Diastolic function has been shown to influence overall cardiac performance significantly, but the effect of intravenous anesthetics on diastolic function has not been previously characterized in vivo. The effects of ketamine and propofol on two indices of left ventricular diastolic function were examined in chronically instrumented dogs. Because autonomic nervous system function may significantly influence the systemic hemodynamic actions produced by intravenous anesthetics in vivo, experiments were performed in the presence of pharmacologic blockade of the autonomic nervous system. Two groups comprising a total of 14 experiments were performed using 7 dogs instrumented for measurement of aortic and left ventricular pressure, the maximum rate of change of left ventricular pressure (dP/dt), subendocardial segment length, and cardiac output. Systemic hemodynamics and diastolic function were recorded and evaluated in the conscious state and after a 20-min equilibration at 25, 50, and 100-mg·kg⁻¹·h⁻¹ infusion doses of ketamine or propofol. Ventricular relaxation was described using the time constant of isovolumetric relaxation (τ) assuming a nonzero asymptote of ventricular pressure decay. Regional chamber stiffness, an index of passive ventricular filling, was described using an exponential equation relating segment length to ventricular pressure between minimum ventricular pressure and the onset of atrial systole. Ketamine produced a significant (P < 0.05) and dose-dependent increase in the time constant of isovolumetric relaxation (τ, 32.8 ± 2.8 during control to 53.3 ± 4.2 ms⁻¹ at 100 mg·kg⁻¹·h⁻¹). Ketamine also caused an increase in regional passive chamber stiffness (Kp, 0.37 ± 0.03 during control to 0.69 ± 0.09 mmHg⁻¹ at 100 mg·kg⁻¹·h⁻¹) in a dose-dependent fashion indicating a decrease in ventricular compliance. Neither isovolumetric relaxation nor regional chamber stiffness changed significantly with propofol. Although the effects of the intravenous anesthetics on systolic function represent a confounding variable that could not be completely excluded from the analysis of the data, the results indicate that ketamine impairs left ventricular diastolic function in the chronically instrumented dog with autonomic nervous system blockade. In contrast, propofol does not appear to alter diastolic function even though it produces a similar hemodynamic profile with the doses administered in this investigation. (Key words: Anesthetics, intravenous; ketamine; propofol. Heart; diastole; diastolic left ventricular function; isovolumetric relaxation; myocardial function; ventricular compliance.)

FUNCTION OF THE LEFT VENTRICLE during diastole has attracted considerable recent attention because diastolic mechanics significantly affect overall cardiac performance. Although clinical congestive heart failure most often occurs as a consequence of compromised systolic function, this syndrome may also occur in certain patients with abnormalities of diastolic function in the absence of significant alterations in systolic performance.¹⁻⁵ Study of the action of anesthetics on diastolic function is important because anesthetics may alter the rate and extent of ventricular filling, factors that play a critical role in the mechanical efficiency of the heart. For example, potent inhalational anesthetics have been shown to prolong isovolumetric relaxation⁶⁻⁸ and may also impair passive ventricular compliance.⁶ These alterations could significantly contribute to depressed cardiac performance observed with the volatile anesthetic agents. Several investigators working in vitro⁷⁻¹⁰ have postulated that ketamine may alter myocardial relaxation; however, the action of this commonly used intravenous anesthetic on diastolic function in vivo has not been previously characterized. Similarly, although the effects of propofol on systemic hemodynamics¹¹⁻¹³ and left ventricular systolic function¹⁴⁻¹⁷ have been described, the effects of this new intravenous agent on diastolic function are also unknown.

The present investigation was undertaken to examine systematically the effects of ketamine and propofol on active (isovolumetric relaxation) and passive (regional chamber stiffness) components of left ventricular diastolic function in the chronically instrumented dog. Experiments were performed in the presence of autonomic nervous system blockade because both ketamine and propofol have been shown to alter autonomic nervous system function variably and to produce indirect effects on systemic hemodynamics mediated via an intact autonomic nervous
system. Therefore, the direct actions of ketamine and propofol on isovolumetric relaxation and regional chamber stiffness were evaluated independent of autonomic nervous system reflexes.

Materials and Methods

All experimental procedures and protocols used in this investigation were reviewed and approved by the Animal Care Committee of the Medical College of Wisconsin. Furthermore, all conformed to the Guiding Principles in the Care and Use of Animals of the American Physiologic Society and were in accordance with the Guide for the Care and Use of Laboratory Animals.

Implantation of Instruments

Surgical implantation of instruments has been previously described in detail. Briefly, conditioned mongrel dogs weighing between 20 and 30 kg were fasted overnight and anesthetized with sodium thiamylal (10 mg·kg⁻¹). Following tracheal intubation, anesthesia was maintained with enflurane (2.0–3.0%) in 100% oxygen (1·min⁻¹) via positive pressure ventilation. A thoracotomy was performed under sterile conditions in the left fifth intercostal space. Heparin-filled catheters were placed in the descending thoracic aorta and the right atrium for measurement of aortic blood pressure and fluid or drug administration, respectively. An ultrasonic flow probe (Transonic, Ithaca, NY) was positioned around the ascending thoracic aorta for measurement of relative cardiac output. A pair of miniature ultrasonic segment length transducers (5 MHz) for measurement of changes in regional contractile function (segment shortening) were implanted within the left ventricular subendocardium. A high-fidelity, miniature micromanometer (PT; Konigsberg Instruments, Pasadena, CA) was implanted in the left ventricle for measurement of left ventricular pressure and of the maximum rate of increase of left ventricular pressure (dP/dt max). A heparin-filled catheter was inserted into the left atrial appendage, and the left ventricular micromanometer was cross-calibrated in vivo against pressures measured via arterial and left atrial catheters (Gould P50 pressure transducer, Oxnard, CA). A precalibrated Doppler ultrasonic flow transducer (20 MHz) was placed around the proximal left anterior descending coronary artery for measurement of diastolic coronary blood flow velocity. All instrumentation was secured, tunneled between the scapulae, and exteriorized via several small incisions. The pericardium was left widely open, the chest wall closed in layers, and the pneumothorax evacuated by a chest tube left in situ. Each dog was fitted with a jacket (Alice King Chatham, Los Angeles, CA) to prevent damage to the instruments and catheters, which were housed in an aluminum box within the jacket pocket.

After surgery, each dog was treated with analgesics (buprenorphine 0.02 mg/kg). Antibiotic prophylaxis consisted of procaine penicillin G (25,000 U/kg) and gentamicin (4.5 mg/kg). The chest tube was removed on the first postoperative day, and dogs were allowed to recover for a minimum of 10 days prior to experimentation. Dogs were trained to stand quietly in a sling during hemodynamic monitoring in the postoperative period. Segment length signals were driven and monitored by ultrasonic amplifiers (Hartley, Houston, TX). End systolic segment length was determined at maximum negative left ventricular dP/dt, and end diastolic segment length was determined at the onset of left ventricular isovolumetric contraction. The lengths were normalized according to the method described by Theroux et al. Percent segment shortening (SS) was calculated by use of the equation: \( \%SS = (\text{EDL} - \text{ESL}) \times 100 / \text{EDL} \), where EDL = end-diastolic segment length and ESL = end-systolic segment length. Diastolic coronary vascular resistance was calculated as the quotient of diastolic arterial pressure and diastolic coronary blood flow velocity (Hz × 10²). All hemodynamic data were continuously recorded on a Hewlett Packard 7758A polygraph (Hewlett Packard, San Francisco, CA) and digitized via a computer interfaced with an analog-to-digital converter.

Experimental Protocol

Dogs (n = 7) were assigned to receive either ketamine or propofol in a random fashion on separate days. All dogs were fasted overnight, and fluid deficits were replaced before experimentation with crystalloid (500 ml lactated Ringer’s solution). After instrumentation was calibrated and baseline hemodynamic data recorded, the autonomic nervous system was pharmacologically blocked with intravenous propranolol (2 mg·kg⁻¹), atropine methyl nitrate (3 mg·kg⁻¹), and hexamethonium (20 mg·kg⁻¹). Blockade of the autonomic nervous system was instituted to prevent reflex changes in systemic hemodynamics produced by ketamine or propofol.

After control hemodynamics had been recorded in the conscious, autonomically blocked state, continuous left ventricular pressure and segment length waveforms (20–25 cardiac cycles) were recorded on a digital storage oscilloscope (Nicolet Model 4094, Madison, WI) for later off-line analysis of isovolumetric relaxation and regional chamber stiffness. Anesthesia was then induced with ketamine or propofol in a random fashion by intravenous bolus (10 mg·kg⁻¹) injection. After tracheal intubation, anesthesia was maintained with ketamine or propofol via a continuous infusion at 25, 50, or 100 mg·kg⁻¹·h⁻¹ in a random order. Each dog’s lungs were mechanically ventilated with a nitrogen (79%) and oxygen (21%) mixture at a constant flow rate of 2 l·min⁻¹. Hemodynamics were
recorded and ventricular pressure and segment length waveforms were obtained in a manner described above after 20 min of equilibration at each dose of intravenous anesthetic. The anesthetic concentration was then changed, and measurements were repeated after similar equilibration. Arterial blood gases were maintained at conscious levels by adjustment of nitrogen and oxygen concentrations during each experiment.

At the completion of all experiments, anesthesia was discontinued and emergence allowed to occur. Three days were allowed between experiments for complete recovery from autonomic nervous system blockade and anesthesia. A total of 14 experiments in two separate groups (ketamine or propofol) were completed in which the same seven dogs were used.

Each of the two phases of diastole, isovolumetric relaxation and regional wall stiffness, was analyzed off-line. Isovolumetric relaxation was described assuming a nonzero asymptote of ventricular pressure decline using the method of Thompson et al. and the modification of Raff and Glantz. Left ventricular pressure between maximum negative dP/dt and 5 mmHg above end-diastolic pressure (physiologically associated with the opening of the mitral valve) versus time data in 2-ms intervals were fitted to a three-constant exponential equation:

$$P = ae^{-t/\tau} + c$$  \hspace{1cm} (1)

where $c$ = the true asymptote to which pressure declines; $a + c$ = ventricular pressure at peak negative dP/dt; and $\tau$ = the rate of relaxation (ms$^{-1}$) assuming a nonzero asymptote. It can be easily shown that

$$\frac{dP}{dt} = \frac{c}{\tau} - \frac{P}{\tau}$$  \hspace{1cm} (2)

Therefore, a plot of dP/dt against ventricular pressure between peak negative dP/dt and 5 mmHg above end-diastolic pressure yields the nonzero asymptotic isovolumetric time constant ($\tau$) as the negative inverse of the slope.

Regional chamber stiffness, a regional indicator of ventricular compliance during passive filling, was derived from ventricular pressure–segment length data as previously described. Beginning at minimum pressure, ventricular pressure was plotted against corresponding segment length at 2-ms intervals until the onset of atrial systole (incorporating both rapid and slow ventricular filling) had been reached. A least squares regression analysis was used to describe a monoeponential relationship between pressure and segment length:

$$P = De^{K_p \cdot L}$$  \hspace{1cm} (3)

where $P$ = left ventricular pressure; $L$ = corresponding segment length; $D$ = a derived constant; and $K_p$ = the regional chamber stiffness constant.

**Statistical Analysis**

Statistical analysis of data within each group during the conscious state with and without autonomic nervous system blockade and during all anesthetic interventions was performed by analysis of variance with repeated measures followed by application of the Student's $t$ test with Bonferroni's correction. Changes within each group were considered statistically significant when the probability ($P$) value was $< 0.05$. Least squares regression analysis was used to characterize the exponential relationship between ventricular pressure and segment length (calculation of $K_p$). The relationship between dP/dt and ventricular pressure used to calculate the time constant of isovolumetric relaxation was described using a linear regression analysis. All data were expressed as mean ± SEM.

**Results**

Autonomic nervous system blockade produced a significant ($P < 0.05$) increase in heart rate and decreases in mean arterial pressure, left ventricular systolic pressure, dP/dtmax, diastolic coronary vascular resistance, systemic vascular resistance, and stroke volume. No changes in left ventricular end-diastolic pressure, rate–pressure product, diastolic coronary blood flow velocity, cardiac output, or percent segment shortening were observed (tables 1 and 2). Regression coefficients ($r^2$) obtained in the calculation of $\tau$ and $K_p$ were $\approx 0.98$ and $\approx 0.94$, respectively.

In the presence of autonomic nervous blockade, ketamine produced significant ($P < 0.05$) decreases in heart rate and rate–pressure product (table 1). Increases in left ventricular end-diastolic pressure (8 ± 1 during control to 13 ± 2 mmHg at 100-mg · kg$^{-1}$ · h$^{-1}$ dose) and systemic vascular resistance (2,000 ± 270 during control to 3,340 ± 540 dyn · s · cm$^{-5}$ at 100-mg · kg$^{-1}$ · h$^{-1}$ dose) were noted with ketamine. Ketamine also caused dose-dependent decreases in cardiac output (2.9 ± 0.2 during control to 1.7 ± 0.2 1·min$^{-1}$ at the high dose). No changes in mean arterial pressure, left ventricular systolic pressure, diastolic coronary blood flow velocity, or diastolic coronary vascular resistance were observed during ketamine anesthesia.

Ketamine produced significant ($P < 0.05$) and dose-dependent decreases in global myocardial contractility as assessed by dP/dt$\max$ (1,830 ± 180 during control to 850 ± 80 mmHg · s$^{-1}$ at 100 mg · kg$^{-1}$ · h$^{-1}$), consistent with a direct myocardial depressant effect independent of the autonomic nervous system. Dose-related decreases in inotropic state were also identified by percent segment shortening (15.7 ± 2.0 during control to 7.1 ± 0.8% at 100 mg · kg$^{-1}$ · h$^{-1}$). The time constant of isovolumetric relaxation increased in a significant and dose-dependent fashion during administration of ketamine (fig 1; 33 ± 3 during control to 53 ± 4 ms at 100 mg · kg$^{-1}$ · h$^{-1}$), indicating a direct prolongation of this phase of diastole. In
TABLE 1. Systemic and Coronary Hemodynamic Effects of Ketamine

<table>
<thead>
<tr>
<th></th>
<th>Conscious Pre-ANS Block</th>
<th>Conscious ANS Block</th>
<th>25</th>
<th>50</th>
<th>100</th>
</tr>
</thead>
<tbody>
<tr>
<td>HR (beats·min⁻¹)</td>
<td>84 ± 4*</td>
<td>114 ± 5</td>
<td>105 ± 6</td>
<td>105 ± 6*</td>
<td>98 ± 6*</td>
</tr>
<tr>
<td>MAP (mmHg)</td>
<td>190 ± 3*</td>
<td>74 ± 7</td>
<td>74 ± 7</td>
<td>72 ± 8</td>
<td>66 ± 6</td>
</tr>
<tr>
<td>RPP (beats·min⁻¹·mmHg·10⁵)</td>
<td>11.6 ± 0.5</td>
<td>10.6 ± 0.9</td>
<td>9.5 ± 1.0</td>
<td>9.2 ± 1.0</td>
<td>7.8 ± 0.8*</td>
</tr>
<tr>
<td>LVSP (mmHg)</td>
<td>139 ± 3*</td>
<td>99 ± 6</td>
<td>97 ± 7</td>
<td>96 ± 8</td>
<td>88 ± 5</td>
</tr>
<tr>
<td>LVEDP (mmHg)</td>
<td>10 ± 1</td>
<td>8 ± 1</td>
<td>10 ± 1</td>
<td>11 ± 1</td>
<td>13 ± 2*</td>
</tr>
<tr>
<td>dp/dt max (mmHg·s⁻¹)</td>
<td>2830 ± 130*</td>
<td>1830 ± 180</td>
<td>13900 ± 110*</td>
<td>12100 ± 110*</td>
<td>850 ± 80*†</td>
</tr>
<tr>
<td>DCBFV (Hz·10⁸)</td>
<td>40.4 ± 4.4</td>
<td>38.0 ± 5.6</td>
<td>35.3 ± 6.0</td>
<td>35.8 ± 5.8</td>
<td>37.2 ± 6.4</td>
</tr>
<tr>
<td>DCVR (ml/min)</td>
<td>2.56 ± 0.29*</td>
<td>1.84 ± 0.38</td>
<td>2.04 ± 0.41</td>
<td>2.01 ± 0.44</td>
<td>1.86 ± 0.45</td>
</tr>
<tr>
<td>CO (l·min⁻¹)</td>
<td>2.8 ± 0.2</td>
<td>2.9 ± 0.2</td>
<td>2.2 ± 0.2*</td>
<td>2.0 ± 0.2*</td>
<td>1.7 ± 0.2†</td>
</tr>
<tr>
<td>SVR (dyn·s·cm⁻⁵)</td>
<td>3270 ± 270*</td>
<td>2000 ± 270</td>
<td>2700 ± 270</td>
<td>3070 ± 270*</td>
<td>3340 ± 340*†</td>
</tr>
<tr>
<td>SV (ml)</td>
<td>33 ± 2*</td>
<td>26 ± 2</td>
<td>21 ± 1*</td>
<td>19 ± 2*</td>
<td>17 ± 2*</td>
</tr>
<tr>
<td>SS (%)</td>
<td>15.7 ± 1.7</td>
<td>15.7 ± 2.0</td>
<td>12.5 ± 1.3</td>
<td>10.0 ± 0.7*</td>
<td>7.1 ± 0.8*†</td>
</tr>
</tbody>
</table>

All data are mean ± SEM; n = 7.

ANS = autonomic nervous system; HR = heart rate; MAP = mean arterial pressure; RPP = rate pressure product; LVSP = left ventricular systolic pressure; LVEDP = left ventricular end diastolic pressure; DCBFV = diastolic coronary blood flow velocity; DCVR = diastolic coronary vascular resistance; CO = cardiac output; SVR = systemic vascular resistance; SV = stroke volume; SS = segment shortening.

* Significantly (P < 0.05) different from conscious, autonomically blocked state.
† Significantly (P < 0.05) different from 25-mg·kg⁻¹·h⁻¹ dose.

In addition, administration of ketamine caused increases in regional chamber stiffness (fig. 2; 0.37 ± 0.03 during control to 0.69 ± 0.09 mm⁻¹ at 100 mg·kg⁻¹·h⁻¹), indicating a significant decrease in passive ventricular compliance.

In the presence of autonomic nervous system blockade, propofol produced hemodynamic effects (table 2) that were similar to those produced by ketamine. Propofol decreased heart rate, mean arterial pressure, left ventricular systolic pressure, and rate–pressure product primarily at the 100-mg·kg⁻¹·h⁻¹ dose (table 2). Cardiac output decreased (2.7 ± 0.2 during control to 2.1 ± 0.2 l·min⁻¹ at 25 mg·kg⁻¹·h⁻¹), but this decline was not dose-dependent. No significant changes in left ventricular end-diastolic pressure, diastolic coronary blood flow velocity, diastolic coronary vascular resistance, or systemic vascular resistance were observed. Propofol produced a significant (P < 0.05) reduction in left ventricular dp/dt max (1,830 ± 120 during control to 1390 ± 130 mmHg·s⁻¹ at 100 mg·kg⁻¹·h⁻¹), consistent with a negative inotropic effect. Regional myocardial contractility, as assessed by percent segment shortening, also decreased with propofol (17.0 ± 1.9 during control to 14.6 ± 1.6% at 100 mg·kg⁻¹·h⁻¹). No changes in the time constants of isovolumetric relaxation or regional chamber stiffness were observed with any dose of propofol (figs. 1 and 2).

TABLE 2. Systemic and Coronary Hemodynamic Effects of Propofol

<table>
<thead>
<tr>
<th></th>
<th>Conscious Pre-ANS Block</th>
<th>Conscious ANS Block</th>
<th>25</th>
<th>50</th>
<th>100</th>
</tr>
</thead>
<tbody>
<tr>
<td>HR (beats·min⁻¹)</td>
<td>83 ± 5*</td>
<td>113 ± 5</td>
<td>105 ± 6</td>
<td>102 ± 6</td>
<td>99 ± 5*</td>
</tr>
<tr>
<td>MAP (mmHg)</td>
<td>99 ± 5*</td>
<td>74 ± 4</td>
<td>70 ± 7</td>
<td>66 ± 6</td>
<td>59 ± 6*</td>
</tr>
<tr>
<td>RPP (beats·min⁻¹·mmHg·10⁵)</td>
<td>10.3 ± 0.4</td>
<td>10.4 ± 0.8</td>
<td>9.7 ± 1.2</td>
<td>8.7 ± 1.0</td>
<td>7.8 ± 0.9*</td>
</tr>
<tr>
<td>LVSP (mmHg)</td>
<td>129 ± 5*</td>
<td>95 ± 4</td>
<td>95 ± 6</td>
<td>87 ± 5</td>
<td>82 ± 5*</td>
</tr>
<tr>
<td>LVEDP (mmHg)</td>
<td>10 ± 1</td>
<td>7.2 ± 2</td>
<td>8 ± 1</td>
<td>8 ± 1</td>
<td>9 ± 2</td>
</tr>
<tr>
<td>dp/dt max (mmHg·s⁻¹)</td>
<td>2610 ± 130*</td>
<td>1830 ± 120</td>
<td>1650 ± 120</td>
<td>1550 ± 135*</td>
<td>1390 ± 130*†</td>
</tr>
<tr>
<td>DCBFV (Hz·10⁸)</td>
<td>39.3 ± 7.6</td>
<td>46.6 ± 8.0</td>
<td>43.8 ± 9.0</td>
<td>46.3 ± 10.6</td>
<td>43.1 ± 9.7</td>
</tr>
<tr>
<td>DCVR (ml/min)</td>
<td>2.43 ± 0.51*</td>
<td>1.51 ± 0.45</td>
<td>1.46 ± 0.20</td>
<td>1.28 ± 0.16</td>
<td>1.16 ± 0.12</td>
</tr>
<tr>
<td>CO (l·min⁻¹)</td>
<td>2.6 ± 0.3</td>
<td>2.7 ± 0.2</td>
<td>2.1 ± 0.2*</td>
<td>2.1 ± 0.2*</td>
<td>2.0 ± 0.2*</td>
</tr>
<tr>
<td>SVR (dyn·s·cm⁻⁵)</td>
<td>5180 ± 300*</td>
<td>2180 ± 240</td>
<td>2820 ± 330</td>
<td>2590 ± 250</td>
<td>2340 ± 250</td>
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<tr>
<td>SV (ml)</td>
<td>32 ± 2*</td>
<td>24 ± 2</td>
<td>20 ± 2</td>
<td>20 ± 1</td>
<td>21 ± 1</td>
</tr>
<tr>
<td>SS (%)</td>
<td>17.0 ± 1.6</td>
<td>17.0 ± 1.9</td>
<td>15.4 ± 1.4</td>
<td>15.0 ± 1.5*</td>
<td>14.8 ± 1.8*†</td>
</tr>
</tbody>
</table>

All data are mean ± SEM; n = 7.

ANS = autonomic nervous system; HR = heart rate; MAP = mean arterial pressure; RPP = rate pressure product; LVSP = left ventricular systolic pressure; LVEDP = left ventricular end diastolic pressure; DCBFV = diastolic coronary blood flow velocity; DCVR = diastolic coronary vascular resistance; CO = cardiac output; SVR = systemic vascular resistance; SV = stroke volume; SS = segment shortening.

* Significantly (P < 0.05) different from conscious, autonomically blocked state.
† Significantly (P < 0.05) different from 25-mg·kg⁻¹·h⁻¹ dose.
FIG. 1. Effects of ketamine and propofol on the time constant of isovolumetric relaxation (T). *Significantly (P < 0.05) different from the autonomically blocked, conscious control (C). †Significantly (P < 0.05) different from the 25-mg·kg⁻¹·h⁻¹ dose. §Significantly (P < 0.05) different from the 50-mg·kg⁻¹·h⁻¹ dose.

Discussion

Ketamine has achieved popularity as an intravenous induction agent in certain patients with hemodynamic compromise. The clinical recognition that the use of ketamine can also lead to acute cardiovascular decompensation in a subset of critically ill patients has stimulated intense study aimed at understanding the direct effects of ketamine on myocardial function. The effects of ketamine on systemic hemodynamics have been extensively described. Ketamine produces dramatic increases in heart rate and arterial pressure, which have been attributed to the central and peripheral sympathomimetic actions of this drug. On a cellular level, ketamine has been shown to block reuptake of monoamines including norepinephrine in adrenergic nerves, a mechanism of action similar to that of cocaine. In the presence of an impaired sympathetic nervous system, ketamine has also been described to produce direct myocardial depressant effects in vivo and in vitro. However, this conclusion remains controversial, as some investigations in vitro have offered evidence that ketamine may, in fact, produce direct myocardial stimulation independent of the actions of this agent on autonomic nervous system function.

The effects of ketamine on left ventricular diastolic function have not been described in vivo. Examination of the effect of anesthetics on this phase of the cardiac cycle is important because alteration of the rate and extent of ventricular filling produced by anesthetic agents may significantly influence overall cardiac function. Four studies completed in vitro have suggested that ketamine may alter ventricular relaxation. Rusy et al. demonstrated that ketamine depressed contractile function in rabbit papillary muscle via inhibition of transsarcolemmal calcium currents. Since ventricular relaxation is an active, energy-dependent process resulting from dissociation of actin–myosin linkages by reuptake of cytoplasmic calcium into the sarcoplasmic reticulum, alteration in transsarcolemmal calcium kinetics demonstrated by these authors may offer a potential mechanism by which ketamine impairs ventricular relaxation. Similarly, Riou et al. identified alterations in the calcium sequestering system, specifically the sarcoplasmic reticulum, in a study of the effects of ketamine on contractility and relaxation in a rat papillary muscle preparation. Ketamine impaired isotonic relaxation, contraction–relaxation coupling, and load sensitivity of relaxation, suggesting that ventricular relaxation is directly altered at a cellular level by this intravenous anesthetic. Most recently, Cook et al. observed decreases in isotonic relaxation induced by ketamine in an elegant study of the effects of this intravenous anesthetic on contractility in ferret papillary muscle. Although ketamine augmented maximum velocity of lengthening and maximal rate of decrease force in an isometric twitch when adrenergic transmission was intact, pretreatment with reserpine (depleting norepinephrine stores) resulted in significant decreases in these variables, implying that relaxation is directly delayed when normal adrenergic synaptic function is impaired. Similar findings were reported by Uhrhaler et al. in canine ventricular trabeculae in the presence of pretreatment with α and β adrenergic antagonists. Thus, experimental evidence in vitro suggests that ketamine probably alters myocardial function during diastole.

The effects of the new intravenous anesthetic, propofol, on systemic hemodynamics and myocardial contractility have been described; however, the actions of this drug on diastolic function in vivo or in vitro remain unexplored. Like barbiturate sedative–hypnotics,
propofol has been shown to produce cardiovascular depression and peripheral vasodilation manifested by decreases in cardiac output, systolic and diastolic arterial pressure, and systemic vascular resistance in a variety of experimental and clinical settings.\textsuperscript{11} In addition, propofol has been demonstrated to cause concentration-dependent decreases in myocardial contractility as assessed by the end-systolic pressure–length relationship,\textsuperscript{15} a relatively load-insensitive measure of contractile state in isolated heart preparations.\textsuperscript{31}

The present investigation represents the first study of the effects of intravenous anesthetics on left ventricular diastolic function \textit{in vivo}. The results of this investigation indicate that ketamine profoundly depresses both active (ventricular relaxation) and passive (regional chamber stiffness) phases of diastole in the chronically instrumented dog with autonomic nervous system blockade. Dose-dependent increases in the time constant of isovolumetric relaxation occurred when ketamine was administered, indicating direct prolongation of this phase of diastole. Ketamine also significantly increased regional chamber stiffness in a dose-dependent fashion, indicating that this intravenous anesthetic may also significantly alter the passive filling properties of the left ventricle. The results of this investigation support previous findings \textit{in vitro}\textsuperscript{7–10} that imply that ketamine produces direct negative lusitropic effects independent of normal adrenergic transmission by altering intracellular calcium handling. No alteration of diastolic function as measured by isovolumetric relaxation or passive diastolic compliance were observed with propofol with any dose, despite the fact that propofol produced a hemodynamic profile that was very similar to that of ketamine with the doses of these intravenous anesthetics used in this investigation.

Quantitative description of ventricular function during diastole has received considerable attention in recent years because diastolic mechanics significantly influence overall cardiac performance.\textsuperscript{1–3} Measurements of indices of diastolic function, however, are complex and depend on both intrinsic (ventricular relaxation and viscoelastic properties) and extrinsic (right ventricular and septal interactions, pericardial restraint, myocardial blood flow, and diastolic suction) factors as well as variables that normally affect systolic function (heart rate, preload, afterload, and myocardial contractility).\textsuperscript{32} Time constants of isovolumetric relaxation have been shown to be variably affected by changes in heart rate and ventricular loading conditions.\textsuperscript{3} The direct negative chronotropic actions of ketamine independent of adrenergic transmission have been previously described.\textsuperscript{30,35} Thus, the decreases in heart rate observed in the present investigation with ketamine at the 50- and 100-mg·kg\textsuperscript{−1}·h\textsuperscript{−1} doses may partially explain observed increases in the period of isovolumetric relaxation. However, no significant change in heart rate was observed at the lowest dose of ketamine, indicating that the changes in isovolumetric relaxation observed could not be solely attributed to alterations in heart rate. Interpretation of increases in the time constant of isovolumetric relaxation must be further qualified because ketamine produced other hemodynamic changes, including increases in left ventricular end-diastolic pressure (at the 100-mg·kg\textsuperscript{−1}·h\textsuperscript{−1} dose) and systemic vascular resistance (at the 50- and 100-mg·kg\textsuperscript{−1}·h\textsuperscript{−1} doses). Also, the alterations in heart rate, loading conditions, and myocardial contractility produced by ketamine may have influenced passive viscoelastic properties and diastolic compliance and could not be completely excluded from the analysis.

Decreases in heart rate and myocardial contractility observed with propofol represent uncontrolled variables that may alter the interpretation of the effects of this agent on diastolic function. Although propofol has been reported to produce modest degrees of peripheral vasodilation in experimental animals and humans with intact autonomic nervous system function,\textsuperscript{14} no changes in preload (left ventricular end-diastolic pressure) or afterload (calculated systemic vascular resistance) were observed with the administration of propofol in the presence of autonomic blockade with current investigation. These findings suggest that propofol does not directly alter isovolumetric relaxation and diastolic compliance, but this conclusion may require some qualification when this drug is administered in the presence of intact autonomic reflexes.

The doses of ketamine and propofol used in this investigation were chosen to provide reliable anesthesia in all animals and to establish similar cardiovascular dose-response relationships. The lower doses of each drug correlate well with those previously described for canine anesthesia.\textsuperscript{13,34} Although identical doses of ketamine and propofol produced similar hemodynamic actions, no direct conclusion about the relative anesthetic potencies of these intravenous anesthetics should be inferred. In addition, plasma concentrations of ketamine and propofol were not obtained in this investigation, therefore, direct comparison of the effects of these agents between the chronically instrumented canine model and humans may be difficult and should be approached cautiously.

In summary, the results of this investigation indicate that ketamine prolongs isovolumetric relaxation and produces a decrease in ventricular compliance as evaluated by regional chamber stiffness in chronically instrumented dogs with pharmacologic blockade of the autonomic nervous system. In contrast, propofol has no effect on left ventricular diastolic function although it produces very similar systemic hemodynamic effects at the doses used in this experimental preparation. The present results for ketamine are supported by investigations \textit{in vitro}\textsuperscript{7–10} that
suggest that ketamine may directly alter intracellular calcium kinetics during both systole and diastole, inducing decreases in contractile state and prolongation of relaxation, respectively. Extension of the findings of this investigation to the clinical setting suggests that acute cardiac decompensation observed in catecholamine-depleted, critically ill patients when ketamine is used as an anesthetic induction agent28 may be partially attributed to direct alterations in left ventricular diastolic function. Such a comparison must be viewed with caution, however, since the doses of ketamine and propofol used in this investigation may exceed those typically used in clinical practice.

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