Influence of Sympathetic Nerve Stimulation on Right Ventricular Outflow-Tract Pressures in Anesthetized Dogs

By John B. Pace, William F. Keefe, J. Andrew Armour, and Walter C. Randall

ABSTRACT

Stellate ganglion stimulation in the anesthetized, open-chest dog consistently resulted in the generation of pressure differences which averaged 20 mm Hg across the infundibular region of the right ventricle. Before stimulation, peak systolic pressures in the sinus and conus were closely matched. Peak sinus pressure showed an average increase of 184 and 162% during stimulation of the left and right stellate ganglia, respectively. Simultaneously, peak conus pressure showed average increases of 88 and 61% during left and right stellate ganglion stimulation, respectively. In addition, the maximal rate of intrasinus pressure development (dP/dt) was usually elevated above conus dP/dt, and this change contributed to the generation of early systolic pressure differences. Cervical vagosympathetic nerve stimulation following atropine administration also resulted in the generation of infundibular pressure differences, but the latter were less marked than those elicited during stellate ganglion stimulation. Elevations in main pulmonary arterial resistance abolished the induced pressure differences by allowing peak conus pressure to rise to the same extent as peak intrasinus pressure. Simultaneous electromagnetic flow recordings of pulmonary arterial blood flow during stellate ganglion stimulation revealed two- to five-fold increases in maximum flow acceleration with relatively little change in stroke volume. Infundibular pressure gradients which developed in early systole were associated with maximum flow changes in the pulmonary artery.

ADDITIONAL KEY WORDS

stellate ganglion stimulation pulmonary arterial occlusion pulmonary arterial blood flow sinus and conus regions of the right ventricle vagosympathetic stimulation right ventricular infundibulum

The early anatomical and embryological studies of Sir Arthur Keith (1, 2) demonstrated that the conus arteriosus of the developing embryo was incorporated into the right ventricular myocardium and formed the terminal portion of the infundibulum in the adult heart. The conus homologue on the left side was obliterated during the embryological development of the left ventricle. In lower forms, such as the tortoise, the conus arteriosus is anatomically distinct from the rest of the right ventricular musculature, and Woodbury and Robertson (3) demonstrated that this region can act as a functional stricture to divert blood through the interventricular foramen to the left ventricle. Studies on the canine heart by March et al. (4) have shown that the inflow or sinus region of the right ventricle is activated before the infundibular region, thus demonstrating physiological inflow-outflow pressure differences. Recently Tobin et al. (5) demonstrated that inotropic drugs such as isoproterenol and acetylstrophanthidin could induce pressure differences in excess of 40 mm Hg between the right ventricle and the
pulmonary artery. These pressures were accompanied by a reduction in the width of the right ventricular outflow tract and were unrelated to the activation sequence of the sinus and conus.

The objectives of the present experiments were to evaluate the inotropic influence of sympathetic nerve stimulation on right intraventricular pressures and to obtain information about the mechanism by which pressure differences are generated.

Methods

Sixteen mongrel dogs of both sexes ranging in weight from 10 to 20 kg were anesthetized with 1-(1-phenylcyclohexyl) piperidine hydrochloride, 2 mg/kg; sodium pentobarbital, 80 mg/kg; and atropine sulfate, 0.5 mg/kg. Bilateral thoracotomy was performed in the fourth or fifth interspace, and the heart was suspended in a pericardial cradle. The right and left stellate ganglia were isolated and bipolar wire electrodes were attached to them and the heart was suspended in a pericardial cradle. The right and left vagosympathetic trunks were sectioned at the cervical level, and the distal ends were stimulated through bipolar Porter electrodes following administration of atropine, 0.5 mg/kg.

Pressures were recorded with either a Statham P23H or P23Db differential transducer system. The ability of the paired Statham differential transducers (P23H) to resolve differential pressures was tested according to the following method. A sine-wave pump was attached to a length of tygon tubing, and the entire system was filled with water. Pressures were recorded through 19-gauge needles separated by 5 cm and inserted through the wall of the tygon. The pump was used to induce sinusooidal pressure variations which were recorded by the differential system. The analog output of the differential was compared with the arithmetic difference between the single-ended transducers. No detectable error was recorded with frequencies up to 17 cps. The 19-gauge needles were used to facilitate the evaluation of the differentiating capability of the paired transducer system but were not employed to record pressures in animal experiments.

Pressures were recorded in animal experiments through special cannulas inserted through the wall of the right ventricle (2). The cannula is constructed of Teflon and has a threaded shaft with a flanged tip. The length of the shaft is 25 mm and its outside diameter is 3.5 mm. After insertion through the free wall of the right ventricle, the tip of the cannula was secured flush with the endocardial surface by turning a knurled nut on the shaft until it was apposed to the epicardial surface. Hence, this device virtually locks to the right ventricular free wall and minimizes the recording artifact due to movement of the catheter relative to the blood. The position of the catheter tip was confirmed by post-mortem examination. The Teflon catheter was attached to the pressure transducer with a 5.5-cm length of PE 50 polyethylene. The damped natural frequency of each of the paired Statham P23H and P23Db transducers was measured with the polyethylene Teflon catheter assembly. The natural frequency was determined using the step-pressure ("pop") technique. The tip of the Teflon catheter was positioned in a chamber with a volume of approximately 1 ml, and the entire system was filled with freshly boiled water. Pressure in the chamber was elevated to 50 or 75 mm Hg by pumping air into it through a side port. The distended rubber diaphragm covering the chamber was then ruptured with a hot cautery tip inducing a step change in pressure at the transducer membrane. Frequencies recorded from this system were above 120 cps. The damping coefficient of the Teflon catheter polyethylene system was 0.66. Pulmonary arterial pressure was measured with an 8- to 9-cm length of PE 100. The damped natural frequency of Statham P23Db transducers with PE 100 was 170 cps and the damping coefficient was 0.57.

The outflow or conus cannula was positioned 5 to 10 mm from the pulmonic valve ring. The sinus or inflow cannula was placed 2.0 cm below the tricuspid valve ring and positioned in the lateral wall of the right ventricle. In most experiments the cannula tips in the inflow and outflow tracts were separated by 5.0 to 8.0 cm. The high or positive end of the differential pressure transducer was attached to the sinus cannula; hence, deflections on the differential trace above zero baseline indicate sinus pressure is elevated above conus pressure. Maximal dP/dt was measured by drawing a line tangent to the steepest slope of systolic pressure on the conus and sinus pressure pulses. The tangent was extended so that it intersected the upper and lower limits of the channel, and maximal dP/dt values were obtained by dividing the cross-channel calibration in mm Hg by the time interval in msec. This method of measuring allows for accuracy to two decimal places. Pulsatile pulmonary arterial pressure was recorded through a polyethylene cannula tied into a lobar pulmonary artery.

In six additional experiments pulmonary arterial blood flow was measured together with conus and sinus pressures. After opening the
pericardium the fat pads which surround the main pulmonary artery were dissected off, and the vessel was separated from the aortic root by blunt dissection over a length of 2.0 cm. The flow transducer was positioned 1.5 to 2.0 cm from the pulmonic valve ring. The left stellate ganglion was disconnected from the rami from T-1 to T-3 and suspended from bipolar electrodes to prevent the stimulus voltage from being impressed on the flow signal. In dogs 1, 4, and 6 of Table 2 this procedure failed to prevent stimulus "noise" from interfering with the flow signal; consequently, pressure and flow traces were recorded immediately after stimulation. Pulsatile blood flow was recorded with a square-wave electromagnetic flow meter (Carolina Medical Electronics, Model 420-R). The manufacturer states that the response of this instrument is flat to 50 cps. Calibrations were carried out following each experiment according to the method outlined by Spencer and Denison (7). Flow pulses were generated by passing 30-ml volumes of the experimental animal's own blood through the flow transducer and recording the flow signal at maximum paper speed on the Dynograph (350 mm/sec). The area under the flow curve was used to calculate the flow calibration. Transducers were calibrated using either a segment of thoracic aorta or a strip of collodion tubing. Conversion of the calibration for volume flow in ml/min to flow velocity in cm/sec was obtained by dividing the volume calibration by the cross-sectional area of the transducer lumen. No correction was made for the thickness of the pulmonary arterial wall. Maximal flow acceleration was determined by drawing a line tangential to the velocity pulse in early systole. The method of calculation was identical to that outlined for the measurement of maximum dP/dt. Stroke volume was measured by integrating the area under the flow pulse with a planimeter, and the product of stroke volume and heart rate yielded cardiac output. The zero flow signal was determined by assuming that net forward flow through the transducer during diastole was zero.

All tracings were recorded on either a Grass model 7 polygraph or an Offner type R dynograph.

Results

Figure 1 illustrates typical right ventricular responses to stellate ganglion stimulation. Before stimulation peak systolic pressures in the sinus and conus regions were identical at 15 mm Hg. At the onset of systole, pressure development in the sinus region reached 24 mm Hg in the conus region, thus creating a pressure difference of 44 mm Hg from sinus to conus. The differential pressure trace showed a positive deflection throughout systole, indicating that sinus pressure exceeded conus pressure during this entire period. However, stellate ganglion stimulation did not alter the sequence of pressure development between the sinus and conus regions.

CONUS
SINUS
SINUS-CONUS

LEFT STELLATE

FIGURE 1
Record showing effects of left stellate ganglion stimulation on right ventricular outflow-tract pressures. The beginning of the black stimulus mark at the top of the figure indicates the onset of stimulation. Pressures recorded with Statham P23H transducer.

CONTROL

RIGHT STELLATE

FIGURE 2
Record showing changes in the maximal rates of pressure rise (dP/dt) in the sinus and conus of the right ventricle during stellate ganglion stimulation. Tangent slopes on the pressure pulses indicate sinus dP/dt is elevated above conus dP/dt during stimulation. Pressures recorded with Statham P23H transducer.
Figure 2 illustrates the differential changes in sinus and conus maximal dP/dt during right stellate ganglion stimulation. Before stimulation sinus and conus systolic pressures were identical at 12.5 mm Hg. During stimulation the peak systolic pressure in the conus region was 25 mm Hg while sinus systolic pressure reached 66 mm Hg. Control maximal dP/dt changed from 0.77 and 1.06 mm Hg/msec in the conus and sinus, respectively, to 4.00 and 5.68 mm Hg/msec during stimulation. Thus, differing rates of systolic pressure development in the sinus and conus can contribute to the generation of infundibular pressure differences in early systole. During stellate ganglion stimulation maximal dP/dt in the conus exceeded maximal dP/dt in the sinus in 30% of the experiments.

Figure 3 illustrates pulmonary arterial pressure responses during left stellate ganglion stimulation. In the control records peak systolic pressure development was identical in the sinus and conus regions at 12 mm Hg and pulmonary arterial pressure was 12/8 mm Hg. Slopes on the sinus and conus pressure pulses indicate that conus maximal dP/dt exceeded sinus maximal dP/dt in the control trace. During stimulation pulmonary arterial pressure increased to 20/10 mm Hg. Similarly peak systolic conus pressure increased to 20 mm Hg while peak systolic sinus pressure reached 46 mm Hg. Stimulation caused maximal sinus dP/dt to be elevated above maximal conus dP/dt with a consequent

Figure 4 illustrates the effect of pulmonary resistance on right ventricular outflow tract pressures (in mm Hg). Before the institution of elevated resistance, left stellate ganglion stimulation resulted in the generation of a marked pressure difference (A). Following an elevation in pulmonary arterial resistance, left stellate ganglion stimulation failed to elicit a marked pressure difference (B and C). PA = pulmonary arterial pressure; SA = systemic arterial pressure. Pressures recorded with Statham P23H transducer.
shift in the rate of pressure rise in the two regions. Peak systolic pressure in the pulmonary artery was reached 26 msec before the attainment of maximal systolic pressure in the conus. These alterations are probably due to the loss of lateral pressure in the conus and the augmentation of the kinetic component of flow in the pulmonary arteries during stimulation.

Wigle (9) has shown that functional obstruction to left ventricular outflow tract is manifest by the development of large pressure differences across the aortic valve during systole. These pressures could be reduced or abolished with elevations in afterload induced by the administration of pressor drugs such as neosynephrine (9). Figure 4 shows the effects of elevated pulmonary arterial resistance on the pressure differential across the infundibular region during stellate ganglion stimulation. Panel A shows right ventricular pressure responses during left stellate ganglion stimulation before an elevation in pulmonary arterial resistance was established. Both sinus and conus systolic pressures were 20 mm Hg before stimulation. Pulmonary arterial pressure was 20/12 and systemic arterial pressure was 125/105 mm Hg. During left stellate ganglion stimulation systolic pressure in the conus region increased to 21 mm Hg, peak sinus pressure reached 50 mm Hg, and the resulting pressure difference increased to 29 mm Hg. Systemic arterial pressure concurrently increased to 187/135. The onset of pressure development in the sinus region preceded that in the conus by 18 msec. Panel B shows the changes in right ventricular pressures resulting from application, 1.5 cm distal to the pulmonic valve ring, of a clamp which partially occluded the main pulmonary artery. Systolic pressures in both conus and sinus regions increased to 28 mm Hg, while lobar pulmonary arterial pressure decreased to 17/12 mm Hg. Pressure development in the sinus region still preceded that in the conus by 18 msec. Systemic arterial pressure was reduced to 118/94 during pulmonary constriction. Panel C illustrates the changes in right ventricular pressures during left stellate ganglion stimulation while elevated outflow resistance was maintained. Peak systolic pressure in the sinus region increased to 51, while conus systolic pressure reached 48 mm Hg. Lobar pulmonary arterial pressure was elevated to 25/14, and systemic arterial pressure increased to 190/150 mm Hg. A peak pressure difference of 16 mm Hg developed across the infundibulum which was essentially the result of the early rise in sinus pressure. In addition, maximal sinus dP/dt was 1.54 mm Hg/msec, and maximal conus dP/dt was 1.20 mm Hg/msec. On the other hand, the pressure differential between the sinus and conus resulting from stellate ganglion stimulation in panel A was primarily a function of the difference in maximum systolic pressure developed in these regions.

Table 1 summarizes the dynamic changes in right ventricular performance resulting from electrical excitation of adrenergic mechanisms in the autonomic nervous system and expresses these results as percent changes from control for 16 individual experiments. Ranges are given adjacent to the mean values. Both the right and left stellate ganglia as well as both cervical vagosympathetic trunks were separately stimulated in each of the 16 animals. Stellate ganglion stimulation induced pressure differences in each animal. Peak sinus pressure, on the average, increased 30% from control during right vagosympathetic stimulation and 70% during left vagosympathetic stimulation. Peak conus pressure increased 11% during right and 15% during left vagosympathetic stimulation. Peak systolic pulmonary arterial pressure increased 8 and 11% during right and left vagal stimulation, respectively. Similarly, maximal conus dP/dt increased 54% from control during right vagosympathetic stimulation and 70% during left vagosympathetic stimulation. Peak conus pressure increased 11% during right and 15% during left vagosympathetic stimulation. Peak systolic pulmonary arterial pressure increased 8 and 11% during right and left vagal stimulation, respectively. Stimulation of the right and left stellate ganglia generated profound changes in right ventricular pressure dynamics. Peak sinus pressure increased 162% during pulmonary constriction of the right stellate ganglion and 184% during left stellate stimulation. Peak systolic
TABLE 1

<table>
<thead>
<tr>
<th></th>
<th>Control</th>
<th>Right cervical vagus</th>
<th>% Change from control</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heart rate (beats/min)</td>
<td>147 (114-210)</td>
<td>164 (144-228)</td>
<td>11</td>
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<tr>
<td>Peak sinus pressure (mm Hg)</td>
<td>15.0 (7.5-22.5)</td>
<td>19.5 (8.7-40.0)</td>
<td>30</td>
</tr>
<tr>
<td>Peak conus pressure (mm Hg)</td>
<td>10.9 (7.4-15.0)</td>
<td>12.1 (6.0-20.0)</td>
<td>11</td>
</tr>
<tr>
<td>Pulmonary arterial pressure (mm Hg)</td>
<td>14.5/6.5 (8.4-18.0)*</td>
<td>15.7/6.9 (10.0-18.0)</td>
<td>8/6</td>
</tr>
<tr>
<td>Maximal sinus dP/dt (mm Hg/msec)</td>
<td>0.59 (0.24-1.10)</td>
<td>0.96 (0.48-3.50)</td>
<td>62</td>
</tr>
<tr>
<td>Maximal conus dP/dt (mm Hg/msec)</td>
<td>0.31 (0.14-0.65)</td>
<td>0.48 (0.24-1.25)</td>
<td>54</td>
</tr>
</tbody>
</table>

Mean values represent averages of 16 animals for each type of stimulation. Ranges are given in parentheses after the mean values. Results from cervical vagosympathetic stimulation were obtained following a blocking dose of atropine.

*Ranges not given for pulmonary diastolic pressure.

pressure in the conus also increased, showing a 61% increase during right stellate stimulation and an 88% increase over control during left stellate stimulation. Pulmonary arterial pressure increased, with the largest percent changes occurring during left stellate stimulation. Maximal sinus dP/dt increased 162% and 200% during right and left stellate stimulation, respectively. Similarly, maximal conus dP/dt increased 129% and 251% during right and left stellate ganglion stimulation, respectively.

Since the catheter in the conus measured lateral pressure, the possibility existed that elevated flow rates during inotropism may induce a reduction in the lateral pressure component in this region and contribute to the formation of infundibular pressure differences in early systole. To evaluate this possibility, conus and sinus pressures were measured together with pulsatile blood flow in the main pulmonary artery. Figure 5 illustrates the alterations in pulsatile pulmonary blood flow associated with left stellate ganglion stimulation and isoproterenol. The instantaneous pressure difference across the infundibulum is shown by the dotted lines above the flow pulses. In the control period the maximum acceleration was 834 cm/sec² and the peak velocity 40 cm/sec. The sinus-conus pressure difference was 2.5 mm Hg in early systole. During stellate ganglion stimulation, maximum acceleration increased to 4,480 cm/sec² and maximum velocity increased to 90 cm/sec. The early systolic pressure difference increased to 25 mm Hg and then declined as the acceleration of flow reached a maximum in the pulmonary artery. Approximately 12 msec after the attainment of maximum flow velocity, a secondary rise in the differential pressure developed, which reached a maximum in late systole when pulmonary arterial flow was decelerating. During stimulation maximum systolic pressure in the pulmonary artery was 39 mm Hg and maximum systolic pressure in the conus was 28 mm Hg, while maximum systolic pressure in the sinus reached 45 mm Hg. These alterations indicate a definite reduction in lateral pressure in the conus during the initial phases of right ventricular ejection. The third panel shows the pressure-flow responses resulting from a single injection of isoproterenol. Maximum acceleration and peak velocity increased to 5,530 cm/sec² and 99 cm/sec, respectively, and the early sinus-conus pressure difference was 17.5 mm Hg. As in stellate ganglion stimulation, a secondary rise in the pressure difference developed at the time of maximum flow velocity and reached a maximum of 30 mm Hg in late systole when pulmonary.
<table>
<thead>
<tr>
<th>Left cervical vagus</th>
<th>% Change from control</th>
<th>Right stellate</th>
<th>% Change from control</th>
<th>Left stellate</th>
<th>% Change from control</th>
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<tr>
<td>150 (144-210)</td>
<td>2</td>
<td>191 (132-234)</td>
<td>29</td>
<td>169 (132-216)</td>
<td>14</td>
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<tr>
<td>25.5 (8.7-63.0)</td>
<td>70</td>
<td>39.4 (10.0-60.0)</td>
<td>162</td>
<td>42.7 (21.0-86.0)</td>
<td>184</td>
</tr>
<tr>
<td>12.6 (7.5-20.0)</td>
<td>15</td>
<td>17.6 (12.5-33.0)</td>
<td>61</td>
<td>20.6 (15.0-31.0)</td>
<td>88</td>
</tr>
<tr>
<td>16.1/7.0 (10.0-21.0)</td>
<td>11/7</td>
<td>18.9/7.4 (10.0-25.0)</td>
<td>30/13</td>
<td>23.3/6.9 (8.0-34.0)</td>
<td>60/6</td>
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<tr>
<td>0.74 (0.43-2.10)</td>
<td>25</td>
<td>1.55 (1.14-4.90)</td>
<td>162</td>
<td>1.77 (1.08-4.10)</td>
<td>200</td>
</tr>
<tr>
<td>0.49 (0.22-1.10)</td>
<td>58</td>
<td>0.71 (0.28-1.40)</td>
<td>129</td>
<td>1.09 (0.33-2.30)</td>
<td>251</td>
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</table>

Record showing typical right ventricular pressure-flow responses to left stellate ganglion stimulation and isoproterenol. Pressure curves above the flow pulses were constructed by subtracting conus pressure from sinus pressure at 8-msec intervals throughout the cardiac cycle. In the control pulse, a pressure difference developed in early systole. The responses to stellate ganglion stimulation and isoproterenol were characterized by marked pressure difference in late systole as well as in early systole. SA = systemic arterial pressure; PA = pulmonary arterial pressure; S-C = sinus-conus pressure difference. Pressures recorded with individual Statham P23Db transducers. Dog 5, Table 2.

arterial flow was decelerating. Although the differential traces in Figures 1 and 2 do not show a bi-modal pattern, a definite inflection can be observed on the rising slope of the curves which probably represents the early systolic pressure gradient fused with
Table 2
Right Ventricular Pressure-Flow Responses to Left Stellate Ganglion Stimulation

<table>
<thead>
<tr>
<th>Dog</th>
<th>Wt (kg)</th>
<th>Condition</th>
<th>HR (beats/min)</th>
<th>Sinus pressure (mm Hg)</th>
<th>Conus pressure (mm Hg)</th>
<th>Max. sinus dP/dt (mm Hg/sec)</th>
<th>Max. conus dP/dt (mm Hg/sec)</th>
<th>Peak flow (L/min)</th>
<th>Peak velocity (cm/sec)</th>
<th>Max. acceleration (cm/sec^2)</th>
<th>Stroke volume (ml)</th>
<th>Cardiac output (ml/min)</th>
<th>Pulmonary arterial pressure (mm Hg)</th>
<th>Systemic arterial pressure (mm Hg)</th>
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<td>1</td>
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<td>25.0</td>
<td>0.55</td>
<td>0.62</td>
<td>4.38</td>
<td>35.7</td>
<td>8.65</td>
<td>110</td>
<td>1870</td>
<td>19.2/7.5</td>
<td>2100</td>
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<tr>
<td></td>
<td></td>
<td>LSS</td>
<td>200</td>
<td>62.5</td>
<td>48.0</td>
<td>1.78</td>
<td>2.79</td>
<td>7.65</td>
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<td>control</td>
<td>190</td>
<td>42.5</td>
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<td>3.74</td>
<td>64</td>
<td>2530</td>
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<td>22.5</td>
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<td>73</td>
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<td>0.52</td>
<td>4.29</td>
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<td>1.04</td>
<td>6.72</td>
<td>88</td>
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<tr>
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<td>199</td>
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<td>0.27</td>
<td>3.03</td>
<td>40</td>
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<td>202</td>
<td>18.2</td>
<td>18.2</td>
<td>0.88</td>
<td>0.33</td>
<td>3.00</td>
<td>51</td>
<td>1450</td>
<td>6.0</td>
<td>900</td>
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<td>203</td>
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<td>4.23</td>
<td>73</td>
<td>2560</td>
<td>5.5</td>
<td>990</td>
<td>20.2/6.2</td>
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<td>3.00</td>
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<td>1450</td>
<td>6.0</td>
<td>900</td>
<td>20.0/4.8</td>
<td>105/77</td>
</tr>
</tbody>
</table>

HR = heart rate; LSS = left stellate ganglion stimulation.
velocity reached 52 cm/sec. In the escape beat the stroke volume was augmented to 19 ml, and maximum velocity and acceleration increased to 104 cm/sec and 2,380 cm/sec², respectively. However, these profound alterations in flow were not accompanied by marked alterations in the sinus-conus pressure difference. The control pressure difference recorded in early systole was 3.8 mm Hg and increased to 8.6 mm Hg in the escape beat. The pressure difference increased proportionately with the flow parameters.

Table 2 shows the right ventricular pressure-flow responses during left stellate ganglion stimulation for six individual experiments. During stellate ganglion stimulation, peak flow in the pulmonary artery increased to approximately twice control values. Maximum acceleration was the flow variable that showed the greatest augmentation during stellate ganglion stimulation. The magnitude of the pressure differences was not as great as those recorded in experiments in which pulmonary arterial flow was not recorded. Distortion of the pulmonary artery by the flow probe may have increased the resistance, thus attenuating the pressure gradient (Fig. 4) (10). In dogs 4 and 6, conus and sinus systolic pressures were equal during stellate ganglion stimulation. The values for control pulmonary arterial flow velocity and acceleration compare with data presented by Spencer and Greiss (11). However, O'Rourke recently reported pulmonary flow velocities in excess of 150 cm/sec (10).

Discussion

Traditionally, the right ventricle is considered a low-pressure volume pump (12).
However, the present study indicates that under the influence of sympathetic nerve stimulation right ventricular systolic pressures can exceed 70 mm Hg. This pressure apparently is not transmitted unattenuated to the pulmonic vasculature because of the peculiar anatomy and physiology of the conus arteriosus which, in the mammalian heart, is incorporated into the terminal portion of the infundibulum of the right ventricle. The experiments of Tobin et al. (5) indicate that right ventricular inotropism is characterized by large infundibular pressure differences with little change in cardiac output. In addition, these authors showed that electrical activation in the sinus preceded electrical activity in the conus by approximately 20 msec. This interval corresponds to the values of initial pressure development between the sinus and conus observed in the present study. Figures 1 and 2 and the results in Table 1 indicate that under the influence of stellate ganglion stimulation there are marked changes in sinus and conus systolic pressures, with peak sinus pressure invariably increasing to a greater extent than conus pressure. The experiment shown in Figure 4 serves to illustrate that the magnitude and form of infundibular pressure differences are determined by the interval of initial pressure rise between the sinus and conus, as well as differential rates of systolic pressure development and maximum systolic pressure in these regions. In most cases the onset of sinus pressure preceded that in the conus by approximately 20 msec, and this interval was not altered during stellate ganglion stimulation. All of the above-mentioned mechanisms contribute to the generation of marked pressure differences during nerve stimulation.

Pressure differences were recorded when the sinus pressure catheter was positioned through the anterior surface of the right ventricle. On the other hand, when the conus pressure differences during nerve stimulation, cm proximal to the pulmonic valve ring, pressure gradients were not demonstrated during stellate ganglion stimulation. Because of the small volume of this low pressure zone relative to the rest of the right ventricle, it is unlikely that the conus has an important function in ejecting the stroke volume from the right ventricle. Priola et al. (13) recorded pressures in the inflow and outflow tracts of the left ventricle and showed that inflow pressure exceeded outflow pressure during diastole and outflow pressure was elevated over inflow pressure during systole. March et al. (4) used cine techniques to show that the sinus or inflow region contracts first and forces blood into the infundibulum which first bulges, then contracts in late systole. Such a series of events can lead to inflow-outflow pressure differences during right ventricular contraction similar to those recorded during normal left ventricular contraction. However, the traces illustrated in Figures 1 and 2 show that sinus or inflow pressure remains elevated above conus pressure for the entire period of systole, indicating that the sinus generates the force responsible for blood flow.

Changes in right ventricular dynamics similar to those elicited from stellate ganglion stimulation could be induced by stimulation of the vagosympathetic trunk after a blocking dose of atropine. The augmentor action of cervical vagosympathetic nerve stimulation on the ventricular chambers has been thoroughly documented and appears to be due to the presence of adrenergic neurons coursing in the vagosympathetic trunk which have fiber terminations ending in the ventricular myocardium (14, 15). Although the changes in right ventricular dynamics induced with vagosympathetic stimulation were less marked than those elicited with stellate ganglion stimulation, the directional changes were identical (Table 1).

Energy losses across a segment of conduit through which fluid is flowing indicate the presence of an impedance in the conduit. Similarly, large pressure differences across the infundibular region during late systole indicate interposition of an impedance between the conus and the remainder of the right ventricular chamber. In addition, the impedance appears to be generated by inotropic interventions and probably involves...
changes in the geometric configuration of the infundibulum. Keith (1) and Mall (16) noted the circular arrangement of the myocardial fibers surrounding the infundibular region of the right ventricle and postulated that the conus had an important function in regulating the pulmonary circulation. Brock (17) has demonstrated that the level of mean pulmonary arterial pressure at which pulmonic valvular incompetence occurred increased when the contractility of the conus was elevated during epinephrine infusion. Tobin et al. (5) demonstrated that right ventricular inotropism is associated with a narrowing of the infundibular zone. Hence, the generation of a stricture in this region could result in a large pressure drop from the sinus to the pulmonary artery. Conceivably, stellate ganglion stimulation and other inotropic interventions may act to generate such pressure differences through extensive circumferential shortening of the looping myocardial fibers which encircle the infundibulum.

Figure 4 illustrates an experiment designed to evaluate this hypothesis. Pulmonary arterial stricture was instituted before stellate ganglion stimulation to increase main pulmonary arterial pressure which could act as a distending force on the conus. The right ventricle was visibly distended during the application of the clamp to the main pulmonary artery. Stellate ganglion stimulation under those conditions resulted in almost identical elevations in sinus and conus peak systolic pressures. However, a pressure difference of 16.0 mm Hg developed in early systole. Possibly the increased distending pressure on the conus prevented the infundibulum from narrowing to the extent necessary to generate pressure differences recorded before the institution of elevated main pulmonary arterial resistance.

References

Influence of Sympathetic Nerve Stimulation on Right Ventricular Outflow-Tract Pressures in Anesthetized Dogs
JOHN B. PACE, WILLIAM F. KEEFE, J. ANDREW ARMOUR and WALTER C. RANDALL

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