Differentiation of Constrictive Pericarditis and Restrictive Cardiomyopathy by Doppler Echocardiography

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Doppler ultrasound recordings of mitral, tricuspid, aortic, and pulmonary flow velocities, and their variation with respiration, were recorded in 12 patients with a restrictive cardiomyopathy and seven patients with constrictive pericarditis. Twenty healthy adults served as controls. The patients with constrictive pericarditis showed marked changes in left ventricular isovolumic relaxation time and in early mitral and tricuspid flow velocities at the onset of inspiration and expiration. These changes disappeared after pericardiectomy and were not seen in patients with restrictive cardiomyopathy or in normal subjects. The deceleration time of early mitral and tricuspid flow velocity was shorter than normal in both groups, indicating an early cessation of ventricular filling, but only patients with restrictive cardiomyopathy showed a further shortening of the tricuspid deceleration time with inspiration. Diastolic mitral and tricuspid regurgitation was also more common in the patients with restrictive cardiomyopathy. These results suggest that patients with constrictive pericarditis and restrictive cardiomyopathy can be differentiated by comparing respiratory changes in transvalvular flow velocities. In addition, although baseline hemodynamics in the two groups were similar, characteristic changes were seen with respiration that suggest differentiation of these disease states may also be possible from hemodynamic data. (Circulation 1989;79:357–370)

The differentiation between constrictive pericarditis and restrictive cardiomyopathy is often difficult by clinical examination as well as with hemodynamic studies. Although elevated and "equalized" diastolic pressures that demonstrate a "dip and plateau" pattern at catheterization suggest a constrictive process, restrictive cardiomyopathy may show similar findings. Furthermore, diastolic pressures may not be equalized in patients who have constriction when additional cardiac pathology is present.1–4 In a patient with constrictive pericarditis, we noted a striking respiratory variation in early mitral and tricuspid flow velocities recorded by Doppler ultrasound. To assess the possible diagnostic value of this finding, transvalvular flow velocities were recorded with respiration in patients with constrictive pericarditis, studies both before and after pericardiectomy, and the results were compared with those found in patients with restrictive cardiomyopathy and 20 healthy adults who served as a control reference group. Hemodynamic data from the patients with constrictive pericarditis and restrictive cardiomyopathy were also compared.

Methods

Subject Groups

Seven patients (mean age, 52±11 years) with a history of long-term peripheral edema and elevated central venous pressure were determined to have constrictive pericarditis (constrictive group) after diagnostic evaluation. The diagnosis was confirmed at surgery, and after pericardial stripping, all patients showed a marked improvement in hemodynamic and clinical status, which was maintained on long-term follow-up. The etiology of the constrictive process was unknown in three patients, whereas two patients had previous cardiac surgery and two had previous radiation therapy. Five of the patients with constrictive pericarditis had repeat echocardiographic studies after surgery (postoperative group).

Twelve patients (mean age, 49±16 years) were determined to have a restrictive cardiomyopathy (restrictive group). Part of the Doppler findings in
these patients have been reported in previous studies.\textsuperscript{5-7} However, except for mitral deceleration time, respiratory changes in Doppler parameters were not described in these reports. In this group, care was taken to include only patients who had a combination of echocardiographic,\textsuperscript{8,9} hemodynamic,\textsuperscript{2,3} computerized tomographic, and endomyocardial biopsy findings compatible with a restrictive process. These findings made constrictive pericarditis unlikely enough that exploratory thoracotomy was not believed to be clinically indicated. Three of these patients had a systemic infiltrative disorder (amyloidosis, two; Fabry's disease, one), one had Charcot-Marie-Tooth disease, one had previous radiation therapy and had undergone previous pericardiectomy, five were cardiac transplant recipients with a history of severe chronic rejection, and two had no known related diseases. In the patients without an infiltrative disorder, all had extensive fibrosis in myocardial biopsy specimens, eight of nine had bialtral enlargement, and four of nine had a 5 mm Hg or larger separation in intracardiac diastolic pressures.

In the patient groups, functional status was defined as: asymptomatic (Class I), shortness of breath on moderate exertion (Class II), shortness of breath on mild exertion (Class III), and shortness of breath with minimal exertion (Class IV).

Because patients with chronic obstructive pulmonary disease may have clinical findings similar to those with a restrictive or constrictive process and marked variation in transvalvular flow velocities have been reported in this group of patients,\textsuperscript{10} six patients with a forced expiratory volume in 1 second of 1.5 1 or less who underwent right and left heart catheterization were also studied and the data was analyzed separately (COPD group). Finally, 20 healthy adults (mean age, 45 ± 9 years) served as a reference group (normal group).

**Echocardiography**

Two-dimensional and M-mode echocardiograms were obtained with a Hewlett-Packard (Andover, Massachusetts) Model 77020 imaging system with a 2.5- or 3.5-MHz transducer. All patients were studied within 12 hours of cardiac catheterization, and the patients in the postoperative group were restudied 6–10 days after surgery. Recordings were assessed for chamber sizes, left ventricular wall thickness, shortening fraction, septal and posterior wall movements, and a pattern consistent with pericardial thickening.\textsuperscript{11} Doppler ultrasound recordings were made with an Irex Exemplar ultrasonograph (2.0-MHz transducer) and simultaneous recordings of electrocardiogram, respiration, and phonocardiogram. With an apical or low parasternal window, blood flow velocities were recorded with pulsed wave Doppler technique across all four cardiac valves at paper speeds of 50 mm/sec for velocity analysis and at 100 mm/sec for measurement of ventricular ejection and isovolumic relaxation times. Recording was done during normal respiration and during short periods of end-tidal volume apnea. Mitral and tricuspid flow velocities were recorded with the sample volume placed between the leaflet tips at a point where the highest peak antegrade velocity was recorded. Left ventricular isovolumic relaxation time (interval from aortic closure on the phonocardiogram to start of mitral flow, Ac-Mo) and peak velocity of mitral and tricuspid flow in early diastole (M1, T1) and at atrial contraction (M2, T2) were measured during apnea and on the first beat after the onset of inspiration and expiration as shown in Figure 1. In cardiac transplant recipients, cardiac cycles in which the native atrial contraction occurred between midsystole and mitral valve opening were excluded from measurement.\textsuperscript{12} The approximate timing of the onset of inspiration and expiration as recorded by the nasal thermistor had been previously determined in relation to changes in intrathoracic (pulmonary wedge) pressure. Because some patients had a progressive shortening of the mitral and tricuspid deceleration times during inspiration, these variables were measured at end-inspiration and end-expiration (Figure 1). Aortic and pulmonary flow velocities were recorded at the valve level. All variables were measured and averaged for six beats during apnea, inspiration, and expiration. Because of individual variation in flow velocities and intervals, the percent change of expiratory to inspiratory values was also calculated for all variables in each subject.

Valvular regurgitation was identified by recording systolic or diastolic reversal of flow across the valve with the pulsed wave sample volume placed just proximal to the valvular orifice. Continuous wave Doppler ultrasound was used to detect valvular stenosis and record the maximal velocity of regurgitation.

**Catheterization**

All patients underwent right and left heart catheterization with fluid-filled catheters attached to manifold micromanometer transducers (Model P-50, Gould, Cleveland, Ohio). Diastolic "equalization" of pressures was defined as a 5 mm Hg or less difference in mean right atrial, mean pulmonary wedge, and ventricular end-diastolic pressures. Pulsus paradoxus was defined as a 15 mm Hg or greater inspiratory decrease in ascending aorta pressure during normal respiration. Simultaneous recording of right and left ventricular pressures was done in all patients with constrictive pericarditis and in 10 of the 12 patients with restrictive cardiomyopathy. Simultaneous left ventricular and pulmonary wedge pressures were recorded in all the patients in the constrictive group and in nine of the 12 patients with restrictive cardiomyopathy. Cardiac output was determined by the Fick method.
Statistical Analysis

All values are expressed as mean±SD. Statistical analysis between groups was performed with an analysis of variance. When differences among groups were present, Scheffe’s test was used to determine which group differed from the others. The hemodynamic data in the patients in the constrictive and restrictive groups were compared by a Student’s t test for unpaired data. Comparison of Doppler ultrasound variables between constrictive patients and those with obstructive pulmonary disease was also made with a Student’s t test.

Results

Clinical and Echocardiographic Findings

Six of the seven patients with constrictive pericarditis and 10 of the 12 patients with restrictive cardiomyopathy were in functional Classes III or IV. Four patients in the restrictive group were in atrial fibrillation, two were in a paced rhythm (one atrial and one ventricular), and six were in sinus rhythm. All patients with constrictive pericarditis were in sinus rhythm. Ventricular chamber sizes were normal in all patients in both groups. Fractional shortening ranged from 22% to 45% (mean, 32%) in the patients with constrictive pericarditis and from 14% to 42% (mean, 27%) in the patients with restrictive cardiomyopathy. The mean change in M-mode left ventricular internal dimension from inspiration to expiration was 5.4±1.5 mm in the constrictive patients. In the patients with restrictive cardiomyopathy, the largest change was 3 mm (mean, 1.8±1.0 mm). An M-mode pattern consistent with pericardial thickening was present in all constrictive patients and in six of the 12 patients with restrictive cardiomyopathy. Four of the restrictive patients had moderately severe tricuspid regurgitation, whereas the other eight showed only mild-to-moderate mitral or tricuspid regurgitation or both by Doppler ultrasound13 or angiographic criteria or both. In the patients with constrictive pericarditis, only mild tricuspid or mitral regurgitation or both was seen.

Hemodynamics

A comparison of the hemodynamic variables in the restrictive and constrictive groups are shown in
Table 1. Comparison of Hemodynamic Variables in the Restrictive and Constrictive Patient Groups

<table>
<thead>
<tr>
<th>Variable</th>
<th>Restrictive</th>
<th>Constrictive</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heart rate (beats/min)</td>
<td>90±18</td>
<td>94±7</td>
<td>NS</td>
</tr>
<tr>
<td>Pressure (mm Hg)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean right atrial</td>
<td>17±3</td>
<td>18±4</td>
<td>NS</td>
</tr>
<tr>
<td>RV peak systolic</td>
<td>39±14</td>
<td>39±9</td>
<td>NS</td>
</tr>
<tr>
<td>RV rapid filling wave</td>
<td>12±3</td>
<td>11±5</td>
<td>NS</td>
</tr>
<tr>
<td>RV A wave*</td>
<td>1±1†</td>
<td>3±2</td>
<td>&lt;0.05</td>
</tr>
<tr>
<td>RV end-diastolic</td>
<td>17±3</td>
<td>21±4</td>
<td>&lt;0.05</td>
</tr>
<tr>
<td>Mean pulmonary artery</td>
<td>30±9</td>
<td>26±5</td>
<td>NS</td>
</tr>
<tr>
<td>Mean pulmonary wedge</td>
<td>20±5</td>
<td>21±4</td>
<td>NS</td>
</tr>
<tr>
<td>LV peak systolic</td>
<td>106±18</td>
<td>120±34</td>
<td>NS</td>
</tr>
<tr>
<td>LV rapid filling wave</td>
<td>9±5</td>
<td>10±4</td>
<td>NS</td>
</tr>
<tr>
<td>LV A wave*</td>
<td>3±3†</td>
<td>3±1</td>
<td>NS</td>
</tr>
<tr>
<td>LV end-diastolic</td>
<td>21±6</td>
<td>25±9</td>
<td>NS</td>
</tr>
<tr>
<td>Mean aortic</td>
<td>85±17</td>
<td>97±12</td>
<td>NS</td>
</tr>
<tr>
<td>Cardiac output (l/min)</td>
<td>4.0±1.1</td>
<td>4.3±1.6</td>
<td>NS</td>
</tr>
</tbody>
</table>

LV, left ventricular; RV, right ventricular; NS, not significant.
Values are mean±SD.
*Increase in ventricular pressure as a result of atrial contraction. †Patients who were in sinus (n = 6) or atrial-paced (n = 1) rhythm.

Table 1. Pulsus paradoxus was present in three of seven patients with constrictive pericarditis but in only one of the 12 patients with restrictive cardiomyopathy. Right ventricular pressure increase with atrial contraction and right ventricular end-diastolic pressure was slightly higher in the patients with constrictive pericarditis (p <0.05); otherwise, there were no significant differences in hemodynamics between the two groups. Equalization of diastolic pressures was seen in five of the seven patients with constrictive pericarditis and seven of the 12 patients with restrictive cardiomyopathy. Figure 2 shows the mean values for respiratory variation from expiration to inspiration in ventricular and pulmonary wedge pressure in the two groups. In patients with restrictive cardiomyopathy, systolic pressure decreased in both ventricles with inspiration, and the respiratory variation in diastolic left ventricular and pulmonary wedge pressure was similar, as shown in Figure 3. Consequently, the diastolic pressure gradient from the pulmonary veins to the left ventricle remained relatively constant throughout the respiratory cycle. In contrast, as shown in Figure 4, in patients with constrictive pericarditis, the peak systolic pressures in the ventricles changed in opposite directions with respiration; the right ventricular systolic pressure increased with inspiration while left ventricular pressure was simultaneously decreasing. In addition, the respiratory variation in pulmonary wedge pressure was larger than in left ventricular diastolic pressure, resulting in a decrease in the pressure difference from the pulmonary veins to the left heart on inspiration and an increased difference on expiration.

**Mitral and Tricuspid Flow Velocities**

Tables 2 and 3 and Figure 5 show the mean values for the mitral and tricuspid flow velocity variables for apnea, inspiration, and expiration and the percent change from expiration to inspiration in both groups of patients and in normal subjects. In Figure 6, individual values for the respiratory variation in isovolumic relaxation time and early mitral and tricuspid flow velocity (expressed as a percent change from apnea) are shown for each of the patients in the restrictive and constrictive groups. In patients with restrictive cardiomyopathy and in normal subjects, respiratory variation in left ventricular isovolumic relaxation time and peak early mitral flow velocity was minimal (mean, <5%), with no individual showing a greater than 15% difference between inspiratory and expiratory values. In contrast, in the patients with constrictive pericarditis, a
marked respiratory variation in these variables was seen (mean, >30%), with all individuals showing a greater than 25% difference between inspiratory and expiratory values. Mean values for peak tricuspid flow velocity in early diastole were increased with inspiration in all three study groups and were not statistically different. However, respiratory variation from expiration to inspiration was larger in the patients with constrictive pericarditis because of a marked decrease in flow velocity on expiration that was not seen in patients with restrictive cardiomyopathy or in normal subjects (Figures 5 and 6).

As shown in Figure 7A, the timing of the respiratory changes in mitral flow velocity was charac-
teristic in all the patients with constrictive pericarditis, with the largest decrease in early mitral flow velocity and increase in left ventricular isovolumic relaxation time on the first beat after the onset of inspiration compared with apnea values. Opposite changes, with a marked increase in early mitral flow velocity and shortening of the isovolumic relaxation interval, were seen on the first beat of expiration. Second and third inspiratory and expiratory beats (when present) showed intermediate values for these variables. The tricuspid flow velocity showed reciprocal changes, with the largest increase in velocity on the first beat of inspiration and the largest decrease in velocity on the first beat after the onset of expiration (Figure 7A). After pericardiectomy, the marked respiratory variation in mitral flow velocity and left ventricular isovolumic relaxation time was no longer present (Figure 7B), and only the normal increase in tricuspid flow velocity with inspiration was seen. As shown in Figures 5 and 6, patients with restrictive cardiomyopathy and normal subjects did not have a marked decrease in tricuspid flow velocity during expiration compared with values during apnea beats.

Although patients with restrictive cardiomyopathy had minimal variation in mitral flow velocity with respiration, characteristic Doppler findings were also seen in these patients. As illustrated in Figure 8, these Doppler features included markedly shortened mitral and tricuspid deceleration times, further shortening of the tricuspid deceleration time (and sometimes the mitral) with inspiration, diastolic mitral and tricuspid regurgitation (nine of 12 patients), and a reduced mitral and tricuspid flow velocity with atrial contration. Most of the patients with constrictive pericarditis also had a shortening of the mitral and tricuspid deceleration time compared with normal subjects, but they did not show further shortening with inspiration (Table 2); diastolic regurgitation was uncommon (one of seven patients); and mitral and tricuspid flow velocity with atrial contraction was usually normal.

### Aortic and Pulmonary Flow Velocities and Ejection Times

The mean aortic and pulmonary flow velocities and ejection times, with percent change from expiration to inspiration, are shown in Table 4. The

## Table 2. Left Ventricular Isovolumic Relaxation Time, Peak Velocities of Early Mitral and Tricuspid Flow, and Mitral and Tricuspid Deceleration Times During Apnea, Expiration, and Inspiration

<table>
<thead>
<tr>
<th></th>
<th>Heart Rate</th>
<th>IVRT (msec)</th>
<th>M&lt;sub&gt;1&lt;/sub&gt; (cm/sec)</th>
<th>M&lt;sub&gt;2&lt;/sub&gt; (cm/sec)</th>
<th>M&lt;sub&gt;a&lt;/sub&gt; (msec)</th>
<th>T&lt;sub&gt;1&lt;/sub&gt; (cm/sec)</th>
<th>T&lt;sub&gt;2&lt;/sub&gt; (cm/sec)</th>
<th>T&lt;sub&gt;a&lt;/sub&gt; (msec)</th>
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<tbody>
<tr>
<td>Normal (n = 20)</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td></td>
<td>a</td>
<td>69±12</td>
<td>84±18</td>
<td>61±14</td>
<td>188±28</td>
<td>56±11</td>
<td>40±5</td>
<td>218±31</td>
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<tr>
<td></td>
<td>c</td>
<td>72±14</td>
<td>85±18</td>
<td>59±17</td>
<td>189±26</td>
<td>56±9</td>
<td>39±6</td>
<td>219±29</td>
</tr>
<tr>
<td></td>
<td>i</td>
<td>74±15</td>
<td>82±17</td>
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<td>189±27</td>
<td>64±10</td>
<td>44±6</td>
<td>220±26</td>
</tr>
<tr>
<td>Restrictive</td>
<td>90±18*</td>
<td></td>
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<tr>
<td>Cardiomyopathy (n = 12)</td>
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<td></td>
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<tr>
<td></td>
<td>a</td>
<td>61±13</td>
<td>89±20</td>
<td>32±12*</td>
<td>123±32*</td>
<td>66±16</td>
<td>28±2*</td>
<td>148±23*</td>
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<td>112±37</td>
<td>74±14</td>
<td>33±16</td>
<td>114±30*</td>
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<tr>
<td>Constrictive</td>
<td>94±7*</td>
<td></td>
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<tr>
<td>Pericarditis (n = 7)</td>
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<tr>
<td></td>
<td>a</td>
<td>67±14</td>
<td>79±16</td>
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<td></td>
<td>e</td>
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<td>153±43</td>
<td>50±9</td>
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<tr>
<td></td>
<td>i</td>
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<td>55±34</td>
<td>146±34*</td>
<td>74±21</td>
<td>38±14</td>
<td>150±45*</td>
</tr>
</tbody>
</table>

IVRT, isovolumic relaxation time; M<sub>1</sub>, T<sub>1</sub>, mitral and tricuspid flow velocities in early diastole; M<sub>2</sub>, T<sub>2</sub>, mitral and tricuspid flow velocities at atrial contraction; M<sub>a</sub>, T<sub>a</sub>, mitral and tricuspid deceleration times; n, total number. a, apnea; e, expiration; i, inspiration. Values are mean±SD.

*<i>p</i> < 0.05 versus normal.

†<i>p</i> < 0.05 versus restrictive cardiomyopathy.

‡<i>p</i> < 0.05 versus restrictive cardiomyopathy and normal.

## Table 3. Percent Change From Expiration to Inspiration in Left Ventricular Isovolumic Relaxation Time, Peak Velocities of Early Mitral and Tricuspid Flow, and Mitral and Tricuspid Deceleration Times

<table>
<thead>
<tr>
<th></th>
<th>IVRT</th>
<th>M&lt;sub&gt;1&lt;/sub&gt;</th>
<th>M&lt;sub&gt;2&lt;/sub&gt;</th>
<th>M&lt;sub&gt;a&lt;/sub&gt;</th>
<th>T&lt;sub&gt;1&lt;/sub&gt;</th>
<th>T&lt;sub&gt;2&lt;/sub&gt;</th>
<th>T&lt;sub&gt;a&lt;/sub&gt;</th>
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<tr>
<td>Normal (%)</td>
<td>2±3</td>
<td>-4±4</td>
<td>-2±6</td>
<td>1±4</td>
<td>14±9</td>
<td>11±10</td>
<td>1±12</td>
</tr>
<tr>
<td>Restrictive</td>
<td>4±7</td>
<td>-3±4</td>
<td>-2±6</td>
<td>-9±0</td>
<td>17±16</td>
<td>16±15</td>
<td>-21±14*</td>
</tr>
<tr>
<td>Cardiomyopathy (%)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Constrictive</td>
<td>50±14*</td>
<td>-33±9‡</td>
<td>-6±4</td>
<td>-3±10</td>
<td>44±22‡</td>
<td>38±25§</td>
<td>6±5†</td>
</tr>
</tbody>
</table>

IVRT, isovolumic relaxation time; M<sub>1</sub>, T<sub>1</sub>, mitral and tricuspid flow velocities in early diastole; M<sub>2</sub>, T<sub>2</sub>, mitral and tricuspid flow velocities at atrial contraction; M<sub>a</sub>, T<sub>a</sub>, mitral and tricuspid deceleration times. Values are mean±SD.

*<i>p</i> < 0.05 versus normal.

†<i>p</i> < 0.05 versus restrictive cardiomyopathy.

‡<i>p</i> < 0.05 versus restrictive cardiomyopathy and normal.
respiratory variation in these variables was seen on the beats immediately after those beats where changes in the mitral and tricuspid flow velocity were observed. In the patients with constrictive pericarditis, the mean inspiratory decrease in aortic flow velocity and left ventricular ejection time was larger ($p < 0.05$) than that seen in the patients with restrictive cardiomyopathy or normal subjects. Respiratory variation in pulmonary artery flow velocity and right ventricular ejection time was also larger in the patients with constrictive pericarditis compared with the other two groups. In the patients with constrictive pericarditis, the largest decrease in aortic flow velocity and left ventricular ejection time occurred on the beat immediately following the largest decrease in mitral flow velocity.

Blood flow from the right ventricle into the pulmonary artery in diastole was recorded in four of the seven patients with constrictive pericarditis and six of the 12 patients with restrictive cardiomyopathy. This was usually associated with inspiration and was seen before, as well as with, atrial contraction.

Postoperative Doppler Findings
After pericardiectomy, respiratory variation in the left heart Doppler variables markedly decreased in all patients with mean values for all variables returning toward those found in the normal group (Figure 5).

Chronic Obstructive Pulmonary Disease
The mean age ($62 \pm 12$ years) of the patients with pulmonary disease was similar to that of the patients
with constrictive pericarditis. The mean heart rate was faster in the patients with constrictive pericarditis (94 ± 7 compared with 78 ± 11 beats/min, p < 0.05). Tables 5 and 6 and Figure 5 show a comparison of the Doppler variables in the two groups and the percent change from expiration to inspiration in these variables. Compared with the patients with constrictive pericarditis, the patients with obstructive pulmonary disease showed less respiratory variation in isovolumic relaxation time, peak early mitral flow velocity, and tricuspid deceleration time (all, p < 0.05). In addition, the timing of the respiratory changes observed in the mitral and tricuspid flow velocity were distinctly different from those

**Figure 7.** Panel A: Tracing of mitral and tricuspid flow velocities recorded together with respiration (resp) in a patient with constrictive pericarditis. Note the marked decrease in early mitral flow velocity (beats 2 and 5, large black arrows) and the increase in left ventricular isovolumic relaxation time (IVRT, pairs of small arrows) on the first beat after the onset of inspiration compared with the other beats. The timing of aortic closure was verified by a simultaneous phonocardiogram not included in the figure. On the first beat after the onset of expiration (beats 3 and 6), an increase in mitral flow velocity and shortening of the IVRT is seen when compared with both inspiration and the intermediate beats. The tricuspid flow velocity shows reciprocal changes, with an increase on the first beat of inspiration (beats 2 and 5) and a decrease on the first beat of expiration (beats 3 and 6, arrows) compared with intermediate beats (1 and 4). The velocity recorded in systole in the tricuspid recording represents systolic flow in the right ventricular inflow tract and should not be confused with transvalvular flow. Panel B: Tracing recorded from the same patient 1 week after pericardiectomy; there is minimal respiratory variation in early mitral flow velocity and IVRT with respiration, and the tricuspid flow velocity on the first beats after the onset of expiration (beats 2 and 5) is larger than the next expiratory beat (beats 3 and 6).
seen in the patients with constrictive pericarditis, the largest decrease in early mitral flow velocity frequently occurring on the second or third inspiratory beat and early tricuspid flow velocity increasing throughout inspiration with no decrease in velocity early in expiration compared with apnea values.

**Discussion**

**Characteristic Doppler Patterns**

The results of this study suggest that despite indistinguishable baseline hemodynamics, patients with constrictive pericarditis can be differentiated from patients with restrictive cardiomyopathy by comparing respiratory variation in transvalvular flow velocity patterns as recorded by Doppler ultrasound. In patients with constrictive pericarditis, respiratory variation in left ventricular isovolumic relaxation time and peak mitral flow velocity in early diastole was observed, which disappeared after surgery, and was not present in patients with restrictive cardiomyopathy or in normal subjects. The respiratory variation was consistent in all constrictive patients, with the largest changes in left ventricular isovolumic relaxation time and mitral

**Table 4. Peak Aortic and Pulmonary Artery Flow Velocities, Left and Right Ventricular Ejection Times With Inspiration and Expiration, and Percent Change From Expiration to Inspiration**

<table>
<thead>
<tr>
<th></th>
<th>Aortic velocity (cm/sec)</th>
<th>LV ejection time (msec)</th>
<th>Pulmonary artery velocity (cm/sec)</th>
<th>RV ejection time (msec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal (n=20)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>e</td>
<td>113±9</td>
<td>305±20</td>
<td>86±12</td>
<td>324±21</td>
</tr>
<tr>
<td>i</td>
<td>109±9</td>
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<td>347±20</td>
</tr>
<tr>
<td>% change</td>
<td>-4±2</td>
<td>-3±3</td>
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<td>7±4</td>
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<tr>
<td>e</td>
<td>91±21</td>
<td>224±32*</td>
<td>65±17</td>
<td>265±29*</td>
</tr>
<tr>
<td>i</td>
<td>87±22</td>
<td>217±32*</td>
<td>67±16</td>
<td>282±24*</td>
</tr>
<tr>
<td>% change</td>
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<td>5±7</td>
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<td></td>
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<tr>
<td>e</td>
<td>111±59</td>
<td>244±17*</td>
<td>66±34</td>
<td>245±29*</td>
</tr>
<tr>
<td>i</td>
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<td>272±28*</td>
</tr>
<tr>
<td>% change</td>
<td>-14±5§</td>
<td>-9±3§</td>
<td>16±4§</td>
<td>11±4§</td>
</tr>
</tbody>
</table>

Values are mean±SD.
LV, left ventricular; RV, right ventricular; n, total number; e, expiration; i, inspiration.
*p<0.05 versus normal.
*tp<0.05 versus restrictive cardiomyopathy.
†p<0.05 versus restrictive cardiomyopathy and normal.
and tricuspid flow velocity on the first beats after the onset of inspiration and expiration. The precise timing and magnitude of these changes in relation to the respiratory cycle helped distinguish patients with constrictive pericarditis from patients with chronic obstructive pulmonary disease who also demonstrated increased respiratory variation in transvalvular flow velocities.

Diagnostic Sensitivity

As shown in Figures 5 and 6, the variation from expiration to inspiration in left ventricular isovolumic relaxation time and early mitral flow velocity appeared to best separate the patients with constrictive pericarditis from those with restrictive cardiomyopathy. In patients with restrictive cardiomyopathy, no individual had more than a 15% respiratory variation in these variables (and usually much less), whereas patients with constrictive pericarditis all had a greater than 25% respiratory variation in these variables. The absolute respiratory change in tricuspid flow velocity in the two groups appears less reliable with some overlap in the two groups being present; however, more than a 10% decrease in early tricuspid flow velocity on the first beat of expiration (compared with apnea) was seen only in the patients with constrictive pericarditis (Figure 6).

Hemodynamic Correlation With Doppler Patterns

Previous studies in animals and humans indicate that the primary determinant of early mitral flow velocity is the pressure gradient from the pulmonary veins (left atrium) to left ventricle in early diastole. The data from this study suggests that respiratory induced changes in this pressure gradient is a key factor that helped distinguish the patients with constrictive pericarditis from those with restrictive cardiomyopathy. As shown in Figure 4, all seven constrictive patients showed less respiratory variation in left ventricular diastolic pressure than in pulmonary wedge pressure. This appeared to result in a reduction in the early diastolic transmural pressure gradient with inspiration and likely explains the later mitral valve opening, longer isovolumic relaxation time, and a decreased early mitral flow velocity that was observed at that time in the constrictive patients. The increase in isovolumic relaxation with inspiration appears to be due to a decrease in left atrial pressure at the time of mitral valve opening and probably does not indicate a change in the rate of left ventricular relaxation or other diastolic properties. A reduced respiratory variation in intracardiac pressures has been reported in constrictive pericarditis and has been attributed to the effect of the pericardial scar in preventing full transmission of changes in intrathoracic pressure to the cardiac chambers. In the patients with restrictive cardiomyopathy, the respiratory variations in pulmonary wedge and left ventricular diastolic pressures were approximately equal (Figure 3), and there was minimal variation in isovolumic relaxation time and early mitral flow velocity. The min-

### Table 5. Left Ventricular Isovolumic Relaxation Time, Peak Early Mitral and Tricuspid Flow Velocity, Mitral and Tricuspid Deceleration Times, Peak Aortic Flow Velocity, and Left Ventricular Ejection Times

<table>
<thead>
<tr>
<th></th>
<th>IVRT</th>
<th>Mi</th>
<th>M0a</th>
<th>T1</th>
<th>T0</th>
<th>Ao</th>
<th>LVET</th>
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<tbody>
<tr>
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<tr>
<td>a</td>
<td>79±14</td>
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<td>220±52</td>
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<td>210±60</td>
<td>44±12</td>
<td>221±37</td>
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<td>53±10</td>
<td>230±39</td>
<td>101±19</td>
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<tr>
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</tr>
<tr>
<td>a</td>
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<td>79±16</td>
<td>156±48</td>
<td>58±17</td>
<td>160±44</td>
<td>105±48</td>
<td>235±18</td>
</tr>
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<td>244±17</td>
</tr>
<tr>
<td>i</td>
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<td>74±21</td>
<td>150±45</td>
<td>97±45</td>
<td>221±20</td>
</tr>
</tbody>
</table>

Values are mean ± SD.

IVRT, isovolumic relaxation time; M1, T1, mitral and tricuspid flow velocities in early diastole; M0a, T0, mitral and tricuspid deceleration times; n, total number; a, apnea; e, expiration; i, inspiration; Ao, peak aortic flow velocity; COPD, chronic obstructive pulmonary disease.

*p<0.05 versus COPD.

### Table 6. Percent Change From Expiration to Inspiration in Left Ventricular Isovolumic Relaxation Time, Peak Early Mitral and Tricuspid Flow Velocity, Mitral and Tricuspid Deceleration Times, Peak Aortic Flow Velocity, and Left Ventricular Ejection Time

<table>
<thead>
<tr>
<th></th>
<th>IVRT</th>
<th>M1</th>
<th>M0a</th>
<th>T1</th>
<th>T0</th>
<th>Ao</th>
<th>LVET</th>
</tr>
</thead>
<tbody>
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<td></td>
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<td></td>
</tr>
<tr>
<td></td>
<td>8±7</td>
<td>-13±8</td>
<td>10±16</td>
<td>24±18</td>
<td>3±7</td>
<td>-9±5</td>
<td>-8±6</td>
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<tr>
<td>Constrictive pericarditis (n=7)</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>50±14</td>
<td>-33±9</td>
<td>-3±10</td>
<td>44±22</td>
<td>6±5</td>
<td>-14±5</td>
<td>-9±3</td>
</tr>
</tbody>
</table>

Values are mean ± SD.

*p<0.05 versus COPD.
imal variation in these Doppler variables in the normal subjects also suggests that respiratory changes in these pressures are similar and “track” each other throughout the respiratory cycle.

Proposed Pathophysiology

If constrictive pericarditis is thought of as a disease process in which ventricular filling is limited by a relatively fixed cardiac volume, then an expiratory increase in left heart filling would likely be associated with a simultaneous decrease in right heart filling. This ventricular coupling was reflected in the patients with constrictive pericarditis in this study by the reciprocal relation seen in ventricular dimensions, peak systolic pressures, ejection times, and aortic and pulmonary flow velocities. In the patients with restrictive cardiomyopathy, the markedly shortened mitral and tricuspid deceleration times indicate that a premature cessation of ventricular filling is present, but the lack of respiratory variation in left heart Doppler variables and relative decrease in mitral and tricuspid flow velocity with atrial contraction suggest that this phenomenon is due to a different process than that present in constrictive pericarditis.

We hypothesize that the differences in Doppler findings observed in the two groups are a result of different pathophysiologic mechanisms that exist in these disease states. In constrictive pericarditis, left ventricular chamber compliance is likely normal at the beginning of diastole, but there is a limitation to cardiac filling that includes both the atria and the ventricles. With total cardiac volume fixed by the pericardium, an increase in filling on one side of the heart will likely impede filling on the other side through displacement of the interventricular septum and ventricular interdependence. However, blood from the atria can be shifted to the ventricles with atrial contraction because total cardiac volume does not increase. In contrast, in restrictive cardiomyopathy it is a marked decrease in left ventricular chamber compliance (most likely due to increased myocardial stiffness) that limits cardiac filling. The abnormal impedance to ventricular filling increases throughout diastole and leads to a reduction in the proportion of filling with atrial contraction and, ultimately, atrial enlargement and failure. With inspiration and an increase in venous return, the right ventricle moves to a steeper portion of its pressure-volume relation, and a larger and more abrupt rise in early diastolic pressure occurs (the rapid filling wave) with a corresponding inspiratory shortening of the tricuspid deceleration time. Because of the lack of pericardial constraint and a relatively noncompliant interventricular septum, there is less ventricular interdependence and inspiratory effect on left ventricular filling.

In patients with restrictive cardiomyopathy, a greater reduction in ventricular, compared with atrial, compliance also may have caused ventricular pressure to increase faster than atrial pressure in early diastole and may possibly explain why diastolic mitral and tricuspid regurgitation was seen more frequently in the patients with restrictive cardiomyopathy. In constrictive pericarditis, atrial and ventricular compliance in mid-diastole and late diastole are likely determined by the pericardium and a more equal pressure increase in the two chambers with diastolic filling might be expected.

Other Disease States With Transvalvular Flow Velocity Variation

Increased respiratory variation in both mitral flow velocity and in left ventricular dimension has been reported in patients with chronic obstructive pulmonary disease. In this study, comparing only the difference between the largest and smallest values for peak early mitral flow velocity in some patients with obstructive pulmonary disease gave values for respiratory changes as large as those seen in patients with constrictive pericarditis. However, by recording respiration together with the flow velocities, the timing of the flow velocity variation in relation to the respiratory cycle was seen to be distinctly different in the patients with obstructive pulmonary disease. In these patients, the lowest mitral flow velocity was often seen on the second or third beats of inspiration, and the highest mitral flow velocity was often seen late in expiration. Perhaps more striking, early tricuspid flow velocity usually continued to increase throughout inspiration and did not decrease below apnea values on the first beat of expiration (Figure 5). This suggests that there is less limitation to cardiac filling in obstructive pulmonary disease and that a different pathophysiologic mechanism is present that results in increased respiratory flow velocity variation. Similar respiratory changes can be seen in patients with marked obesity. We have also observed an inspiratory decrease in mitral flow velocity in patients with acute right ventricular dilatation due to right ventricular infarction or large pulmonary emboli, but in these patients, early cessation of tricuspid flow indicates restriction to ventricular filling is present.

Comparison With Previous Studies

Previous studies have shown that there is minimal respiratory variation in left ventricular dimension and isovolumic relaxation and ejection times in normal adults and an increase in respiratory variation in diastolic left ventricular dimension in patients with constrictive pericarditis. The presence of bialtrial enlargement in the patients with restrictive cardiomyopathy and the lack of it in all but one patient with constrictive pericarditis (who had documented atrial enlargement before the development of constriction) are in agreement with other studies. Flat posterior left ventricular wall motion in mid-diastole on M-mode echocardiograms has been reported in patients with constrictive pericarditis and early cessation of left ventricular filling has been shown by angiography and
M-mode and Doppler echocardiography.\textsuperscript{25–29} An increase in ventricular dimension with atrial contraction has been shown in some patients with constrictive pericarditis\textsuperscript{19,23} but was apparently absent in a patient with severe constriction.\textsuperscript{30}

In this study, early cessation in ventricular filling (short deceleration times) was seen in both the restrictive and constrictive patients. This is in contrast to other studies that describe a reduced rate of early diastolic filling in patients with restrictive cardiomyopathy.\textsuperscript{25,26} Abnormal left ventricular relaxation has been demonstrated in patients with restrictive cardiomyopathy\textsuperscript{31} and, in the presence of relatively normal pressures, might result in a reduced rate of ventricular filling in early diastole. However, with elevation of left atrial pressure (as seen in the patients in this study), a normal or rapid rate of early diastolic filling can occur despite the presence of abnormal relaxation.\textsuperscript{6,32,33} These results suggest that the rate of ventricular filling is dependent on multiple factors and may not reliably separate patients with constrictive pericarditis from patients with restrictive cardiomyopathy, as previously suggested.\textsuperscript{25,26}

Five of the 12 patients with restrictive cardiomyopathy in this study were cardiac transplant recipients. Although cardiac transplant patients have not classically been associated with this disease state, these patients had clinical, hemodynamic, pathologic, and Doppler findings similar to those reported in other patients with a restrictive process.\textsuperscript{34–37} and two such patients have undergone retransplantation for irreversible “diastolic” heart failure. A reduction in diastolic left ventricular compliance has been shown in transplant recipients during acute rejection\textsuperscript{38} and in some transplant patients during exercise\textsuperscript{39} and after volume loading.\textsuperscript{40} In the present study, there were no statistical differences in either the Doppler or hemodynamic data in the cardiac transplant recipients compared with the rest of the patients with restrictive cardiomyopathy. Similarly, excluding these patients from analysis did not change the results. This suggests that the marked decrease in ventricular compliance in the transplant recipients had the same physiologic effect as more traditional restrictive processes and that these patients may represent an important new group with this disorder.

The reported incidence of pulsus paradoxus in constrictive pericarditis varies widely.\textsuperscript{51,42} In this study, no attempt was made to standardize respiratory effort in the patients or the normal group. It is notable that despite the increased respiratory variation in mitral and aortic flow velocities and left ventricular ejection times in the patients with constrictive pericarditis, only three of seven patients had pulsus paradoxus at catheterization. The relation between the Doppler and hemodynamic correlates of pulsus paradoxus will require further investigation.

Patients with constrictive pericarditis secondary to radiation therapy present special problems because they may also have a coexistent restrictive process. A restrictive process may be suspected when there is marked shortening of the deceleration times with further shortening on inspiration and with diastolic mitral or tricuspid regurgitation.\textsuperscript{5} In addition, the recording of venous flow velocities with respiration may help in recognizing that both conditions are present.\textsuperscript{33} Similarly, patients with “effusive-constrictive” disease\textsuperscript{44} may present special diagnostic problems that may require serial studies as the effusion resolves.

In this study, diastolic flow into the pulmonary artery was recorded in both patients with constrictive pericarditis and restrictive cardiomyopathy and did not help in the differentiation between the two. Presystolic pulmonary valve opening has been described previously in other patients with constrictive pericarditis.\textsuperscript{45,46}

\textbf{Study Limitations}

Because constrictive pericarditis and restrictive cardiomyopathy are uncommon diseases, this study includes a relatively small number of patients, and the possibility of selection bias cannot be excluded.

It has been shown that patients with a less-advanced restrictive process and lower filling pressures than those included in this study have longer deceleration times, less diastolic regurgitation, and more filling with atrial contraction.\textsuperscript{37} Whether patients with milder (or more severe forms) of constrictive pericarditis exhibit similar findings to those in this study will require further investigation.

All patients with constrictive pericarditis in this study were in normal sinus rhythm. What effect the presence of atrial fibrillation or other arrhythmias have on the findings reported in this study is presently unknown. Similarly, the effect of ventricular pacing and mitral and tricuspid regurgitation on the Doppler variables measured in this study are possible confounding variables. A recent study\textsuperscript{47} has demonstrated that right ventricular pacing decreases the rate of left ventricular relaxation and early diastolic filling. However, it seems unlikely that pacing would affect respiratory changes in transvalvular flow velocities. In patients with rapid heart rates or first-degree atrioventricular block, an analysis of the mitral flow velocity pattern may not be possible if atrial contraction occurs in close proximity to mitral valve opening so that a passive filling phase is not distinctly present.

\textbf{Doppler Methods}

The movement of valvular structures in relation to the Doppler ultrasound sample volume with respiration should be observed because this may result in spurious changes in flow velocities, but such changes are not accompanied by alterations in left ventricular isovolumic relaxation or ejection times. For measurement of the deceleration time, pulsed wave technique should be used and the position of the sample volume standardized because sample volume posi-
tions at the anulus can give lower velocities and different deceleration times than a position between the leaflet tips. Deceleration time was measured instead of deceleration slope because it is independent of velocity. Continuous wave technique is not adequate for these recordings and always gives longer deceleration times than pulsed wave technique. For recording diastolic regurgitation, the sample volume should be clearly on the atrial side of the valve to avoid eddies on the ventricular side that may appear as reversal of flow.

Conclusion

In patients with constrictive pericarditis, an increased respiratory variation in early mitral flow velocity is seen, which is not present in patients with restrictive cardiomyopathy, and makes differentiation between the two groups of patients possible. Patients with other diseases also may show an inspiratory decrease in mitral flow velocity, but these patients can be differentiated from those with constrictive pericarditis by the absence of reciprocal changes in ventricular filling, which indicates a limitation to total cardiac filling is present.

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Differentiation of constrictive pericarditis and restrictive cardiomyopathy by Doppler echocardiography.

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