical defibrillation. However, the ability to convert to a sinus rhythm is often temporary, and fibrillation frequently recurs in minutes to hours.

**Sinoatrial block**
SA block is failure of a normally generated SA nodal action potential to appropriately conduct to the atria and lead to atrial depolarization. SA block differs from sinus arrest in that SA block is a failure of conduction, while sinus arrest is failure of the SA node to depolarize (failure of impulse generation). It can be difficult to distinguish between them with routine Lead II ECG analysis in anesthetized patients. First-degree SA block is a prolonged period from SA nodal firing and atrial depolarization. This is undetectable on ECG, as SA nodal firing is not recorded. Second-degree SA block is identified by a pause after a sinus beat or beats, wherein the duration of the pause is an exact multiple of that of the underlying normal sinus rhythm P–P interval. SA block appears otherwise identical to sinus arrest. Sinus block can be the result of atrial disease (enlargement, fibrosis, cardiomyopathy, and neoplasia), drug toxicity (beta and calcium channel blockers), or potentially sick sinus syndrome. SA nodal blocks typically do not require treatment. However, if severe bradycardia develops, treatment should be considered, as they may be responsive to atropine. If the rhythm fails to respond to anticholinergics and the patient is clinical for the arrhythmia, transcutaneous or transjugular cardiac pacing may be required.

**Persistent atrial standstill**
Atrial standstill is failure of normally generated SA nodal potentials to depolarize the atria. The ECG appears as a flat line with no P waves. Atrial standstill can be due to diseased atrial myocardium that is unable to depolarize normally, or more commonly, electrolyte disturbances such as hyperkalemia, where elevated serum potassium levels are sufficiently high to prevent atrial depolarization. Common causes of hyperkalemia include urinary obstruction, renal failure, uroabdomen, and hypoadrenocorticism. At moderate to severe serum potassium levels, the SA node and ventricular myocardium maintains their ability to depolarize, albeit slowly, but no P waves are seen on the ECG; slowed and widened QRS complexes can be seen. Elevations in serum potassium are not correlated to the severity of arrhythmias; alterations in the ECG can be seen at severe hyperkalemia, and classic changes in the ECG waveform can be seen with low serum potassium levels. However, typically as potassium increases, the T waves become “tall and tented,” P waves become flattened, and the P–R interval increases in duration, progressing to atrial standstill followed by widening of the QRS complex until the ECG appears as a sine wave. Ventricular arrhythmias may also present at any time.

Treatment for hyperkalemia is focused on identification and treatment of the underlying cause. Immediate stabilization of the hyperkalemic patient involves decreasing serum potassium levels and treating underlying acid–base disturbances to move potassium intracellularly. These mechanisms are critically important in reducing serum potassium levels in a patient who requires general anesthesia to treat the underlying disease.

Calcium gluconate (50–100 mg kg$^{-1}$ as a slow 5-min IV bolus) or calcium chloride (10 mg kg$^{-1}$ as a similar bolus) can be given to counteract the electrochemical effects of hyperkalemia on resting membrane hyperpolarization and rapidly treat the ECG side effects of hyperkalemia. Improvements in ECG can be seen within minutes of administration and can last between 30 and 60 min, allowing time for other treatments to reduce the hyperkalemia. Calcium given too rapidly can cause bradycardia and worsen the rhythm, and so
should be given slowly while monitoring the patient with an ECG placed.

Sodium bicarbonate can be used to buffer an underlying acidosis and reverse the shift of transmembrane antiport of hydrogen ions and potassium, thus moving potassium back into cells. Once venous or arterial blood gas analysis is complete (pH, base excess, bicarbonate, and PCO₂), total bicarbonate deficit can be estimated with the formula: total deficit = 0.3 × base excess × body weight (kilograms). If bicarbonate therapy is appropriate, it is recommended to replace no more than 1/3–1/2 of the deficit. Administration of a larger dose of bicarbonate risks overcorrection and development of an alkalosis. One of the more significant buffering mechanisms for bicarbonate therapy is the generation of CO₂ based on the carbonic anhydrase equation: \( \text{HCO}_3^- + \text{H}^+ \leftrightarrow \text{H}_2\text{CO}_3 \leftrightarrow \text{H}_2\text{O} + \text{CO}_2 \), where carbonic anhydrase catalyzes the reaction from carbonic acid to CO₂ and water. The patient must be capable of ventilating off the generated CO₂, an estimate of which is possible on the basis of a normal or low partial pressure of CO₂ on blood gas analysis. If hypercapnic, further elevations in CO₂ associated with bicarbonate administration will generate a respiratory acidosis and can worsen blood pH. Slow administration of bicarbonate is thus recommended. If the patient is anesthetized during bicarbonate administration, the anesthetist should be aware of the impending increase in CO₂ and adjust ventilation as necessary to maintain normal end-tidal CO₂. Lastly, the administration of sodium bicarbonate will increase measured serum sodium and may potentially lead to increases in serum osmolarity, where calculated osmolarity = 2[Na⁺ + K⁺] + BUN/2.8 + Glucose/18. Clinical signs of hyperosmolarity are not typically seen until osmolarity is >340 mOsm/l. Although it is unlikely that serum osmolarity will increase to this extent with sodium bicarbonate, if the patient is at risk for hyperosmolarity (unregulated diabetes, severe azotemia, etc.), bicarbonate must be carefully titrated and serum osmolarity monitored.

A third strategy for decreasing serum potassium in the hyperkalemic patient is to cotransport potassium with glucose into cells under the influence of insulin. Recommendations for insulin/dextrose therapy are 0.25 units kg⁻¹ of regular insulin IV given with 1–2 g of dextrose for every full unit of insulin administered. Serial glucose monitoring is recommended, and patients may require a dextrose infusion (1.25–2.5%) to prevent hypoglycemia. In humans, onset time of insulin/dextrose therapy is 20 min, with a duration of 30–60 min.¹⁶⁵

**First-degree AV block**

First-degree AV block is defined as the prolongation of the P–R interval due to slowed conduction of atrial depolarization action potentials through the AV node to >0.13 s in dogs and 0.09 s in cats.¹⁶⁶ Causes include AV nodal disease (fibrosis, ischemia, and cardiomyopathy), vagal stimulation, electrolyte imbalance (hyperkalemia and hypokalemia), and drug side effects (propranolol and digitalis toxicity). First-degree AV block is not usually clinically significant. However, it may be an indication of underlying disease or a predictor of worsening AV nodal function.

**Second-degree AV block**

Second-degree AV block is characterized by intermittent failure or delay in the association of the atrial depolarization through the AV node to the Bundle of His and subsequent ventricular depolarization. This appears as one or more isolated P waves that are not followed by QRS complexes.

Second-degree AV blocks are described either as Mobitz Type I or II or as low or high grade. Mobitz Type I is characterized by the increase in the duration of the P–R interval in successive sinus beats until a P wave is completely blocked and is not conducted through the AV node. Most Mobitz Type I blocks are due to altered AV nodal physiology, AV nodal disease (as for first-degree AV block), or drug side effects (low dose anticholinergics, digitalis toxicity, and alpha-2 agonists). Mobitz Type I blocks may be normal in high vagal tone species such as the very athletic dog, juvenile animals, and horses.¹⁶⁹

Mobitz Type II second-degree AV block is acute, intermittent failure of conduction of a P wave through the AV node, but the P–R intervals of successfully conducted P waves are of normal duration. If there are many P waves that are not conducted so that a P–R interval is not able to be assessed, the term “high grade” second-degree AV block is applied, especially when there are four or more nonconducted P waves for every conducted P wave and QRS complex. High grade second-degree AV block can be due to the same causes as less severe AV blocks but may be a sign that AV nodal disease is severe and may degrade into complete AV dissociation (third-degree AV block). High grade second-degree AV block may be more
resistant to treatment and may require the placement of a permanent ventricular pacemaker.

**Third-degree AV block**
Third degree AV block is complete failure of AV nodal conduction and subsequent dissociation.\(^{161}\) While SA nodal function, atrial conduction pathways, and atrial depolarization are normal, the wave of depolarization is not conducted through to the ventricles. The cause of third-degree AV block is often idiopathic. The characteristic findings on ECG are normal P wave generation, with a regular P–P interval at a normal sinus rate. Owing to the lack of supraventricular input, the ventricles depolarize because of ventricular automaticity (∼30–50 beats per minute in dogs and 60–80 beats per minute in cats), and there develops a superimposed ventricular rhythm (a wide QRS ventricular escape rhythm) that has no association to the P waves, often with a regular R–R interval. It is critical that this escape rhythm not be interpreted and treated as VPCs, and the ECG be carefully evaluated for association between P waves and QRS complexes. If no association exists, third-degree AV block must be strongly considered and ruled out before antiarrhythmics are considered. If the ventricular escape rhythm is treated with lidocaine, it may suppress the escape rhythm and lead to cardiac arrest.

Treatment for third-degree AV block most commonly requires placement of a permanent ventricular pacemaker. Temporary measures to support (ventricular) HR, CO, and perfusion include transcutaneous, transesophageal, or transvenous temporary cardiac pacing. Medical interventions have included isoproterenol infusion, epinephrine, atropine, dopamine infusions, and dobutamine infusions.\(^{170}\)

**Bundle branch blocks**
The bundle branches are the first two divisions of the Bundle of His as the conduction system travels from the AV node down the interventricular septum toward the ventricular myocardium. The left bundle branch divides into one anterior and one posterior fascicle. Bundle branch or fascicular blocks are the result of loss of rapid conduction through one or more of these bundles and result from combined rapid and slow conduction through the ventricular myocardium; the bundle branch that remains unblocked allows conduction through the bundle and into the Purkinje system, causing rapid depolarization of the ventricle and a narrow QRS complex. The block of bundle conduction from the AV node results in the cell-to-cell spread of depolarization and a resultant slow, wide QRS complex. The combination of rapid and slow conduction leads to a QRS complex that appears wide and bizarre but typically not as wide as a VPC.

Left bundle branch blocks can be due to significant underlying disease, including cardiomyopathy, degenerative conduction system disease, ischemia, AS, and drug toxicity (i.e. adriamycin) and can be secondary to left ventricular hypertrophy. Right bundle branch blocks can be normal in dogs and cats but can also develop because of right ventricular conduction abnormalities or because of right ventricular hypertrophy, in association with VSD, cardiomyopathy, and heartworm disease. Concurrent left and right bundle branch blocks have the same appearance and effects as third-degree AV block.

Bundle branch blocks will have a P wave present before the widened QRS complex, as supraventricular and AV nodal function are normal. This is an important distinction from a VPC. Bundle branch blocks typically do not lead to impairment of cardiac performance, CO, and perfusion, but should alert the anesthetist to evaluate the patient for possible underlying causes of cardiac disease.

**Systemic and pulmonary arterial hypertension**

**Systemic hypertension**

**Incidence and pathophysiology**
Systemic hypertension is defined as a persistently elevated BP. Most authors agree that SAPs >160–180 mmHg and DAPs >90–100 mmHg define systemic hypertension.\(^{171,172}\) Systemic hypertension is often classified as either essential hypertension or secondary hypertension. Essential hypertension is defined as consistent, measurably repeatable high BPs for which a cause cannot be identified despite a thorough diagnostic workup. Secondary hypertension is due to a known cause that changes either the components of CO or SVR.

Most patients with hypertension present during middle age. However, hypertension can also be caused by or is seen concurrent with many geriatric diseases. An important breed exception is greyhounds, which have higher BP and CO due to cardiac hypertrophy unrelated
to disease that does not lead to patient morbidity. Essential hypertension has also been reported in a line of Siberian Huskies, which might be due to their selection for endurance. Common causes for hypertension include chronic renal disease, hyperthyroidism, hyperadrenocorticism, and a variety of miscellaneous uncommon to rare causes, including pheochromocytoma, hyperadrenocorticism, polycythemia, diabetes mellitus, increases in intracranial pressure (Cushings response), and hypercholesterolemia. Drugs can also cause elevations in BP and include steroids, cyclosporine, phenylpropanolamine, and erythropoietin. Toxicities can also increase BP and include, but are not limited to, high salt, lead, nicotine and Vitamin D intake, alpha and beta-1 agonist administration, and steroid use.

As noted earlier, MAP is the product of CO and SVR. CO increases with increases in HR, vascular volume (preload), or myocardial contractility (Figure 1.4). Hypertension is caused by either increases in one variable contributing to CO or increases in SVR. Renal disease leads to neurohormonal activation, which increases sympathetic system activation and has direct effects on angiotensin II and RAAS, as well as changes in body fluid balance. Thyroid hormones increase HR (positive chronotropic effect) and result most commonly in a sinus tachycardia with hypertension. Thyrotoxicosis also leads to increases in contractility and peripheral vasodilation; yet, despite the decrease in SVR, the major cardiovascular side effect of hyperthyroidism is a significant increase in CO. Increases in circulating glucocorticoids, whether endogenous due to hyperadrenocorticism or exogenously administered, lead to salt and water retention with subsequent increases in preload and CO and potential overproduction of renin with subsequent increases in SVR. Pheochromocytoma is a malignant tumor of the catecholamine-producing chromaffin cells of the adrenal medulla. Secretion of epinephrine and norepinephrine is intermittent and is thought to be unrelated to stressors; the increase in circulating catecholamines leads to hypertension and tachyarrhythmias among other clinical signs unrelated to hypertension. Any medications that increase SVR (alpha-1 adrenergic agonists or vasopressin-1 receptor agonists) or HR and contractility (beta-1 adrenergic agonists) have the potential to increase BP dramatically because of toxicity or inadvertent overdose.

Unfortunately, consequences of systemic hypertension can often go unrecognized for long periods, given the difficulty in recognizing and interpreting signs of hypertension by patient owners. Often, secondary hypertension is not recognized until signs of the primary disease are recognized. Ophthalmic consequences of hypertension include acute blindness, retinal detachment, hyphema, retinal atrophy, or rarely corneal ulcers. Renal hypertension can lead to potential pressure diuresis, glomerulonephritis, and renal failure. The cardiovascular system can exhibit gallop rhythms, heart murmurs, or other arrhythmias; patients can show exercise intolerance, dyspnea, and, rarely, CHF. The vascular system remodels the intimal and medial layers, resulting in atherosclerosis and vascular stiffening and can lead to hemorrhage exhibited as hyphema, epistaxis, or bleeding in other locations. Neurologic symptoms of hypertension can include stroke, infarcts, or hemorrhage and can lead to head tilt, seizures, paresis, or other neurologic signs.

Anesthetic management

Treatment for hypertension should be aimed at identification and treatment of the underlying cause and of potential or identified consequences of hypertension and may subsequently be based on the severity of hypertension. Treatment of the underlying cause in itself may lead to resolution of the hypertension, and antihypertensive medication(s) may not be required. However, if hypertension is severe or if organ damage is identified (ophthalmic, cardiovascular, neurologic, renal, or vascular), treatment with antihypertensive agents may be necessary despite treatment of the underlying cause. Antihypertensive agent options include vasodilators (arteriodilators or venodilators), beta-adrenergic blockers, diuretics, ACE inhibitors, calcium channel blockers, and combinations of these. The choice of initial therapy has largely been extrapolated from human protocols and is a matter of species, identification of the underlying cause, and personal experience. Generally, ACE inhibitors are recommended when hypertension is identified with chronic renal disease. ACE inhibitors will inhibit RAAS-mediated vasoconstriction and are indirect vasodilators. Alternatively, amlodipine is a calcium channel blocker, which also reduces SVR. Amlodipine has a slow onset of action and carries a lower risk for acute hypotension. Hydralazine is a direct
arteriodilator and is generally not a first-line treatment for hypertension but is added to combination therapy for refractory hypertension.

Recommendations for anesthetic management of patients with systemic hypertension in veterinary patients are lacking. Human guidelines for anesthetic management are well accepted and can serve as guidelines for management of veterinary patients. Thus, recommendations for anesthetic management include evaluation for magnitude of preanesthetic hypertension, evaluation for end-organ damage due to hypertension, administration of prescribed antihypertensive agents according to treatment schedule before induction of anesthesia, and close monitoring of patient BP during anesthesia.

Most anesthetics reduce BP by multiple mechanisms, including inducing bradycardia, peripheral vasodilation, and/or negative inotropy. It is generally accepted that the minimum acceptable MAP is >60–70 mmHg for healthy patients. However, it is unknown if higher minimum MAPs are required for veterinary patients with preexisting hypertension. The literature discussing anesthetic care for human patients with preexisting hypertension offers no consensus aside from recognizing that patients with preexisting hypertension are at higher risk for cardiovascular instability under anesthesia. Minimum acceptable BP for these veterinary patients remains an area for future research. However, anesthetic drugs that increase BP are generally avoided in patients with preexisting hypertension, including alpha-2 adrenergic agonists and dissociative anesthetics. Excitement, stress, pain, and other causes of catecholamine release should be minimized, with sufficient sedation and analgesia throughout all phases of anesthesia. The choice of anesthetic agents for patients with systemic hypertension is equally reliant on the degree of hypertension, as well as any underlying disease(s).

Pulmonary arterial hypertension

Incidence

PHT is defined as an abnormally high pressure in the blood vessels of the pulmonary circulation and can be due to either an increase in blood flow, an increase in blood viscosity, or an increase in pulmonary vascular resistance (i.e. pulmonary vasoconstriction). Pulmonary artery pressure >25–35 mmHg is considered abnormally high. Normal systolic pulmonary arterial pressure averages 15–25 mmHg, and normal diastolic pulmonary artery pressure averages 5–10 mmHg. Classification of PHT can be divided by the mechanisms of disease and includes primary pulmonary arterial hypertension (PAH), PAH due to left heart disease, pulmonary hypoxia, or thrombotic/embolic disease.

Typical breeds presenting with PHT are small to toy breed dogs and are typically middle age to older. Primary PHT can be difficult to distinguish from those of underlying cardiac and pulmonary disease. Clinical features can include cough, dyspnea, lethargy, syncope or collapse, exercise intolerance, heart murmurs, and/or ascites. Signs of underlying disease may also be present and most commonly include those of right heart failure, heartworm disease, cyanosis, and/or tachypnea. Cardiopulmonary examination may reveal tricuspid or mitral murmurs, split heart sounds, increased bronchovesicular sounds, or crackles and abdominal fluid wave due to ascites.

Diagnosis of PHT is aimed at determining the magnitude of PHT and the underlying cause and, most importantly, should include thoracic radiography and echocardiography. Thoracic radiography helps to identify underlying cardiorespiratory diseases that predispose to PHT. Right ventricular enlargement and dilated pulmonary arteries should increase suspicion of PHT. Characteristic echocardiographic findings include concentric right ventricular hypertrophy and dilation of the main pulmonary artery, although identification of underlying cardiac pathology can help assist in the identification of predisposing diseases. Echocardiography also allows for grading of the severity of PHT from mild to severe by assessment of tricuspid valve regurgitation velocity, a number that estimates pulmonary artery systolic pressure. ECG can often be normal and may identify only arrhythmias because of underlying cardiac disease rather than be specific for PHT.

Treatment for PHT is aimed at reducing clinical signs, improving exercise tolerance, decreasing pulmonary arterial pressure, and identifying and treating underlying causes. Unfortunately, treatment often fails unless the specific underlying cause can be identified and addressed before pulmonary vascular remodeling occurs and pulmonary vascular resistance becomes fixed. Vessel remodeling is characterized by vessel intimal proliferation, medial hypertrophy, and decreased compliance. If the cause cannot be immediately identified, treatment is generally aimed at reducing pulmonary vascular resistance and controlling right
ventricular pressure overload. The primary pulmonary vasodilator currently used in veterinary medicine is sildenafil, which appears to provide benefits by a number of pathways, of which, direct pulmonary vasodilation is the most significant.\textsuperscript{182,183} Sildenafil has been shown to improve survival and quality of life in dogs with PHT.\textsuperscript{182}

Anesthetic management
The most important factor in planning anesthesia for patients with PHT is to be aware of the potential cardiopulmonary derangement associated with the disease. This assessment is based on PE, potential clinical signs consistent with PHT, and results of diagnostic tests. Treatment and stabilization of underlying diseases are optimal. Currently, no peer-reviewed publications exist regarding anesthetic management of PHT in veterinary patients; however, the topic has been extensively reviewed in human medicine.\textsuperscript{183–187} Therefore, symptomatic treatment is recommended on the basis of the possible mechanisms of PHT. For example, providing oxygen by facemask before anesthetic induction will increase the \( \text{FiO}_2 \), partial pressure of inspired oxygen, \( \text{PAO}_2 \), and \( \text{PaO}_2 \), as described by the oxygen pathway (Figure 1.13).

Maintenance of anesthesia with 100% oxygen is recommended, as oxygen is also a pulmonary vasodilator via stimulation of nitric oxide production.\textsuperscript{180} The goals of anesthesia are to maintain \text{CO} by optimizing preload and contractility and minimizing decreases in \text{SVR}. To that end, choosing anesthetic premedications, induction, and maintenance agents should be done to minimize cardiovascular depression, as outlined previously in this chapter. It is crucial to avoid worsening or increasing pulmonary vascular resistance by preventing acidosis, hypoxia, hypercapnia, agitation, pain, and hypothermia.\textsuperscript{183} Invasive BP monitoring should be strongly considered, as it provides a continuous monitor of BP, as well as enables arterial blood gas sampling. Good sedation with premedications is ideal to prevent stress and pain, which lead to increases in catecholamine release and systemic and pulmonary
Heart failure

Introduction

Heart failure is defined as the inability of the heart to function as a pump and create forward flow (i.e. normal CO to meet tissue oxygen demands and systemic BP). It represents a final common pathway of a number of cardiac or pulmonary diseases and is associated with activation of neurohormonal and vascular mechanisms that compensate for the lack of forward flow. Initially, these mechanisms are beneficial in that they improve BP and perfusion but eventually become detrimental as heart failure worsens. CHF is defined as the failure of the left or right ventricle and the subsequent mechanisms that lead to fluid accumulation in the lungs (pulmonary edema with left heart failure) or abdomen (ascites with right heart failure).\(^{188}\)

Pathophysiology

The causes of heart failure or CHF are numerous but can be the end result for a wide variety of cardiac diseases. The underlying mechanisms for heart failure can be classified into four categories as follows: (i) myocardial failure (primary or secondary), (ii) pressure overload, (iii) volume overload, and (iv) decreased ventricular filling due to poor venous return or abnormal ventricular compliance (Table 1.8).

Myocardial failure is characterized by loss of contractile strength of the heart, whether primary (DCM) or secondary to other etiologies. Myocardial failure leads to activation of compensatory mechanisms that increase circulating blood volume through sodium and water retention that increases end-diastolic volume and leads to ventricular dilation. SV is initially maintained despite ventricular dilation, which can lead to AV valve insufficiency.

A pressure overload is due to an increase in myocardial wall stress subsequent to increases in ventricular systolic pressures. Most commonly, this results from valvular stenosis (PS and AS) or increases in systemic...
or pulmonary vascular resistance from either systemic hypertension or PHT, respectively. Pressure overload leads to concentric hypertrophy of the ventricle that can be identified on echocardiogram. Inner layers of hypertrophied muscle may be underperfused and become ischemic, which can lead to ventricular arrhythmias, fibrillation, and sudden death.

A volume overload is most commonly seen with valvular insufficiency (usually AV valvular insufficiency) or anatomic shunts such as a PDA or VSD. It is defined as an increase in end-diastolic chamber size but normal end-systolic chamber size, an indicator that contractility is normal and SV has increased. Volume overload leads to eccentric hypertrophy to manage the increase in ventricular volume and increase forward flow. Anatomic shunts also increase ventricular volume, as they allow an increase in ventricular filling. For example, a PDA allows aortic blood to backflow into the pulmonary artery, increasing left atrial and left ventricular blood volume. Eventually, myocardial failure can result.

Reduced ventricular filling occurs when there is a physical obstruction to blood flow, blood volume is reduced, or there is impaired relaxation and filling of the ventricle. Physical obstruction to blood flow can occur because of enlarged abdominal organs (gastric dilatation volvulus, liver or splenic neoplasia, insufflation of hollow viscera, gravid uterus, etc.), surgical manipulation of vasculature responsible for venous return (cranial and caudal vena cava and tributaries), and positive pressure ventilation, among others. Reduced preload can be acute or chronic depending on the cause. For example, reduced blood volume can occur with dehydration, third spacing of fluids, or blood loss. Reductions in ventricular compliance occur with HCM and constrictive pericarditis, where the ventricle cannot relax normally, and stiffening due to muscular hypertrophy or a thickened pericardium that prevents diastolic relaxation. Compliance is the pressure–volume relationship in the ventricle; poor compliance leads to abnormally high filling pressure with relatively normal filling volumes. Abnormally high ventricular pressure leads to backup of blood to the atria and eventually organ congestion and/or edema.

Aside from the mechanisms for heart disease and pathophysiology briefly described, compensatory mechanisms exist to maintain homeostasis in the face of poor heart function to maintain BP and tissue perfusion. While they have been extensively described elsewhere,189–191 a brief review is presented in this section. Compensatory mechanisms include the Frank–Starling mechanism and activation of the SNS, RAAS, and neuroendocrine pathways, which include endothelin and natriuretic peptides. In the acute phase of hypotension, decreased myocardial function activates baroreceptor responses to increase SNS tone, leading to vasoconstriction and increases in contractility and HR. The SNS also stimulates ADH and renin release. ADH causes fluid reabsorption in the kidneys, and renin stimulates the RAAS. The RAAS is further stimulated by reduced renal perfusion, SNS activation, and decreased sodium delivery to the macula densa. These mechanisms provide vasoconstriction and increase blood volume and venous return to return perfusion to normal. Although beneficial in the short term, chronic stimulation of these mechanisms is detrimental to homeostasis.

The New York Heart Association classifications192 for heart failure have been adapted for veterinary use (Source: American Heart Association, Inc.) as follows: Class I: heart disease without clinical signs of heart disease such as exercise intolerance, Class II: patients who present with mild exercise intolerance but may not have radiographic evidence of disease, and Class III: veterinary patients who have clinical signs of heart failure during normal activity and have multiple radiographic signs of heart failure, including cardiomegaly, pulmonary edema, distended vasculature, and left atrial enlargement; Class IV patients are in obvious distress with signs of heart failure at rest. Radiographs have the aforementioned signs along with severe pulmonary infiltrates and potentially pleural or abdominal effusion.190 Treatment strategies vary on the basis of the degree of heart disease and clinical signs along the spectrum of patients who present from mild to severe disease.

Anesthetic management
Planning in advance for and responding to complications during an anesthetic event in a patient at risk for heart failure, one who has recently been treated for heart failure, or one how has evidence of heart failure tests the knowledge and skill of the anesthetist. Patients can present anywhere along the spectrum of classification for heart failure from minimal to severe risks for anesthesia.

Preoperative assessment of patient status is a critical step in assessing risks and planning for potential
complications, as well as choosing appropriate premedication/induction agents and preparing appropriate monitoring tools. It should include a complete history and PE, focusing on clinical signs of dyspnea, exercise intolerance, collapse, coughing, weakness, and other signs relevant to cardiopulmonary function. Of most importance are any recent changes in patient behavior. All medications for heart disease as well as the most recent dosing regimen should be noted. Although it is controversial to feed a patient anything before anesthesia, ensuring that the patient received morning doses of medications is prudent. PE should focus on parameters indicative of cardiopulmonary function such as mucous membrane color and refill, thoracic and cardiac auscultation, pulse rhythm and intensity, presence of jugular pulsations, and palpation/ballottement for organomegaly and/or fluid waves. Diagnostic procedures may consist of preanesthetic ECG, BP, thoracic radiography, abdominal ultrasonography, and echocardiography. Any abnormalities should prompt further investigation, as patient status may have changed since last examined. If the patient presenting with anesthesia is under the care of a veterinary cardiologist, patient reevaluation may be suggested and/or pursued.

The veterinary adaptation of the New York Heart Association classes of heart failure can be very useful in placing patients into an ASA status (Table 1.1). Although no classification system is optimal, and ASA status is not formally an assessment of risk of complications, it is reasonable to expect that as heart failure classification becomes more serious, ASA status will increase. The general strategies listed in the following section are intended to be specific to a patient presenting with heart failure. Obviously, if the nature of the procedure or the presence of comorbidities presents higher risk to the patient independent of the nature of their heart disease, ASA status would be higher than for the heart disease alone.

Patients who are Class I will likely be ASA status I and can likely be anesthetized with any combination of premedications (opioids, anticholinergics, benzodiazepines, ketamine, and acepromazine) and induction agents (ketamine/benzodiazepine, propofol +/- benzodiazepine), with the possible caveat that alpha-2 adrenergic agonists would be best avoided. Standard monitoring of ECG, BP, SpO₂, and temperature is likely to be sufficient. Standard IV fluids administered at 5–10 ml kg⁻¹ min⁻¹ are likely to be tolerated well.

Patients who are Class II present a higher potential for complications and are likely to be an ASA status III and should be treated accordingly. Acepromazine and alpha-2 adrenergic agonists should likely be avoided as premedications; reliance on opioids for sedation and dose reduction is recommended. Older, less stable patients may sedate well with a combination of an opioid and benzodiazepine. Induction agent dose, whether propofol or ketamine is used, should be reduced with good sedation from premedication and combination with a benzodiazepine. Inhaled anesthetic dose requirements should be reduced as much as possible with the combination of premedications, opioid, or possibly other analgesic infusions (lidocaine and ketamine), as well as local or regional anesthesia techniques. Maintenance fluid rates may be normal or reduced depending on patient status. Positive inotropic agents should be available in case of hypotension unresponsive to reducing inhalant dose and optimization of HR and rhythm. Standard anesthetic monitoring may be sufficient; however, advanced monitoring (invasive BP and CVP) may be required for unstable patients or for the nature of the procedure.

Patients who are Class III and IV present serious potential for decompensation and severe complications under anesthesia and are likely to be ASA status IV or V. The need for an anesthetic event must be carefully weighed against the benefit of a procedure, as the potential for life-threatening complications can be very high. These patients are very critical and require the highest level of intensive monitoring and support, including invasive BP monitoring, evaluation of arterial blood gases for oxygenation and acid–base balance, CVP monitoring, and advanced ECG interpretation. Positive inotropic agents, vasopressors, and antiarrhythmic agents should be available, and the anesthetist should be comfortable with their use. CPR status should be discussed and known to the anesthesia team. Mechanical ventilation is extremely beneficial in optimizing ventilation and oxygenation, as well as preventing respiratory acidosis and the pH-related changes in cardiac function and electrolyte shifting. Premedication, induction, and maintenance phases of anesthesia should be aimed at minimally impacting cardiovascular function. Agents with short durations of action and/or reversibility are recommended should the patient decompensate. For this reason, opioids are good choices as premedication and induction agents. Acepromazine, ketamine, and
alpha-2 adrenergic agonists should be avoided, whereas benzodiazepines and possibly anticholinergics are also recommended. Induction of anesthesia is accomplished with combinations of opioids and benzodiazepines such as fentanyl and or etomidate and midazolam. Chamber or “box” inductions with inhaled anesthetics are not recommended because anesthetic induction and transition through the excitement phase are slow, monitoring of vital parameters is impossible, airway access is slow and poor, and the dose of inhaled anesthetic required for intubation is higher (deeper) than is required for surgical procedures. These doses of inhaled anesthetics invariably lead to moderate to severe cardiovascular depression, however short they may (or may not) be. Chamber inductions are a last-choice option for patients with severe cardiovascular disease and should only be considered for severely fractious patients for whom handling and premedication may lead to detrimental stress, catecholamine release, and potential arrhythmogenic effects. If a chamber induction cannot be avoided, it is recommended that patients not be anesthetized to the point of intubation (owing to depth required and cardiovascular depression) but rather to the point of safe handling (immediately deep to the excitement phase) and then removed to place a facemask of inhalant only. At that point, the patient can be removed, monitoring equipment and an IV catheter can be placed, and the induction completed with a less cardiovascular depressant option such as low dose propofol or etomidate/benzodiazepine. This typically leads to a more satisfactory and efficient intubation as compared to inhalant only.

Inhaled anesthetic agent requirements should be reduced to the lowest possible levels with the application of constant rate infusions (Tables 1.2 and 1.3) and local/regional anesthesia techniques. Fluid rates should be significantly reduced to minimize the risk of volume overload; meeting metabolic requirements at 2–5 ml kg$^{-1}$ h$^{-1}$ is recommended. Fluid boluses and colloids should be avoided or administered cautiously to avoid precipitating or worsening heart failure and pulmonary edema/ascites.

**Canine and feline cardiomyopathies**

Cardiomyopathy is a general term applied to diseases of the cardiac muscle tissue leading to structural impairment and subsequent decrease in cardiac function. This separates cardiomyopathies from valvular, congenital, electrical or conduction abnormalities, and traumatic or metabolic disturbances. A primary cardiomyopathy is due to intrinsic disease of the muscle; a secondary cardiomyopathy is due to derangements in a different organ system with secondary effects in the heart.

**Hypertrophic cardiomyopathy**

**Pathophysiology**

HCM is due to idiopathic concentric thickening of the cardiac muscle, leading to stiffening of the myocardium and a failure of relaxation, a form of diastolic dysfunction wherein the heart fails to relax normally. It is known to be autosomal dominant in Maine Coon cats and is hereditary in Persians and some American Short Hair cats. Disease onset can be seen as early as 6 months of age. Cats may be nonclinical even with severe disease, and sudden death is possible at any time.

HCM tends to affect the left ventricular free wall and interventricular septum/papillary muscles preferentially. The etiology in most cases is idiopathic; however, other possible causes include hyperthyroidism, hypergonadotropism, and secondary to hypertension. This thickening leads to a decrease in the internal volume of the ventricle when relaxed (end diastolic volume), and this inability to accept venous return leads to an eventual increase in left atrial pressure, mitral regurgitation, pulmonary edema, and the cascade of events leading to left heart failure. HOCM is a variant in which muscular hypertrophy can pull the anterior mitral valve leaflet into the LVOT and lead to dynamic obstruction of ventricular outflow. It is believed that increases in HR and velocity of blood flow through the LVOT can also predispose to systolic anterior motion (SAM) of the mitral valve leaflet and worsening of left ventricular CO. Systolic anterior motion may also worsen mitral regurgitation. Poor blood flow due to poor ventricular diastolic compliance leads to blood stasis and thrombus formation typically in the left atrium, leading to the potential for pulmonary thromboembolism. Diagnosis of HCM is typically due to identification of septal or free wall thickening in a nondilated ventricle with echocardiography. Poor diastolic ventricular filling also leads to poor CO and BP.

**Treatment**

Treatment for HCM typically involves identification and treatment of the underlying cause. No definitive treatments have been shown to achieve reversal of
hypertrophy, although many veterinary cardiologists recommend empirical beta-adrenergic blocker or calcium channel blocker therapy. Therefore, management is typically directed at treating the sequelae of reduced ventricular compliance: preventing myocardial ischemia, treatment of congestion and secondary arrhythmias, and potentially improving diastolic dysfunction.

Anesthetic management

Anesthetic management of HCM varies on the basis of the severity of disease. Patients with occult disease may fail detection and are likely successfully anesthetized with all combinations of anesthetic drugs. Patients with mild disease and heart murmurs with minimal structural change can similarly be anesthetized with nearly any combinations of anesthetics. However, the use of dissociative anesthetics such as ketamine and tiletamine is more controversial in mild cardiac disease. Dissociatives are generally considered contraindicated in more severe HCM, particularly if elevated BP or increased afterload is detrimental to heart function. Dissociative anesthetics cause an increase in HR, myocardial contractility, and BP due to SNS stimulation and increased sympathetic discharge. This stimulation leads to an increase in myocardial work and oxygen demand. HCM is characterized by thickening of the myocardium leading to diastolic dysfunction, potential systolic anterior motion, and LVOTO. Increases in velocity of blood flow through the LVOT may worsen SAM and lead to obstruction of ventricular ejection. Therefore, the sympathomimetic effects of dissociative anesthetics can be quite detrimental to ventricular outflow, and ketamine and tiletamine are likely better off avoided in these cases. Invasive arterial BP monitoring is recommended in moderately to severely affected cats. Fluid therapy and boluses are intended to improve venous return and are controversial in patients with mild HCM, as diastolic compliance, if affected, may not be able to tolerate additional venous return. In patients with severe disease, particularly with a history of CHF, high fluid rates and boluses are contraindicated, as the increase in preload may precipitate congestion and pulmonary edema. Colloids are contraindicated, as fluid overload with colloids is more difficult to treat compared to volume overload due to crystalloids because colloids have a long duration of action and rely on liver metabolism for elimination.

Reduction in inhaled anesthetic concentrations is a critical tool in preventing anesthetic induced hypotension. The anesthetist should consider all strategies to reduce inhaled anesthetic requirement, including analgesic boluses or infusions, local and regional analgesia, and potential for avoidance of general anesthesia if possible. Positive inotrope administration is controversial in cats with HCM. While positive inotropes improve contractility, HCM is mainly associated with diastolic dysfunction (lusitropy, not inotropy), and typically systolic function is not reduced. Increasing contractility may be detrimental, as it increases cardiac work (and myocardial oxygen demand in thickened,
poorly perfused myocardium) and can worsen systolic anterior motion in HOCM by increasing the velocity of flow through the LVOT. Positive inotropes can also be arrhythmogenic and can precipitate or worsen underlying cardiac arrhythmias. For these reasons, vasopressors used to increase SVR have been recommended. Although new research has questioned these conclusions, more investigation is required.

Premedication of cats with HCM typically includes opioids for mild sedation, facilitation of catheter placement, and reduced anesthetic induction doses. Acepromazine is controversial because it leads to long acting vasodilation that is not reversible and can precipitate hypotension. Alpha-2 adrenergic agonists are contraindicated due to the severe increase in afterload and decrease in CO. Benzodiazepines are very safe choices for patients with cardiac disease due to lack of cardiovascular effects but can be variable sedatives in cats and may lead to excitement and aggression.

Induction of anesthesia can be achieved with combinations of propofol with a benzodiazepine to reduce total propofol dose in patients with mild to moderate disease. Patients with more severe disease can be induced with combinations of etomidate with a benzodiazepine. Although combinations of fentanyl with a benzodiazepine are attractive in that they cause minimal cardiovascular depression, the slow transition to unconsciousness (and potential to be overridden with sufficient stimuli), as well as the potential for severe dysphoria in cats, makes this combination successful in only the most debilitated cats. However, in these patients, it may offer an advantage if etomidate is unavailable.

As discussed previously, for patients with moderate to severe cardiovascular disease, mask, chamber, or “box” inductions with inhaled anesthetics are not recommended. Induction of anesthesia is prolonged, and transition through excitement is slow, which could lead to patient stress. Intensive monitoring that these patients require is impossible; ability to intubate is brief, slow to achieve, and poor in quality, and the dose of inhaled anesthetic for intubation causes moderate to severe cardiovascular depression for the duration of the slow induction process. Chamber inductions should only be considered for severely fractious patients for whom handling and premedication may lead to detrimental stress, catecholamine release, and potential arrhythmogenic effects.

Opioid infusions can be used to provide analgesia, as well as reduce inhaled anesthetic requirements. Doses may need to be lowered toward the end of anesthesia to allow metabolism and prevent dysphoria in recovery. Local and/or regional anesthesia techniques are strongly encouraged to reduce systemic drug requirements. Hypotension can be treated as stated previously. Ventilation should be supplemented to prevent respiratory acidosis, and patients with arrhythmias should be monitored with continuous ECG waveform. Pulse oximetry should be used to monitor for oxygen saturation in all patients with cardiac disease. Invasive arterial BP monitoring and arterial blood gas analysis is the gold standard of monitoring, and should be strongly considered in patients with a recent or current history of CHF. Patients with CHF should be medically stabilized before anesthesia, provided it is not an emergency situation. Referral to a cardiologist or anesthesiologist may be considered for severe cases.

Dilated cardiomyopathy (DCM)
Incidence and pathophysiology
DCM is the most common cardiovascular disease diagnosed in dogs, followed by mitral valve and heartworm diseases. It is most commonly found in large breed dogs, including the Doberman Pinscher, Great Dane, Irish Wolfhound, Boxer dogs, and less commonly in mixed breed dogs, with male dogs appearing to be more affected than the female dogs. Although not proven, it is likely that there is a heritable component to canine DCM.

DCM is characterized by an idiopathic primary loss of myocardial contractility. Secondary causes of DCM exist and include nutritional deficiency (taurine-deficiency-associated DCM in Cocker Spaniels and potentially in Labradors and Golden Retrievers), tachycardia-induced DCM (secondary to SVT or atrial flutter), and adriamycin toxicity. Loss of contractility leads to systolic dysfunction associated with reduced ejection fraction, fractional shortening, and rate of ejection, as well as an increase in end-systolic volume. These changes lead to progressive dilation of the ventricle followed by left-sided or biventricular CHF. The term “occult” DCM is used before clinical signs are seen and is characterized by the loss of contractility and ventricular remodeling. Clinical signs may include irregular pulse rhythm, decreased intensity of cardiac sounds, weak pulses, or jugular distension. The overt phase of DCM
presents with clinical signs relative to onset of CHF, including lethargy, syncope, pulse deficits, dyspnea, cough, and/or abdominal distension. Patients can easily present with heart failure or sudden death as the first sign of DCM. Diagnosis is via demonstration of loss of systolic function without an identifiable cause. Patients may present with SVT, ventricular ectopy, atrial flutter, or atrial fibrillation.

Anesthetic management
The goal of DCM treatment is to prevent or reverse the remodeling associated with the loss of contractility. Unfortunately, as most cases are idiopathic, therapy is limited to treatment/prevention of heart failure, treatment of cardiac arrhythmias, and improving quality of life. Treatment of heart failure must be tailored to the individual, as no one treatment strategy is sufficient for all patients; however, common strategies include diuretics, positive inotropes, phosphodiesterase inhibitors, pimobendan, and antiarrhythmics. Long-term management may include diuretics, beta-adrenergic blockers, ACE inhibitors, pimobendan, and/or oral antiarrhythmics.

Anesthetic management of patients diagnosed with DCM is multifactorial and includes planning for and maintenance of systolic function, prevention of heart failure, management of arrhythmias, and inotropic support. Since even nonclinical patients may already have significant loss of systolic function and remodeling, the following techniques can likely be applied to all patients with occult or overt DCM. Patients presenting with heart failure are at severe anesthetic risks, and anesthesia should be postponed until the patient is stabilized.

Patients with overt DCM with reduced systolic function and forward flow develop heart failure, as they cannot eject diastolic preload. Therefore, perianesthetic fluid therapy should be titrated to the lowest effective dose for hydration and ongoing losses. Balanced electrolyte crystalloid administration rates should be 3–5 ml kg\(^{-1}\) h\(^{-1}\); higher fluid rates may precipitate volume overload and heart failure. Colloids are contraindicated as previously discussed.

Common arrhythmias associated with DCM include VPCs, couplets, triplets, or more complicated ventricular ectopy, atrial fibrillation, and, rarely, atrial flutter or SVT. ECG monitoring should begin before induction of anesthesia, and the cardiac rhythm should be stabilized before anesthesia if possible. Antiarrhythmic agents including, but not limited to, lidocaine and diltiazem should be available.

For inotropic support, dobutamine is the clear choice over dopamine to increase contractility, SV, CO, and BP. While dopamine activates beta-1 adrenergic receptors and is a positive inotrope when delivered between 5 and 10 mcg kg\(^{-1}\) min\(^{-1}\), dopamine will cross to the alpha-1 adrenergic receptors at higher doses, subsequently inducing vasoconstriction and increasing afterload, which may severely reduce fractional shortening and CO. Dobutamine is preferred in these patients, as it has limited alpha-1 adrenergic effects. Dobutamine increases HR and contractility as a result of nonspecific beta-adrenergic (mainly beta-1) agonist effects.

Common premedication techniques for patients with DCM often include opioids because of their cardiovascular safety. Opioid-induced bradycardia may be treated with anticholinergics if necessary. Benzodiazepines are inconsistent sedatives in dogs. However, sedation with benzodiazepines is improved when combined with an opioid. Acepromazine is not recommended, as it leads to long acting, irreversible vasodilation and can easily precipitate hypotension with variable effects on contractility and HR. Alpha-2 adrenergic agonists are absolutely contraindicated due to the severe increase in afterload, as well as the decrease in CO.

Nearly all anesthetic induction agents are negative inotropes to some degree, and will reduce contractility dose-dependently. Although patients with very mild disease may be successfully induced with propofol while maintaining cardiovascular function, those with mild, moderate, or severe disease can most safely be induced with either etomidate or fentanyl and a benzodiazepine (midazolam or diazepam) or fentanyl. Etomidate has a more reliable transition to unconsciousness compared to fentanyl but has other effects, including adrenocortical suppression, higher cost, lower availability, and very high osmolality (~4800 mOsm l\(^{-1}\)). While the sympathomimetic effects of ketamine will increase HR, contractility, and BP by increasing circulating norepinephrine concentrations, ketamine has a direct negative inotropic effect that is typically overwhelmed by the sympathomimetic effects. The potential for further reductions in myocardial contractility in a patient with DCM may be severely detrimental to fractional shortening and ventricular ejection. As safer alternative induction options exist, ketamine is not
recommended for induction of anesthesia in patients with DCM.

Maintenance with inhaled anesthetics is often unavoidable. However, all inhaled anesthetics produce a moderate to severe dose-dependent reduction in contractility and subsequent decrease in SV and CO. All attempts to minimize (or avoid) inhaled anesthetic doses must be applied. These include opioid infusions as well as local and regional anesthesia/analgesia.

**Arrhythmogenic cardiomyopathy**

**Incidence and pathophysiology**

Arrhythmogenic cardiomyopathy (ARVC) is a variant of canine cardiomyopathy seen in Boxer dogs. Patients often present with syncope or exercise intolerance; however, pulse deficits and arrhythmias may be identified incidentally. Unfortunately, sudden death may be the only identifier of the disease. A small percentage of dogs may develop systolic dysfunction and heart failure. Short periods of ECG monitoring may fail to identify abnormal ECG rhythms, and Holter monitoring is recommended to evaluate for extent of arrhythmogenic disease. Criteria for advanced diagnosis of occult ARVC are lacking. Treatment for affected dogs may not reverse or delay the onset of more severe clinical signs but may decrease syncopal events and is generally recommended for >1000 VPCs in a 24-h Holter period, if R-on-T phenomenon is identified or there are paroxysms of ventricular tachycardia.

**Anesthetic management**

Anesthetic management is similar to patients with DCM. Preinduction monitoring of the ECG and treatment of ventricular ectopy are recommended before induction. Increases in sympathetic tone due to pain, stress, or excitement are to be avoided to reduce the potential for arrhythmogenic effects of catecholamine release.

**Heartworm disease**

**Incidence and pathophysiology**

Heartworm disease is prevalent across the United States and can affect all dogs and cats, regardless of age, environment, or gender. It is most common within 150 miles of the Gulf and Atlantic coasts and along the Mississippi river valley, with up to 5% seroprevalence in the South. Other areas of the United States can see infection rates in up to 5% of the unprotected population. All dogs must be viewed as susceptible, and heartworm preventative is a mainstay of prophylactic veterinary medicine.

Heartworm infection is due to the parasite Dirofilaria immitis and is transmitted between dogs by mosquitoes, which transmit a larval stage of the parasite. Newly infected dogs develop adult heartworms that reside in the heart and pulmonary vasculature within 5–6 months of infection. Adult heartworms induce endothelial and myointimal thickening of both small and large pulmonary arteries from antigenic stimulation. Inflammatory mediators reacting to exposed subendothelial collagen and to adult worms lead to endothelial proliferation and development of villi-like projections on the arterial luminal surface. Arteries dilate and become torturous, leading to the classic radiographic findings. Altogether, these changes along with obstruction of flow due to physical presence of worms leads to an increase in pulmonary vascular resistance and is the underlying cause of PHT. The development of PHT, if severe, can then lead to a pressure overload of the right ventricle, although the degree of PHT can vary from mild to severe. Right heart failure is an end result of fulminant heartworm disease, although it is unclear if this is a direct result of PHT or some other mechanism. The fragmentation of dying or dead heartworms can lead to pulmonary thromboembolism and severe ventilation/perfusion imbalances. Pulmonary parenchymal disease characterized by inflammatory-mediated interstitial edema and eventual pulmonary fibrosis from chronic inflammation may also be seen.

Clinical signs of heartworm disease are dependent on worm burden in the heart and lungs. Early and mild infections may not have recognizable clinical signs; however, dogs with moderate worm burdens typically present with exercise intolerance, cough, and abnormal lung sounds. Dogs with severe worm burden can present with signs because of cardiac, pulmonary, hepatic, or renal dysfunction, including cough, exercise intolerance, dyspnea, hepatomegaly, syncope, ascites, heart murmurs, signs of right-sided heart failure, and/or acute death. Severe cases may also have signs of hypoxemia. Heart murmurs can auscult as left basilar ejection murmurs, split S2 sounds, systolic clicks, or murmurs supportive of tricuspid insufficiency. Severe disease can also present with pulmonary thromboembolism, disseminated intravascular coagulation, hemoptysis, or signs of allergic reactions directed against adult worms. Abnormalities may include eosinophilia and
basophilia in mildly affected dogs. Severely affected dogs may show thrombocytopenia and anemia due to caval syndrome (see the following section), signs of organ damage due to hypoxemia, or decreased organ perfusion. Heartworm screening includes antigen and antibody testing in dogs.

**Feline heartworm disease**

Feline heartworm disease is far less common, as cats are not a typical target for mosquitoes, and dose of microfilariae for clinical infection and disease is higher than dogs.206 PEIs of cats with feline heartworm disease are often normal. However, they may present with mild cough and may infrequently have heart murmurs, arrhythmias, or abnormal lung sounds. Cats may present with asthmatic signs owing to immune system response to adult worms. No single abnormality on serum chemistry and blood count is diagnostic for adult heartworm infection. Combined antigen and antibody testing is recommended in cats, and a positive antigen test confirms infection, although infected cats are often antigen negative.206

**Caval syndrome**

Caval syndrome is a life-threatening presentation of advanced heartworm disease and is characterized by a severe burden of adult worms with associated severe tricuspid regurgitation, decreased CO, intravascular hemolysis, marked hemoglobinemia, and hemoglobinuria. Clinical signs are due to acute accumulation of heartworms in the right ventricle and across the tricuspid valve, leading to severe ventricular dysfunction and tricuspid valve incompetence. It is unknown why the mass of heartworms invades the right heart, but moderate to severe PHT and a large worm burden are precipitating factors. Heartworms typically do not invade the right ventricle, as they are quickly moved into the pulmonary arteries because of downstream blood flow. Severe decreases in forward flow due to experimental administration of beta-blockers or thiopental have the potential to allow adult worms to “fall into” the right ventricle and precipitate caval syndrome. This argues that any severe decrease in forward flow, particularly in patients with high worm burdens or signs of PHT, have the potential to acutely develop caval syndrome in response to sudden decreases in CO. The lack of forward flow is the reason heartworms can recede into the right ventricle post-mortem.

**Anesthetic management**

In mildly to moderately affected dogs, no single anesthetic protocol appears to have significant advantages over others, and no particular anesthetics are contraindicated with positive heartworm antigen tests. As with any anesthetized patient, appropriate monitoring, including BP, pulse oximetry, and ECG is critically important to evaluating patient stability and changes over time. Cardiovascular support for hypotensive patients can likely be provided as in normal patients.

In severely affected patients with moderate to severe worm burdens, particularly in those at risk for caval syndrome due to sudden decreases in CO, optimizing anesthetic plans to maintain CO and minimize changes in cardiac function and perfusion is strongly recommended. For patients with signs of right heart failure, anesthetic management has been previously described in this chapter. In patients who present with either heart failure or caval syndrome, choosing anesthetic plans that have minimal effects on CO or effects that are readily treatable is safest. If possible, avoidance of general anesthesia with sedation and/or locoregional anesthesia/analgesia is preferred to avoid the risks associated with general anesthesia.

Whether for sedation alone or as premedication before general anesthesia, sedation with opioids and benzodiazepines is preferred in that they have minimal cardiovascular effects, provided the opioid-mediated bradycardia is minimal or prevented with concurrent administration of anticholinergics. Premedication with alpha-2 adrenergic agonists is contraindicated in patients at risk for caval syndrome or with high worm burdens due to the severe reductions in CO at typical premedication doses equal to or higher than 5 μg kg⁻¹. Acepromazine is controversial, as the alpha-1 adrenergic antagonist-mediated decrease in SVR can lead to decreases in BP that are long acting and irreversible. Etomidate or fentanyl combined with a benzodiazepine have minimal effects on cardiac contractility and SVR and are ideal induction agents to maintain CO. Induction doses of opioids have the potential to significantly depress HR and ventilation, and these side effects must be controlled.

In addition to basic monitoring tools, advanced monitoring for severely affected patients is strongly recommended. Invasive arterial BP monitoring provides accurate, continuous BP monitoring. Access to arterial blood and availability of arterial blood gas analyses are
critical tools for the assessment of ventilation/perfusion imbalances and can assist in the diagnosis of pulmonary thromboembolism. Doppler crystal placement also allows for a second assessment of BP should an arterial catheter fail.

**Summary**

The large variety of cardiovascular diseases and the wide range of severity and clinical presentation of cardiac diseases present a significant challenge to the clinician in planning for an anesthetic event. Thus, one of the most important concepts to understand is that the wide range of diagnoses and underlying pathophysiologies should prompt the clinician to investigate the nature of any sign of cardiovascular disease carefully and completely and use that information to design an appropriate anesthetic and analgesic plan to maximize the safety of the patient through the anesthetic process. This chapter presents appropriate information for the clinician to prepare an individually tailored anesthesia plan for each patient presenting with cardiac disease.

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