Hemodynamic Effects of Rapid Atrial Stimulation in Adult and Young Dogs

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SUMMARY We evaluated the use of rapid atrial stimulation (RAS) to produce 2:1 atrioventricular (AV) block as a method for treating supraventricular tachycardias. We studied the cardiovascular hemodynamic changes before and after block in eight adult dogs and nine young dogs (3-4½ weeks old). In each dog an electrocardiogram; cardiac index; aortic, pulmonary, and left ventricular (LV) systolic and end-diastolic pressures; and LV (dp/dt)/p were recorded simultaneously and pulmonary and systemic resistances were calculated. Measurements were obtained during (1) the control state, (2) RAS with maximal 1:1 AV conduction, (3) RAS with 2:1 AV block, and (4) RAS with 1:1 AV conduction at 50% of the rate which resulted in 2:1 AV block. Comparison of the hemodynamic effect of RAS with maximal 1:1 AV conduction and hemodynamics in the control state showed that there was a significant decrease in cardiac index and aortic mean pressure of 39% and 15%, respectively. When hemodynamic changes during RAS with 2:1 AV block were compared with those during RAS with maximal 1:1 AV conduction, cardiac index, LV systolic pressure, and aortic mean pressure increased by 52%, 17%, and 22%, respectively. LV (dp/dt)/p increased by 20% and was significantly higher during RAS with 2:1 AV block than at higher ventricular rates obtained with RAS and maximal 1:1 AV conduction. We found that in this acute study the hemodynamic findings for the young dogs were similar to those for adult dogs. The data suggest that (1) significant hemodynamic improvement is obtained by RAS causing 2:1 AV block when compared to higher ventricular rates associated with 1:1 AV conduction; (2) in addition to increasing the diastolic filling period, reducing the very high ventricular rates improves the cardiac contractile state, and (3) RAS and 2:1 AV block may provide a useful technique for the management of some patients with intractable supraventricular tachycardia.

THE ADVERSE hemodynamic effects of the rapid ventricular rates caused by supraventricular tachyarrhythmias have been observed clinically in adults as well as in infants and children.1-5 Treatment usually has consisted of reflex vagal stimulation, drug therapy, or electrical cardioversion.6 Many previous studies have shown the effect of premature atrial beats and rapid atrial stimulation (RAS) on atrioventricular (AV) conduction and the ventricular response. These studies were conducted at pacing rates of up to 200 beats/min.4,8 A recent study in children, using atrial stimulation at rates of up to 600 beats/min, showed that when the atrial rate is gradually increased the ventricular response changes predictably, so that a plot of the ventricular response against atrial rate resembles an M-shaped curve. With an atrial pacing rate of up to 270 beats/min there is 1:1 AV conduction and a gradual increase in the P-R interval. This constitutes the first ascending limb of the M-shaped curve. When the atrial pacing rate is increased further there is increased impairment of AV conduction in the form of Wenckebach periodicity with a decrease in ventricular rate to give the first descending limb of the M-shaped curve. This impairment of conduction has been shown to occur at the AV node and occurs in children at atrial pacing rates of 160-300 beats/min. The 2:1 AV block is noted at atrial pacing rates of 200-536 beats/min, with corresponding ventricular rates of 100-268 beats/min (second ascending limb). Blocks both at the stimulation site and at the AV node that result in irregular ventricular responses at reduced rates occur with rates exceeding 300 beats/min (second descending limb).8 Various techniques for electrical stimulation of the atria and ventricles have been proposed to reduce the ventricular rate and to improve systemic hemodynamics in the treatment of supraventricular tachycardias.1,9-11 However, no data are available concerning the extent of hemodynamic improvement expected with atrial stimulation that produces 2:1 AV block and decreases ventricular rate.

The purpose of this study was (1) to define the hemodynamic effects that occur with RAS when maximal 1:1 AV conduction is attained, and (2) to evaluate the use of higher rates of atrial stimulation resulting in 2:1 AV block and a decreased ventricular rate as a potential means of treating some types of intractable supraventricular tachycardias.

Methods

The study was carried out in eight adult dogs weighing 8-20 kg and in nine young dogs, 3-4½ weeks old, weighing 1.4-2 kg. All dogs were anesthetized with morphine (1 mg/kg) and chloralose (50 mg/kg) given intravenously.

An electrocardiogram (lead II) and left ventricular (LV), aortic, and pulmonary artery pressures were recorded simultaneously on an Electronics for Medicine DR-8. The electrocardiogram was recorded between 0.1 and 500 Hz. LV pressures and LV (dp/dt)/p were obtained with a Millar catheter-tip micromanometer. In addition, a no. 5 pacing catheter was placed in the right atrium and connected to a digital threshold stimulator (Medtronic model 1187). Cardiac output was measured using the indocyanine green dye-dilution technique with...
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injection into the right atrium and sampling from the aorta. The average of two consecutive dye curves was recorded for each measurement. The green dye-dilution curves for measurements of cardiac output were obtained with a Waters densitometer (model XP302). To avoid sudden changes in intravascular blood volume in the young dogs, a continuous flow system was used. Blood from the ascending aorta was channeled through the cuvette densitometer and returned to the pulmonary artery using a roller pump. LV, aortic, and pulmonary artery pressures, LV (dp/dt)/p, and an electrocardiogram were recorded as in the adult dogs.

All measurements were obtained in four different steady state situations:

1. Control, with the dogs in normal sinus rhythm.
2. During RAS with maximal 1:1 AV conduction. To achieve this state the stimulus rate was increased gradually until a Wenckebach periodicity or 2:1 AV block was observed. The pacing rate then was decreased by 10-20 beats/min to obtain stable 1:1 AV conduction.
3. Higher rates of RAS resulting in 2:1 AV block. In this state the hemodynamic measurements were obtained at the stimulation rate at which stable 2:1 AV conduction was observed.
4. Atrial stimulation at 50% of the rate that resulted in 2:1 AV block. In this state the ventricular rate was identical to that for state 3 but conditions differed in that each ventricular beat was preceded by an atrial contraction in a 1:1 relation.

A representative example of tracings obtained in the four states is shown in Figure 1, as are the corresponding values for each variable recorded. After initiating each state of the experimental protocol, an interval of 5-7 minutes was permitted to elapse prior to final measurements of these hemodynamic variables. This time lapse was allowed to achieve a steady state.

The experimental protocol and timing of the measurements was the same for all experiments. Cardiac index was calculated by dividing the cardiac output by body surface area obtained from tables previously published. Total systemic and pulmonary vascular resistances were calculated by dividing the mean aortic or pulmonary artery pressure by the cardiac index, and were expressed as resistance units/m². The significance of changes was evaluated by paired t-test.

Results

COMPARISON OF HEMODYNAMIC EFFECTS OF RAS WITH MAXIMAL 1:1 AV CONDUCTION VS. CONTROL STATE

Compared to control conditions, RAS with maximal 1:1 AV conduction (Table 1A) induced a 100% increase in heart rate in the adult dogs, and significant decreases in cardiac index (39%), LV systolic pressure (16%), and aortic mean pressure (15%). Calculated pulmonary and systemic vascular resistances increased by 52% and 39%, respectively. Changes in LV end-diastolic pressure, pulmonary arterial mean pressure, and LV (dp/dt)/p were not statistically significant.

In young dogs the control heart rate was higher than in adult dogs. The hemodynamic studies of RAS and maximal 1:1 AV conduction were carried out at a heart rate that was 63% higher than the control (Table 1B).

Compared to control, RAS with 1:1 AV conduction resulted in a decreased cardiac index (29%) and decreased LV systolic pressure and aortic mean pressure (15% and 16%, respectively). Calculated pulmonary and systemic resistances increased by 35% and 18%, respectively. As in the adult dogs, changes in LV end-diastolic pressure, pulmonary arterial pressure, and LV (dp/dt)/p were not statistically significant.

COMPARISON OF HEMODYNAMIC EFFECTS OF RAS WITH 2:1 AV BLOCK VS. RAS WITH MAXIMAL 1:1 AV CONDUCTION

In adult dogs RAS with 2:1 AV block (Table 2A) caused a decrease of 33% in ventricular rate when compared to RAS with maximal 1:1 AV conduction. Cardiac index increased by 52%, LV systolic pressure, aortic mean pressure, and LV (dp/dt)/p increased by 17%, 22%, and 20%, respectively. Calculated systemic and pulmonary vascular resistances decreased by 21% and 22%, respectively. In spite of the atrial contribution to ventricular filling when RAS was used at 50% of the rate required to induce 2:1 AV block, there were no statistically significant changes in any of the measured variables from the values obtained with RAS with 2:1 AV conduction.

In young dogs with RAS and 2:1 AV block the mean decrease in ventricular rate was 32% when compared to RAS and maximal 1:1 AV conduction (Table 2B). Cardiac index increased by 38% and LV systolic pressure increased by 15%. Calculated pulmonary and systemic resistances decreased by 34% and 17%, respectively. As in the adult dogs, no significant hemodynamic changes were observed when RAS with 2:1 AV block was compared to atrial stimulation at 50% of this rate with 1:1 AV conduction.
In this acute study the cardiocirculatory changes induced by RAS in all states were not significantly different when values for adult dogs were compared to values for young dogs.

**Discussion**

The unfavorable cardiocirculatory effects of rapid supraventricular tachycardia, particularly in patients with underlying heart disease, are well known to the clinician.1-9 Although hemodynamic studies have been carried out using right atrial pacing in adult patients,4-8 these data were obtained at heart rates under 200/min, well below the range of atrial and ventricular rates observed with some rapid supraventricular tachycardias in infants and children. A previous study4 has defined the response of the AV specialized conduction system in children to RAS at rates ranging from 150 to 600 beats/min. In this study 2:1 AV conduction was observed over a range of rates of 200-536 stimuli/min. However, because of the brief duration of atrial pacing (20-30 seconds) and the desire to avoid possible hemodynamic deterioration, hemodynamic studies were not made.

In the present investigation maximal 1:1 AV conduction was achieved at an average atrial stimulation rate of 328/min in the adult dogs, and at a rate of 344/min in the young dogs. These rates were not significantly different. At these rapid ventricular rates cardiovascular function was impaired severely in both groups of dogs. This is shown by the significant decreases in cardiac output and LV systolic and aortic mean pressures, as well as in the increases in calculated systemic and pulmonary vascular resistances. The decreases in cardiac output and LV systolic and aortic mean pressures can be explained primarily on the basis that impaired ventricular filling, secondary to increases in calculated systemic and pulmonary vascular resistances. The decreases in cardiac output and LV systolic and aortic mean pressures can be explained primarily on the basis that impaired ventricular filling, secondary to

**Table 1** Comparison of Effects of Rapid Atrial Stimulation (RAS) with Maximal 1:1 Atrioventricular (AV) Conduction and Control Values during Sinus Rhythm

<table>
<thead>
<tr>
<th>State</th>
<th>Atrial rate/min</th>
<th>Ventricular rate/min</th>
<th>CI (l/min/m²)</th>
<th>LVSP (mm Hg)</th>
<th>LVEDP (mm Hg)</th>
<th>AoP (mm Hg)</th>
<th>PAP (mm Hg)</th>
<th>PRU</th>
<th>SRU</th>
<th>LV (dp/dt)/p (sec⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>164</td>
<td>164</td>
<td>2.69</td>
<td>133</td>
<td>5.3</td>
<td>107</td>
<td>15</td>
<td>5.96</td>
<td>40.5</td>
<td>57.7</td>
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<tr>
<td></td>
<td>±13</td>
<td>±13</td>
<td>±0.21</td>
<td>±6</td>
<td>±0.9</td>
<td>±6</td>
<td>±2</td>
<td>±0.94</td>
<td>±3.09</td>
<td>±3.1</td>
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<tr>
<td>RAS with max.</td>
<td>328</td>
<td>328</td>
<td>1.66</td>
<td>112</td>
<td>4.0</td>
<td>91</td>
<td>13</td>
<td>9.05</td>
<td>56.4</td>
<td>64.5</td>
</tr>
<tr>
<td>1:1 conduction</td>
<td>14</td>
<td>14</td>
<td>±0.21</td>
<td>±7</td>
<td>±0.9</td>
<td>±6</td>
<td>±1</td>
<td>±1.75</td>
<td>±4.94</td>
<td>±5.5</td>
</tr>
<tr>
<td>% change</td>
<td>+100</td>
<td>+100</td>
<td>-39</td>
<td>-16</td>
<td>-24</td>
<td>-15</td>
<td>-13</td>
<td>+52</td>
<td>+39</td>
<td>+11</td>
</tr>
<tr>
<td>P</td>
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<td>&lt;0.01</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
<td>NS</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
<td>NS</td>
</tr>
<tr>
<td>Control</td>
<td>211</td>
<td>211</td>
<td>2.64</td>
<td>98</td>
<td>4</td>
<td>81</td>
<td>12</td>
<td>4.67</td>
<td>32.10</td>
<td>88</td>
</tr>
<tr>
<td></td>
<td>±5</td>
<td>±5</td>
<td>±0.20</td>
<td>±5</td>
<td>±0.4</td>
<td>±5</td>
<td>±1</td>
<td>±0.52</td>
<td>±2.98</td>
<td>±10</td>
</tr>
<tr>
<td>RAS with max.</td>
<td>344</td>
<td>344</td>
<td>1.88</td>
<td>83</td>
<td>3.5</td>
<td>68</td>
<td>11</td>
<td>6.33</td>
<td>37.95</td>
<td>87</td>
</tr>
<tr>
<td>1:1 conduction</td>
<td>10</td>
<td>10</td>
<td>±0.16</td>
<td>±5</td>
<td>±0.4</td>
<td>±6</td>
<td>±1</td>
<td>±1.97</td>
<td>±12.19</td>
<td>±11</td>
</tr>
<tr>
<td>% change</td>
<td>+63</td>
<td>+63</td>
<td>-25</td>
<td>-15</td>
<td>-12</td>
<td>-16</td>
<td>-8</td>
<td>+35</td>
<td>+18</td>
<td>-1</td>
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<tr>
<td>P</td>
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<td>&lt;0.01</td>
<td>&lt;0.01</td>
<td>&lt;0.05</td>
<td>NS</td>
<td>&lt;0.05</td>
<td>NS</td>
<td>&lt;0.05</td>
<td>NS</td>
<td></td>
</tr>
</tbody>
</table>

Results are expressed as mean ± se. Abbreviations as in Table 1.

**Table 2** Comparison of Effects of Rapid Atrial Stimulation (RAS) with Maximal 1:1 Atrioventricular (AV) Conduction and Effects of RAS with 2:1 AV Block

<table>
<thead>
<tr>
<th>State</th>
<th>Atrial rate/min</th>
<th>Ventricular rate/min</th>
<th>CI (l/min/m²)</th>
<th>LVSP (mm Hg)</th>
<th>LVEDP (mm Hg)</th>
<th>AoP (mm Hg)</th>
<th>PAP (mm Hg)</th>
<th>PRU</th>
<th>SRU</th>
<th>LV (dp/dt)/p (sec⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. Adult dogs (n = 8)</td>
<td>328</td>
<td>328</td>
<td>1.66</td>
<td>112</td>
<td>4.0</td>
<td>91</td>
<td>13</td>
<td>9.05</td>
<td>56.4</td>
<td>64.5</td>
</tr>
<tr>
<td>1:1 conduction</td>
<td>±14</td>
<td>±14</td>
<td>±0.21</td>
<td>±7</td>
<td>±0.9</td>
<td>±6</td>
<td>±1</td>
<td>±1.75</td>
<td>±4.94</td>
<td>±5.5</td>
</tr>
<tr>
<td>RAS with 2:1 AV block</td>
<td>437</td>
<td>218</td>
<td>1.53</td>
<td>131</td>
<td>5.1</td>
<td>111</td>
<td>16</td>
<td>7.07</td>
<td>43.98</td>
<td>77.5</td>
</tr>
<tr>
<td>% change</td>
<td>±18</td>
<td>±9</td>
<td>±0.26</td>
<td>±6</td>
<td>±0.9</td>
<td>±8</td>
<td>±2</td>
<td>±1.63</td>
<td>±3.4</td>
<td>±7.1</td>
</tr>
<tr>
<td>P</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
<td>&lt;0.05</td>
<td>NS</td>
<td>&lt;0.05</td>
<td>NS</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
<td>NS</td>
</tr>
<tr>
<td>B. Young dogs (n = 9)</td>
<td>344</td>
<td>344</td>
<td>1.88</td>
<td>83</td>
<td>3.5</td>
<td>68</td>
<td>11</td>
<td>6.33</td>
<td>37.95</td>
<td>87</td>
</tr>
<tr>
<td>1:1 conduction</td>
<td>±10</td>
<td>±10</td>
<td>±0.16</td>
<td>±5</td>
<td>±0.4</td>
<td>±6</td>
<td>±1</td>
<td>±1.97</td>
<td>±4.06</td>
<td>±11</td>
</tr>
<tr>
<td>RAS with 2:1 AV block</td>
<td>459</td>
<td>259</td>
<td>2.61</td>
<td>96</td>
<td>3.3</td>
<td>78</td>
<td>10</td>
<td>4.18</td>
<td>31.47</td>
<td>102</td>
</tr>
<tr>
<td>% change</td>
<td>±8</td>
<td>±7</td>
<td>±0.17</td>
<td>±6</td>
<td>±0.4</td>
<td>±6</td>
<td>±0.7</td>
<td>±0.33</td>
<td>±3.47</td>
<td>±10</td>
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<tr>
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<td>&lt;0.01</td>
<td>&lt;0.01</td>
<td>&lt;0.05</td>
<td>NS</td>
<td>NS</td>
<td>&lt;0.01</td>
<td>NS</td>
<td>&lt;0.01</td>
<td>NS</td>
</tr>
</tbody>
</table>

Results are expressed as mean ± se. Abbreviations as in Table 1.
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a markedly shortened diastole, caused a decrease in stroke volume and aortic mean pressure. The increase in systemic vascular resistance observed in both groups of dogs during RAS with maximum 1:1 AV conduction probably is related to a reflex mechanism that causes systemic vasoconstriction in response to a decrease in aortic pressure.16

The hemodynamic improvement observed in both groups of dogs when RAS resulted in 2:1 AV block, as compared to RAS with maximal 1:1 AV conduction, was manifested by a significant increase in cardiac output, aortic mean pressure, and LV (dp/dt)/p, as well as a decrease in the calculated systemic and pulmonary vascular resistances. The increase in cardiac output in the presence of a slower ventricular rate indicates a substantial increase in stroke volume related primarily to a prolongation of the diastolic filling time and probably to an improvement in myocardial contractility.

It is of interest to note that LV (dp/dt)/p was significantly higher during RAS with 2:1 AV conduction as compared to RAS with maximum 1:1 AV conduction, that is, in the presence of a substantially lower ventricular rate. This finding contrasts with the currently held notion that LV (dp/dt)/p and LV dp/dt increase with increasing heart rates.17,18 Our findings indicate that with extremely high ventricular rates, and probably beyond a crucial ventricular rate, myocardial contractility as measured by (dp/dt)/p is impaired. This impairment in myocardial contractility with very rapid ventricular rates is a second mechanism (in addition to the decrease in diastolic filling time) which contributes to the deterioration of the hemodynamic state. If the ventricular rate is increased well beyond the physiological range, as was the case in both groups of dogs during RAS and maximum 1:1 AV conduction, LV (dp/dt)/p no longer increases. Significantly higher values of LV (dp/dt)/p are obtained when the effective ventricular rate is halved by using RAS with 2:1 AV block. Indeed, values of LV (dp/dt)/p obtained with RAS and 2:1 AV block are very close to the values obtained with identical ventricular rates and 1:1 conduction.

It is known that infants and younger children show a marked deterioration of cardiovascular function during supraventricular tachycardia when compared to the effect of similar tachycardia on adults.5,2 The data from this acute study show that cardiocirculatory changes in adult dogs atrially paced at various rates were compared to similar measurements on young dogs. This probably was the result in part of the short period during which each dog was in each state and also in part because the differences in RAS with 1:1 AV conduction between the two groups of dogs were not great.

No data are currently available on the effects of RAS with 2:1 AV block on myocardial oxygen consumption or myocardial blood flow. Since myocardial oxygen consumption is related in part to ventricular rate and myocardial blood flow depends in part on the duration of diastole, it reasonably can be assumed that a decrease in ventricular rate will have beneficial effects on both parameters. Early reports on long-term atrial stimulation resulting in high degree of AV block did not indicate any unfavorable effects,19 even in patients with atherosclerotic heart disease. The clinical trial of Waldo et al.11 led them to conclude that rapid atrial pacing is a safe and effective method to treat recurrent supraventricular tachyarrhythmia.

It is interesting to note that the hemodynamic improvement with RAS and 2:1 block was comparable in the adult dogs and in the young dogs. The significant degree of hemodynamic improvement induced by increasing the rate of atrial stimulation to that inducing 2:1 AV block indicates that this method may provide an instantaneous and effective mode of treatment for some patients with intractable supraventricular tachyarrhythmias who do not respond to other therapy or in whom immediate slowing of the heart is essential for survival, as in postoperative patients.11

Acknowledgments

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