Systolic Direct Ventricular Interaction Affects Left Ventricular Contraction and Relaxation in the Intact Dog Circulation

Bryan K. Slinker, Yoichi Goto, and Martin M. LeWinter

Changes in right ventricular systolic function directly influence left ventricular systolic function. Most of our knowledge of this systolic direct ventricular interaction comes from studies of isolated hearts, which suggest that changes in right ventricular size only affect left ventricular systolic function at low pressures and volumes. However, almost nothing is known about systolic direct ventricular interaction in a heart functioning in situ as a part of the intact circulation. We used sudden constriction of the pulmonary artery to assess the immediate effect of a change in right ventricular pressure and contraction pattern on left ventricular contraction and relaxation on the beat following the pulmonary artery constriction in anesthetized open-chest dogs. By focusing on this first beat, we were able to avoid the confounding effect of series ventricular interaction, which changes left ventricular filling and, thus, indirectly influences left ventricular function. At baseline left ventricular end-diastolic pressure of 9.6±2.1 mm Hg (mean±SD), sudden pulmonary artery constriction increased left ventricular peak systolic pressure by 3±2 mm Hg (2% change), left ventricular stroke volume by 2±2 ml (8% change), and monoeponential time constant of left ventricular pressure fall during relaxation by 9±6 msec (22% change). This increased left ventricular relaxation time constant was associated with altered regional segment length changes in the posterior and anterior left ventricular free walls during relaxation. We conclude that systolic direct ventricular interaction affects left ventricular systolic function and relaxation under normal conditions in the intact circulation. (Circulation Research 1989;65:307–315)

Changes in right ventricular function are well known to influence left ventricular function through ventricular interaction.1–4 Diastolic ventricular interaction is reasonably well understood, but relatively little information is available about the importance of systolic ventricular interaction in determining left ventricular contraction and relaxation.

Most studies of the direct influence (i.e., through the interventricular septum) of the right ventricle on left ventricular systolic function have been done in isolated hearts so that the confounding effect of series interaction (i.e., through the pulmonary circulation) could be controlled. These studies showed that increased right ventricular systolic pressure and volume produced small upward and leftward shifts of the left ventricular peak3 or end-systolic4 pressure-volume relation. Similarly, Elzinga et al5 showed small improvements in left ventricular pump function (at low left ventricular pressures) in the isolated cat heart when the right ventricle was beating isovolumically compared with when the right ventricle was ejecting into a low-pressure load. On the other hand, Mouloupoulos et al,6 who studied an in situ but totally bypassed heart, showed that both distended and empty right ventricles decreased left ventricular peak +dP/dt, and Santamore et al7 showed decreased left ventricular peak pressure at large right ventricular volumes. Thus, there are conflicting reports from experiments in isolated heart preparations, and even in those studies that do show systolic interaction, it has been considered to be important only at low pressures and volumes.5,8

Few studies of systolic direct ventricular interaction, per se, have been performed in the intact circulation. This is in large measure due to the difficulty in separating the effects of direct and series interaction. In only two studies has the study design or data analysis allowed such a separation. Langille and Jones9 reported that there was about a
4 mm Hg increase in peak left ventricular systolic pressure on the first beat after a sudden pulmonary artery constriction in the intact rabbit circulation. However, this result provides little information about the effect of the right ventricle on left ventricular pumping. Slinker and Glantz used a statistical analysis of the time series of beat-to-beat changes in right and left ventricular pressure and dimension during occlusion and release of the venae cavae and pulmonary artery to separate series from direct interaction in the intact dog circulation. Unlike most of the isolated heart studies, their results suggested an important systolic direct interaction effect at physiological ventricular pressures and volumes. However, because their results can only be interpreted in relative terms (i.e., the ratio of series to direct interaction), the absolute importance of systolic direct interaction in determining left ventricular pump function remains unknown.

In addition, virtually nothing is known about how elevated right ventricular systolic pressures and volumes affect relaxation in the left ventricle. Elzinga et al. using an isolated cat heart preparation, showed that elevated right ventricular pressure during late systole resulted in higher left ventricular pressure during relaxation, but they made no quantitative analysis of these data. The effect of systolic direct ventricular interaction on left ventricular relaxation in the intact circulation is unknown.

Hence, the purposes of this study were to directly measure the influence of increased right ventricular systolic pressure and volume on left ventricular systolic pressure and stroke volume in the intact circulation and to determine the effect of increased right ventricular systolic pressure and volume on the rate of left ventricular pressure fall and regional muscle-segment length changes during relaxation. We compared the beats before and immediately after sudden pulmonary artery constriction to study direct interaction in the absence of series interaction.

Materials and Methods

Experimental Preparation

We collected data in 13 open-chest random source male dogs (19–31 kg) anesthetized with 25 mg/kg intravenous sodium pentobarbital 30 minutes before preanesthesia with 1 mg/kg subcutaneous morphine sulfate. The dogs were intubated and ventilated (respirator, Harvard Apparatus, South Natick, Massachusetts) with an initial tidal volume of 15 ml/kg and rate of 12 breaths/min. Respiratory rate and tidal volume were adjusted, and intravenous sodium bicarbonate was given as necessary to maintain PCO₂ at 35–45 mm Hg, HCO₃⁻ at 20–28 mmol/l, and pH at 7.3–7.4. Arterial PO₂ always exceeded 80 mm Hg.

In all dogs, we opened the chest with a median sternotomy and bilateral fifth intercostal space thoracotomies; we then made a 3–5-cm pericardial incision beginning over the mid-left atrial appendage and extending cranially to just beyond the aortic root. We dissected between the pulmonary artery and aorta for placement of an aortic root electromagnetic flow probe (Carolina Medical Electronics, King, North Carolina), ligated the azygous vein, placed umbilical tape snares around both venae cavae (for another study) and the main pulmonary artery, and inserted a 30F catheter into the right ventricle by way of the right atrial appendage (also for another study). 7F catheter-tip micromanometers (Millar Instruments, Houston, Texas) were placed in the right ventricle by way of a femoral vein and in the left ventricle by way of a femoral artery. The lumens of these catheters were connected to pressure transducers (model P23XL, Statham, Oxnard, California) with midchest zero references. The Millar signal was matched to the fluid pressure to correct for baseline drift.

In six of the dogs, we also placed a cannulating flow probe (Carolina Medical Electronics) in the left anterior pulmonary vein at its junction with the left atrium. In another six of the dogs, we placed four pairs of 2-mm ultrasonic piezoelectric crystals to measure midwall muscle segment lengths around the left ventricular minor axis circumference. These were placed through small slits in the pericardium in the septum and posterior, lateral, and anterior free walls. In 11 of the dogs, we placed a 3.5-cm flat air-filled balloon over the right or left ventricle to measure pericardial pressure (for another study). In the dogs instrumented with sonomicrometer crystals, the pericardial incisions were left open, whereas in the other dogs the pericardial incision was loosely reaproximated with two or three stitches of 2-0 silk, which left a gap of 4–5 mm.

Protocol

Respiration was suspended at end expiration. After a few steady-state control beats, we suddenly constricted the pulmonary artery during diastole (using the snare). This protocol was repeated as necessary to obtain the correct timing of the intervention.

Using this protocol, we collected data at three steady-state levels of left ventricular end-diastolic pressure: approximately 5, 10, and 15 mm Hg. These pressure levels were obtained by infusing 6% dextran in saline into a femoral vein. (At each pressure level, we also constricted the venae cavae and withdrew volume from the right atrial cannula between two beats, but those data were used for another study.) The protocol was repeated after pericardiotomy.

Data Analysis

Data selection. All transducer signals were low-pass–filtered (100 Hz for pressures and 30 Hz for flows), amplified, recorded on a chart recorder, and digitized on line with a PDP 11/73 computer at a sampling rate of 200 Hz. Left ventricular dP/dt was calculated off line with a sliding three-point Lagrangian algorithm.¹¹
Left and right ventricular peak systolic pressure and end-diastolic pressure were measured at the time left ventricular dP/dt exceeded a threshold of 10% of peak +dP/dt on each beat of interest. The monoexponential time constant (T) of left ventricular pressure decay during isovolumic relaxation (defined as the period between the time of peak -dP/dt and the time left ventricular pressure fell below a value 10 mm Hg above the previous end-diastolic pressure) was computed by the derivative method. This does not assume a zero asymptote of pressure decay. However, like all methods for computing T, this method estimates T from an assumed linear relation (in this case the relation between left ventricular dP/dt and left ventricular pressure). Although this may not strictly be true, T nonetheless provides a useful measure of the rate of left ventricular pressure decay during isovolumic relaxation. Stroke volume was estimated as the integral of aortic flow over one cardiac cycle after setting zero flow equal to the average flow signal over the 50-msec preceding end diastole. Segment length changes during isovolumic relaxation were measured over the same time period from which T was calculated. All data were analyzed as the change in value from the average of the two or three beats before constriction to the value on the beat immediately after constriction.

Statistical analyses. Data are summarized as mean±SD. Changes in left ventricular systolic function and relaxation before and after pericardectomy were analyzed by a one-way analysis of variance. Because that analysis showed no significant pericardial effect, these data were pooled, and the effect of pulmonary artery constriction at different levels of end-diastolic pressure was analyzed by two-factor repeated-measures analysis of variance with multiple linear regression and dummy variables. The factor of most interest was the effect of pulmonary artery constriction. The second factor was the steady-state level of baseline end-diastolic pressure. To test whether these factors had statistically significant effects, we computed F ratios by using the appropriate subjects by factor interaction effects from the analysis of variance as determinants. Paired t tests were used to compare segment length data (only reported for baseline end-diastolic pressure of 10 mm Hg) before and after pulmonary artery constriction.

To further explore the influence of increased right ventricular pressure on the time constant of left ventricular pressure decay, we used multiple linear regression with dummy variables to perform an analysis of covariance to analyze the change in T (∆T) as a function of change in right ventricular peak systolic pressure (ΔPr). We fit these data to the equation:

\[
\Delta T = A_0 + A_{Pr} \Delta P_r + A_{AV} \Delta V + A_{PL} \Delta P_L + A_{PL} P_{10} + A_{P_{13}} P_{13} + \sum_{i=1}^{n-1} A_{D_i}
\]

where A is the regression parameter, ΔV is change in left ventricular stroke volume, ΔPr is change in left ventricular peak systolic pressure, P10, P13, P, and D are so-called “dummy” variables that quantify different experimental conditions, and peri is pericardiectomy. Specifically, P10 is 1 if baseline left ventricular end-diastolic pressure is 10 mm Hg; if not, P10 is 0. P13 is 1 if baseline left ventricular end-diastolic pressure is 15 mm Hg; if not, P13 is 0. P is 1 if pericardium is removed; P is 0 if pericardium is intact. D is 1 if dog i; D is −1 if dog n; D is 0, otherwise (for i = 1 to n − 1).

The principal relation of interest is the relation between ∆T and ∆Pr quantified by the regression parameters A0 and APr. The parameter estimates AAV and APr quantify the effect of stroke volume and left ventricular peak pressure, respectively, on ∆T. The remaining parameter estimates quantify the effects of different experimental conditions to produce parallel shifts in the relation between ∆T and ∆Pr: APr is the effect of baseline end-diastolic pressure of 10 mm Hg compared with 5 mm Hg; APr is the effect of baseline left ventricular end-diastolic pressure of 15 mm Hg compared with 5 mm Hg; P is the effect of pericardial removal; and the Di dummy variables account for the between subjects variability. No analysis is based on the Di dummy variables, but they are necessary to focus the analysis on the relations of interest by, in effect, removing the variability between dogs from the analysis.

Results

Baseline Hemodynamics

The average baseline values of several hemodynamic variables are shown in Table 1. The target

<table>
<thead>
<tr>
<th>Desired LVEDP (mm Hg)</th>
<th>Left Ventricle</th>
<th>Right Ventricle</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>EDP (mm Hg)</td>
<td>PKP (mm Hg)</td>
</tr>
<tr>
<td>5</td>
<td>5.1±1.4</td>
<td>117±18</td>
</tr>
<tr>
<td>10</td>
<td>9.6±2.1</td>
<td>136±16</td>
</tr>
<tr>
<td>15</td>
<td>14.0±2.0</td>
<td>146±27</td>
</tr>
</tbody>
</table>

Values are mean±SD for 13 dogs. Desired LVEDP, target baseline left ventricular end-diastolic pressure; EDP, actual baseline end-diastolic pressure; PKP, peak systolic pressure; SV, stroke volume; T, monoexponential time constant of isovolumic pressure fall; HR, heart rate.
baseline levels of left ventricular end-diastolic pressure were achieved, and the other variables changed as expected as left ventricular end-diastolic pressure increased.

Change in Left Ventricular Function

The typical hemodynamic response to a pulmonary artery constriction is shown in Figure 1 (arrow). The duration of the right ventricular developed pressure pulse was increased, and often, as in this example, right ventricular pressure exceeded left ventricular pressure late during isovolumic relaxation. The effect of pulmonary artery constriction on pulmonary venous flow is immediate (Figure 2), and thus, an analysis of systolic direct ventricular interaction must be confined to the first beat after pulmonary artery constriction to avoid the confounding effect of series interaction on left ventricular filling. The average increase in peak right ventricular pressure at each of the three baseline conditions is shown in Table 2.

Left ventricular systolic pump function. The changes in left ventricular pressure and aortic flow caused by pulmonary artery constriction can be better appreciated in Figure 3, in which the left ventricular pressure and aortic flow signals from the beat before pulmonary artery constriction have been overlaid on the corresponding signals from the beat after pulmonary artery constriction. In this case, there is a 4.8 mm Hg (3.5%) increase in left ventricular peak systolic pressure and a 1.7 ml (4.4%) increase in stroke volume. The average absolute changes in left ventricular stroke volume and peak systolic pressure are shown in Table 2; the corresponding percent changes are shown in Table 3. Analysis of variance showed no statistically significant difference in these responses to pulmonary artery constriction at the three baseline levels of end-diastolic pressure (P>0.50) or with pericardectomy (P>0.50).

Percent septal segment shortening decreased by 1.1% (±1.4) when the pulmonary artery was constricted at a baseline left ventricular end-diastolic pressure of 10 mm Hg. This change was marginally statistically insignificant (P=0.086) by paired t test.

Left ventricular relaxation. Pulmonary artery constriction slowed left ventricular isovolumic pressure decay on the beat after pulmonary artery constriction, particularly during late relaxation (Figure 3). For the data shown in Figure 3, T increased by 12 msec (from 38 to 50). Average values of the change in T at each of the three baseline levels of end-diastolic pressure are given in Tables 2 and 3 and were not significantly different at the three baseline.

Figure 1. Plots of effect of sudden pulmonary artery constriction (arrow) on right ventricular pressure, left ventricular pressure, and aortic flow. The ventricular pressures are plotted on the same scale to show the relative magnitude and timing of the pressures before and after pulmonary artery constriction.

Figure 2. Plots of the effect of pulmonary artery constriction on pulmonary venous flow. Other tracings are to provide a reference of the timing of events. The effect of pulmonary artery constriction is almost immediate. Therefore, the analysis must be restricted to comparing the first beat after pulmonary artery constriction with those before. LV, left ventricle; RV, right ventricle.
TABLE 2. Absolute Changes in Systolic Function Due to Pulmonary Artery Constriction

<table>
<thead>
<tr>
<th>LVEDP (mm Hg)</th>
<th>ΔLVPKP (mm Hg)</th>
<th>ΔSV (ml)</th>
<th>ΔT (msec)</th>
<th>ΔRVPKP (mm Hg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>3 ± 2</td>
<td>1 ± 1</td>
<td>10 ± 4</td>
<td>21 ± 9</td>
</tr>
<tr>
<td>10</td>
<td>3 ± 2</td>
<td>2 ± 2</td>
<td>9 ± 6</td>
<td>27 ± 11</td>
</tr>
<tr>
<td>15</td>
<td>4 ± 1</td>
<td>2 ± 1</td>
<td>10 ± 4</td>
<td>26 ± 6</td>
</tr>
</tbody>
</table>

*p < 0.01

Values are mean ± SD for 13 dogs. LVEDP, target baseline left ventricular end-diastolic pressure; ΔLVPKP, change in left ventricular peak systolic pressure; ΔSV, change in stroke volume; ΔT, change in monoexponential time constant of left ventricular isovolumic pressure decay; ΔRVPKP, change in right ventricular peak systolic pressure.

Two-way repeated measures analysis of variance used to test for statistical significance of the effect of pulmonary artery constriction on the hemodynamic variables.

levels of end-diastolic pressure (p > 0.5) or with pericardiectomy (p > 0.5).

To evaluate the assumption of monoexponential left ventricular pressure decay during relaxation and to provide an additional graphical representation of the changes in left ventricular pressure decay during relaxation, we plotted dP/dt versus left ventricular pressure for the beats before and after pulmonary artery constriction (Figure 4). Although the assumption of monoexponential decay of left ventricular pressure is not strictly true, T still is useful for quantifying pressure decay during isovolumic relaxation.

To further explore the influence of increased right ventricular pressure on the increased time constant of left ventricular pressure decay, we did an analysis of covariance as described in Equation 1 to analyze ΔT as a function of the change in right ventricular peak systolic pressure, change in left ventricular systolic function (stroke volume and peak systolic pressure), baseline left ventricular end-diastolic pressure, and whether the pericardium was present. The principal relation of interest was the relation between ΔT and change in right ventricular peak pressure (Figure 5), the slope of which is quantified by A_{pP} in Equation 1: as right ventricular peak pressure change increased, ΔT increased (Figure 5 and Table 4). The effects of left ventricular stroke volume, A_{SV}, and systolic pressure, A_{pP}, on the relation between ΔT and change in right ventricular systolic pressure were not statistically significant (Table 4). The relation between ΔT and change in right ventricular pressure was shifted downwards at higher baseline left ventricular end-diastolic pressures (Figure 5). This shift is

FIGURE 3. Plots of left ventricular pressure and aortic flow from the beats before and after pulmonary artery constriction (PAC) overlaid to better show the effects of the pulmonary artery constriction. These data are the same as shown in Figure 1.

FIGURE 4. Plots of left ventricular dP/dt vs. pressure for the beats before and after pulmonary artery constriction. The isovolumic relaxation segment is the lower left hand portion of the curve beginning at the bottom of the loop (minimum dP/dt) and extending up and to the left as both dP/dt and pressure fall. The data in the upper graph are from the same beats shown in Figures 1 and 3; the data in the lower graph are from the same beats shown in Figure 6.

TABLE 3. Percent Change From Baseline Due to Pulmonary Artery Constriction

<table>
<thead>
<tr>
<th>LVEDP (mm Hg)</th>
<th>ΔLVPKP</th>
<th>ΔSV</th>
<th>ΔT</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>3%</td>
<td>6%</td>
<td>26%</td>
</tr>
<tr>
<td>10</td>
<td>2%</td>
<td>8%</td>
<td>22%</td>
</tr>
<tr>
<td>15</td>
<td>3%</td>
<td>7%</td>
<td>22%</td>
</tr>
</tbody>
</table>

LVEDP, target baseline left ventricular end-diastolic pressure; ΔLVPKP, change in left ventricular peak systolic pressure; ΔSV, change in stroke volume; ΔT, change in monoexponential time constant of left ventricular isovolumic pressure decay.
Typical pressure-segment length loops at the four sites around the minor axis are shown in Figure 6. Note the inhomogeneity during isovolumic relaxation on the beats after pulmonary artery constriction. We compared isovolumic relaxation phase dimension change (positive numbers indicate lengthening) before and after pulmonary artery constriction with paired t tests (Table 5). In the anterior and posterior segments, there was a statistically significant change from a pattern of no isovolumic length change to one of isovolumic shortening. In the lateral segment, a small amount of control isovolumic lengthening did not change, and in the septal segment, a large control isovolumic lengthening tended to become larger (p=0.126). The conclusion that there was no statistically significant change in septal segment dimension change during isovolumic relaxation contrasts with the visual impression given in Figure 6. In fact, in five of six dogs, the pattern was like that seen in Figure 6. The other dog had a different pattern, such that the paired t test led us to conclude that, on the average, there was a marginally insignificant change (p=0.126).

### Discussion

These data indicate that systolic direct interaction affects left ventricular pump function and relaxation in the intact circulation operating at normal ventricular pressures and volumes.

#### Effect of Interaction on Left Ventricular Systolic Function

**Left ventricular stroke volume.** Sudden pulmonary artery constriction increased left ventricular stroke volume by 1–2 ml (6–8 percent; p<0.01). This is the first direct demonstration that systolic direct ventricular interaction increases cardiac output in the intact circulation. Hence, we have

### Table 4. Regression Coefficients From Analysis of Covariance Relating AT to Change in Right Ventricular Pressure

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Regression coefficient</th>
<th>p value</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>A_R _P</td>
<td>0.42</td>
<td>&lt;0.001</td>
<td>Larger ΔRVPKP are associated with larger ΔT</td>
</tr>
<tr>
<td>Change in LV systolic function</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A_L _V</td>
<td>0.05</td>
<td>&gt;0.5</td>
<td>No effect of left ventricle stroke volume or peak pressure</td>
</tr>
<tr>
<td>A_L _C</td>
<td>0.85</td>
<td>0.1&lt;p&lt;0.2</td>
<td></td>
</tr>
<tr>
<td>Baseline LVEDP</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A_P _R</td>
<td>-3.5</td>
<td>&lt;0.02</td>
<td>A given ΔRVPKP is associated with smaller changes in ΔT at higher baseline LVEDP</td>
</tr>
<tr>
<td>A_P</td>
<td>-3.2</td>
<td>0.06</td>
<td></td>
</tr>
<tr>
<td>A_P _P</td>
<td>-0.32</td>
<td>&gt;0.5</td>
<td>No effect of pericardectomy</td>
</tr>
</tbody>
</table>

Data were fit to the equation:

\[ ΔT = A_1 + A_2 \Delta RVPKP + A_3 \Delta V + A_4 \Delta P_L + A_5 \Delta P_{R\_P} + A_6 \Delta P_{R\_S} + A_7 \Delta P_{R\_I} + \sum_{i=1}^{n} A_{\Delta D_i} \]

A, regression parameter; R\_P, right ventricular peak systolic pressure; V, change in left ventricular stroke volume; P\_L, change in left ventricular peak systolic pressure; P\_R\_P and P\_R\_S, "dummy" variables that quantify different experimental conditions; P\_R\_I, pericardiectomy; ΔRVPKP, change in right ventricular peak systolic pressure; ΔT, change in monoexponential time constant of left ventricular isovolumic pressure decay; LVEDP, target baseline left ventricular end-diastolic pressure.
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FIGURE 6. Representative left ventricular pressure-segment loops for four regions around the left ventricular minor axis hoop showing the effect of pulmonary artery constriction (PAC) on these muscle segments during relaxation. Results of quantitative analysis of segment length changes during isovolumic relaxation are shown in Table 5.

affirmed the finding of Slinker and Glantz that there is a systolic direct interaction under normal physiological conditions, and in addition, we have determined its magnitude in terms of an effect on pump function.

The change in stroke volume could be due to either a geometric change caused by septal displacement toward the left ventricle or, if the septal wall stress decreased, an active increase in septal muscle shortening. There is considerable evidence that septal displacement occurs, but there is no information about the behavior of septal muscle fibers on the first beat after sudden pulmonary artery constriction.

Because it has been estimated that septal wall stress decreases with pulmonary artery constriction, it is reasonable to hypothesize that septal muscle shortening could increase. However, we did not find sufficient evidence to conclude that increased shortening contributed to the increased stroke volume. On the contrary, septal segment shortening actually decreased slightly by about 1% due to an increase in end-systolic length (systolic shortening fraction changed from 0.31 to 0.30). However, because these segments were long (approximately 30 mm), an artifact is introduced that by itself would lead to an apparent segment lengthening as the septal radius of curvature flattened in association with a leftward septal shift. Reported changes in radius of curvature of 15%-27% during steady-state pulmonary artery constriction indicate that this "lengthening" error is approximately 0.5 mm. This is about the same as the increase in end-systolic septal segment length that we observed (0.7 mm). Thus, the small error introduced by the long segments accounts for the small decrease in fiber shortening that we observed. Therefore, we conclude that there is no increased active septal muscle shortening and that the increased stroke volume is most likely due to simple leftward displacement of the interventricular septum.

Left ventricular pressure. Sudden pulmonary artery constriction increased left ventricular peak systolic pressure by 2-5 mm Hg. This finding is consistent with several reports from both intact and isolated hearts. The pressure "cross-talk" gain between the right and left ventricles (i.e., Δ left

Table 5. Isovolumic Segment Length Change on Beats Before and After Pulmonary Artery Constriction

<table>
<thead>
<tr>
<th>Dog</th>
<th>Before</th>
<th>After</th>
<th>Before</th>
<th>After</th>
<th>Before</th>
<th>After</th>
<th>Before</th>
<th>After</th>
</tr>
</thead>
<tbody>
<tr>
<td>301</td>
<td>0.49</td>
<td>2.16</td>
<td>-0.39</td>
<td>-0.49</td>
<td>0.36</td>
<td>-0.21</td>
<td>0.30</td>
<td>-0.53</td>
</tr>
<tr>
<td>302</td>
<td>1.07</td>
<td>1.79</td>
<td>0.34</td>
<td>0.02</td>
<td>0.08</td>
<td>0.28</td>
<td>-0.18</td>
<td>-0.30</td>
</tr>
<tr>
<td>303</td>
<td>1.70</td>
<td>1.38</td>
<td>-0.07</td>
<td>-0.41</td>
<td>0.42</td>
<td>0.36</td>
<td>0.05</td>
<td>-0.11</td>
</tr>
<tr>
<td>304</td>
<td>0.80</td>
<td>1.22</td>
<td>0.19</td>
<td>-0.06</td>
<td>-0.13</td>
<td>-0.01</td>
<td>0.28</td>
<td>-0.08</td>
</tr>
<tr>
<td>305</td>
<td>0.57</td>
<td>0.71</td>
<td>0.36</td>
<td>0.24</td>
<td>0.57</td>
<td>0.69</td>
<td>-0.13</td>
<td>-0.32</td>
</tr>
<tr>
<td>307</td>
<td>1.98</td>
<td>2.36</td>
<td>-0.20</td>
<td>-0.36</td>
<td>0.02</td>
<td>0.03</td>
<td>-0.21</td>
<td>-0.79</td>
</tr>
</tbody>
</table>

Mean: 1.10  1.60  0.04  -0.18  0.22  0.19  0.02  -0.36
SD: 0.61  0.62  0.31  0.29  0.27  0.32  0.23  0.27

p* 0.126  0.004  0.803  0.023

*Values from paired t test; positive values indicate lengthening during isovolumic relaxation.
ventricular pressure/Δ right ventricle pressure) averaged 0.13 (95% confidence interval, 0.11–0.15), which is the same as recently reported for the isolated dog heart.

**Pericardial effect.** Removing the pericardium had a small, statistically insignificant effect on both left ventricular peak pressure and stroke volume responses to pulmonary artery constriction. This contrasts with previous reports in both isolated and intact hearts. The explanation may be that we are unable to detect a small effect of pericardial removal on an already small change due to pulmonary artery constriction. In contrast, the other studies that have shown pericardial effects examined interaction over a much wider range of ventricular volumes and pressures and over a longer period of time, during which there were additional geometric rearrangements, including decreased left ventricular volume. Thus, there was a greater chance of observing a pericardial effect in those studies.

Although these data demonstrate that ventricular interaction affects left ventricular pump function under normal conditions in the intact circulation, this effect is small relative to other determinants of left ventricular function. However, our interpretation of these data is that the effect of systolic interaction on left ventricular function is stronger than most previous reports indicate. This is particularly true with respect to our findings of a clear effect at normal ventricular pressures and volumes, whereas most previous reports describe an effect only under conditions of hypotension. The relatively small magnitude does not mean that systolic direct ventricular interaction is unimportant; this interaction may help the left ventricle make fine adjustments needed to balance right and left ventricular outputs as cardiac loading conditions change, as suggested by Slinker and Glantz.

**Effect of Interaction on Left Ventricular Isovolumic Relaxation**

In terms of both absolute and percent change, the increase in the monoeXponential time constant of left ventricular pressure decay during isovolumic relaxation of about 10 msec on the beat after a pulmonary artery constriction is the largest hemodynamic effect we observed. The relation between dP/dt and left ventricular pressure (Figure 4) shows that minimum dP/dt decreases with pulmonary artery constriction and that at any dP/dt, left ventricular pressure during isovolumic relaxation is higher in the beat after pulmonary artery constriction when compared with the beat before. This is simply a graphical restatement of the information conveyed by the increase in T. The isovolumic segment of the dP/dt versus pressure relation (Figure 4) is slightly nonlinear. However, the slope of a linear approximation is useful for quantitative comparison of these segments, especially because the nonlinearity is similar in both beats.

The simplest explanation for the prolonged left ventricular relaxation is that it is due to pressure cross talk between the ventricles. The data shown in Figure 5 demonstrate that as the change in right ventricular peak systolic pressure was larger, the time constant of left ventricular pressure decay was prolonged. Furthermore, the left ventricular time constant of pressure decay was more affected by a given change in right ventricular pressure when baseline left ventricular pressures were lower (Figure 5 and Table 4). Both of these findings are consistent with a simple pressure cross-talk effect, in which elevated right ventricular pressure late in systole increases the external pressure on the left ventricle during relaxation (Figure 1) and, thus, causes left ventricular pressure to decay more slowly.

A second possible explanation has to do with the fact that changes in relaxation have been linked to changes in systolic performance. To examine this, we took the analysis of the relation between ΔT and the change in right ventricular systolic pressure a step further and found that there was no statistically significant additional effect of changes in either left ventricular stroke volume or peak systolic pressure to prolong T (Table 4). Thus, it would appear that there is not a significant functional relation between the changes in systolic performance and the prolonged time constant, at least over the limited range of changes we observed.

A third possible explanation is regional inhomogeneity (Figure 6). On the beat before pulmonary artery constriction, the septal and lateral segments tended to lengthen during isovolumic relaxation, but there was no clear pattern in the posterior and anterior segments. On the beat after pulmonary artery constriction, the septal segment lengthened more, the posterior and anterior segments tended to shorten, and the lateral segment was unaffected. Thus, the observed slowing of pressure decay is associated with greater inhomogeneity in regional wall motion during relaxation. Whether the prolonged pressure decay and the regional inhomogeneity are causally linked, as suggested by Brutsaert and his coworkers, or are simply independent manifestations of the increased right ventricular pressure cannot be determined from our data.

In summary, this study confirms the findings of Slinker and Glantz that altered right ventricular systolic function normally affects left ventricular pump function. While this systolic direct ventricular interaction effect is relatively small, it is not necessarily unimportant. Furthermore, this study is the first to demonstrate slowed left ventricular relaxation due to systolic direct ventricular interaction. This slowed relaxation is associated with regional inhomogeneity in relaxation of muscle segments in the left ventricular wall.

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References


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