Pulmonary Blood Volume in Congestive Heart Failure

By Bernard F. Schreiner, Jr., M.D., Gerald W. Murphy, M.D., and Paul N. Yu, M.D.

In analyzing the clinical and hemodynamic features of congestive heart failure due to myocardial disease or associated with mitral stenosis, many authors indicate or clearly imply that a significant augmentation in pulmonary blood volume plays a major role in the pathogenesis of pulmonary congestion and edema. These conclusions have depended largely upon indirect evidence such as clinical evaluation, the interpretation of chest roentgenograms, and the measurement of pulmonary vascular pressures and central blood volume.

Utilization of indicator-dilution techniques, combined with simultaneous right and transseptal left heart catheterization, has made more precise quantitation of the true pulmonary blood volume (PBV) possible. The technique of Milnor and associates has been employed in our laboratory in the study of several hundred patients with valvular and other forms of acquired heart disease.

It is the purpose of this presentation to (1) report the changes in PBV in a group of patients with heart failure associated with severe mitral stenosis and in another group of patients with nonvalvular congestive heart failure; (2) compare values of PBV in these patients with those obtained in a separate group of patients who had normal hemodynamics; and (3) offer a modified hypothesis concerning the pathogenesis of pulmonary congestion and edema in which alterations in PBV need not play a dominant role.

Methods

Twenty-five patients between the ages of 14 and 57 years were studied. Twelve of these patients were studied hemodynamically because of a precordial systolic murmur which could not be evaluated with reasonable certainty by routine clinical investigations. This group included nine men and three women, between the ages of 14 and 45 years. None of these patients had hemodynamic abnormalities.

Thirteen patients were studied while in congestive heart failure. Six patients between the ages of 32 and 55 years were in heart failure secondary to mitral stenosis. Five of these six patients were women. Each patient had evidence of right ventricular decompensation.

Seven patients, all men between the ages of 28 and 57 years, were in congestive heart failure as a result of myocardial insufficiency. Five of the seven patients were in biventricular failure while the remaining two had manifestations of left-sided failure only. The diagnosis for six of the seven patients was thought to be nonobstructive cardiomyopathy. The seventh patient, J. McE., had documented rheumatic heart disease with severe aortic incompetence which had been successfully treated 4 months previously by prosthetic valve replacement.

Right heart and transseptal left heart catheterization were carried out in the manner described previously in detail. The left heart catheter was introduced into a saphenous vein or via a percutaneous femoral vein puncture. In most instances the left ventricle was entered. Left ventricular pressures were recorded at different levels of gain in order to facilitate measurement of left ventricular systolic and diastolic pressures.

Indicator-dilution curves were recorded after rapid successive injections of indocyanine green (Cardio-Green*) into the pulmonary artery (PA)

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From the Cardiopulmonary Unit, Department of Medicine, University of Rochester School of Medicine and Dentistry, and Medical Clinic, Strong Memorial Hospital, Rochester, New York.

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*Hynson, Westcott and Dunning, Inc., Baltimore, Maryland.
and left atrium (LA) as previously described.7 Each curve was transcribed electronically onto IBM data cards which were fed into a previously programmed IBM Model 1620 computer for the determination of cardiac output and mean transit time. The programmed results and those obtained by manual computation were essentially identical.

The “central” blood volume (CBV) is that volume between the main pulmonary artery and the brachial artery, including all temporally equidistant branches. It was calculated by the Stewart-Hamilton method⁸ as follows:

\[
\text{CBV} = \text{CI} \times T_m(\text{PA-BA})
\]

Where CBV = central blood volume (ml/m²)

\[
\text{CI} = \text{mean cardiac index (ml/m²/sec)}
\]

\[
T_m(\text{PA-BA}) = \text{mean transit time in seconds from the pulmonary artery to the brachial artery.}
\]

The pulmonary blood volume is that volume within the pulmonary arteries, pulmonary capillaries, pulmonary veins, and an indeterminant portion of the left atrium. It was calculated from the mean cardiac index and mean transit time from the main pulmonary artery to the left atrium as follows:

\[
\text{PBV} = \text{CI} \times \left[ T_m(\text{PA-BA}) - T_m(\text{LA-BA}) \right]
\]

Where PBV = pulmonary blood volume (ml/m²)

\[
T_m(\text{LA-BA}) = \text{mean transit time in seconds from left atrium to brachial artery.}
\]

The mean distending or intravascular pressure in the pulmonary vessels and relative pulmonary vascular compliance was calculated as suggested by Milnor and associates.⁷ The former is the average of the pulmonary artery mean and left atrial mean pressures, while the latter, expressed in ml/m²/mm Hg, is the ratio of PBV to mean distending pressure.

Pulmonary vascular resistance was calculated as follows:

\[
PVR = \frac{\text{PA}_m - \text{LA}_m}{\text{CO}} \times K
\]

Where: PVR = pulmonary vascular resistance in dynes • sec cm⁻⁵

\[
\text{PA}_m = \text{pulmonary artery mean pressure in mm Hg}
\]

\[
\text{LA}_m = \text{left atrial mean pressure in mm Hg}
\]

\[
\text{CO} = \text{cardiac output in L/min}
\]

\[
K = \text{conversion factor (1.36 × 60)}.
\]

During a control period, pulmonary artery, left atrial, and brachial artery (BA) pressures were recorded along with the electrocardiogram. In most instances simultaneous left ventricular (LV) pressure was also recorded. The left heart catheter was then repositioned in the mid-left atrium. Minute ventilation and mixed expired air oxygen tension were continuously monitored to determine when a relatively steady state had been achieved. The PBV was then measured and simultaneous pressures were again recorded.

**Results**

The pertinent data from the patients with normal hemodynamics are presented in table 1. Comparable hemodynamic data from the patients in cardiac failure are presented in table 2. Table 3 summarizes and compares the data obtained from all three groups.

**Patients with Normal Hemodynamics**

In the group of patients with normal hemodynamics the average cardiac index, heart rate, and stroke index were, respectively, as follows: 3.34 L/m², 77 beats/min, and 45 ml/m² The right atrial mean pressure varied between 1 and 5 mm Hg and the pulmonary artery mean pressure between 9 to 17 mm Hg. The left atrial mean pressure was 12 mm Hg or less in each patient. The average pulmonary intravascular distending pressure was 10.5 mm Hg. In no patient did the left ventricular end-diastolic pressure exceed 13 mm Hg. Small systolic pressure gradients from 4 to 10 mm Hg due to catheter movement were noted between the left ventricle and a systemic artery in five patients. Systemic artery pressures were within the normal range in all patients.

The mean central blood volume was 596 ml/m² while the mean pulmonary blood volume was 271 ml/m². The relative pulmonary vascular compliance averaged 26.4 ml/m²/mm Hg. Pulmonary vascular resistance averaged 80 dynes • sec cm⁻⁵.
Patients with Normal Hemodynamics

<table>
<thead>
<tr>
<th>Name</th>
<th>Age, yr &amp; Sex</th>
<th>BSA</th>
<th>CI (L/min/m²)</th>
<th>HR (beats/min)</th>
<th>SI (ml/beat/m²)</th>
<th>RA (mm Hg)</th>
<th>PA (mm Hg)</th>
<th>LA (mm Hg)</th>
<th>Pp (mm Hg)</th>
<th>LV (s/d)</th>
<th>SA (s/d, mm Hg)</th>
<th>Blood volume</th>
</tr>
</thead>
<tbody>
<tr>
<td>B.B.</td>
<td>21 F</td>
<td>1.53</td>
<td>3.16</td>
<td>80</td>
<td>39</td>
<td>5</td>
<td>15</td>
<td>9</td>
<td>12</td>
<td>120/11</td>
<td>133/75.90</td>
<td>596</td>
</tr>
<tr>
<td>R.S.</td>
<td>21 M</td>
<td>1.84</td>
<td>4.40</td>
<td>80</td>
<td>55</td>
<td>1</td>
<td>11</td>
<td>3</td>
<td>7</td>
<td>144/5</td>
<td>140/64.108</td>
<td>594</td>
</tr>
<tr>
<td>W.H.</td>
<td>45 M</td>
<td>1.90</td>
<td>3.67</td>
<td>60</td>
<td>61</td>
<td>4</td>
<td>10</td>
<td>8</td>
<td>9</td>
<td>120/8</td>
<td>140/80.110</td>
<td>572</td>
</tr>
<tr>
<td>D.G.</td>
<td>17 M</td>
<td>1.86</td>
<td>3.49</td>
<td>60</td>
<td>58</td>
<td>5</td>
<td>17</td>
<td>12</td>
<td>14.5</td>
<td>125/13</td>
<td>130/90.90</td>
<td>748</td>
</tr>
<tr>
<td>F.H.</td>
<td>45 M</td>
<td>2.20</td>
<td>2.74</td>
<td>60</td>
<td>46</td>
<td>5</td>
<td>14</td>
<td>6</td>
<td>10.0</td>
<td>100/6</td>
<td>90/55.66</td>
<td>679</td>
</tr>
<tr>
<td>R.C.</td>
<td>23 M</td>
<td>1.92</td>
<td>3.78</td>
<td>83</td>
<td>46</td>
<td>2</td>
<td>12</td>
<td>8</td>
<td>10.0</td>
<td>144/8</td>
<td>130/90.96</td>
<td>618</td>
</tr>
<tr>
<td>J.C.</td>
<td>14 M</td>
<td>1.74</td>
<td>3.59</td>
<td>74</td>
<td>45</td>
<td>4</td>
<td>15</td>
<td>11</td>
<td>10.5</td>
<td>125/10</td>
<td>125/75.100</td>
<td>616</td>
</tr>
<tr>
<td>J.B.</td>
<td>20 F</td>
<td>1.77</td>
<td>3.53</td>
<td>90</td>
<td>39</td>
<td>4</td>
<td>13</td>
<td>8</td>
<td>10.5</td>
<td>112/11</td>
<td>108/64.75</td>
<td>558</td>
</tr>
<tr>
<td>L.G.</td>
<td>20 M</td>
<td>1.83</td>
<td>2.70</td>
<td>73</td>
<td>37</td>
<td>3</td>
<td>16</td>
<td>7</td>
<td>11.5</td>
<td>105/10</td>
<td>112/90.100</td>
<td>645</td>
</tr>
<tr>
<td>L.W.</td>
<td>14 M</td>
<td>1.99</td>
<td>3.22</td>
<td>70</td>
<td>46</td>
<td>5</td>
<td>12</td>
<td>9</td>
<td>10.5</td>
<td>140/12</td>
<td>130/81.104</td>
<td>440</td>
</tr>
<tr>
<td>J.M.</td>
<td>21 M</td>
<td>2.05</td>
<td>3.10</td>
<td>96</td>
<td>32</td>
<td>1</td>
<td>9</td>
<td>4</td>
<td>6.5</td>
<td>125/5</td>
<td>125/80.90</td>
<td>530</td>
</tr>
</tbody>
</table>

| R.L. | 40 F         | 1.72| 3.16          | 110            | 12.0            | 1          | 16         | 8          | 12.0       | 125/7   | 125/75.95       | 485          |

BSA = body surface area (m²); CI = cardiac index (L/min/m²); HR = heart rate (beats/min); SI = stroke index (ml/beat/m²); RA = right atrial mean pressure; PA = pulmonary artery mean pressure; LA = left atrial mean pressure; Pp = pulmonary distending pressure; LV = left ventricular pressure; SA = systemic arterial pressure; s = systolic; d = diastolic; m = mean; CBV = central blood volume (ml/m²); PBV = pulmonary blood volume (ml/m²); C = relative pulmonary vascular resistance (ml/m² mm Hg); and PVR = pulmonary vascular resistance (dynes * sec cm⁻²).

Patients with Congestive Heart Failure

Of the six patients with severe mitral stenosis, five had evidence of congestive heart failure and right ventricular failure. The sixth patient, F.S., developed acute pulmonary edema and stroke indices were severely compromised. The right atrial mean pressure was significantly elevated and averaged 103 mm Hg. Marked pulmonary hypertension was present, and the systolic pulmonary artery pressure averaged 173 mm Hg. The left ventricular end-diastolic pressure was severely elevated and averaged 27 mm Hg. Both pressures were significantly elevated in the latter two patients, as well as in the first three patients, was less than 10 mm Hg in each systemic artery.
### Table 2

**Patients in Congestive Heart Failure**

<table>
<thead>
<tr>
<th>Name</th>
<th>Age, yr &amp; sex</th>
<th>BSA</th>
<th>CI</th>
<th>HR</th>
<th>SI</th>
<th>RA&lt;sub&gt;m&lt;/sub&gt;</th>
<th>PA&lt;sub&gt;m&lt;/sub&gt;</th>
<th>LA&lt;sub&gt;m&lt;/sub&gt;</th>
<th>P&lt;sub&gt;D&lt;/sub&gt;</th>
<th>LV (s/d)</th>
<th>SA (s/d, m)</th>
<th>Blood volume</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mitral stenosis</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>F.S.</td>
<td>43 F</td>
<td>1.60</td>
<td>2.19</td>
<td>190</td>
<td>12</td>
<td>11</td>
<td>71</td>
<td>40</td>
<td>55.5</td>
<td>125/7</td>
<td>125/85.95</td>
<td>656</td>
</tr>
<tr>
<td>E.K.</td>
<td>42 F</td>
<td>1.57</td>
<td>1.20</td>
<td>98</td>
<td>12</td>
<td>11</td>
<td>70</td>
<td>30</td>
<td>50.0</td>
<td>108/10.89</td>
<td>547</td>
<td>269</td>
</tr>
<tr>
<td>J.P.</td>
<td>45 F</td>
<td>1.57</td>
<td>1.83</td>
<td>72</td>
<td>25</td>
<td>13</td>
<td>38</td>
<td>24</td>
<td>31.0</td>
<td>120/9</td>
<td>630</td>
<td>248</td>
</tr>
<tr>
<td>M.G.</td>
<td>45 F</td>
<td>1.35</td>
<td>2.15</td>
<td>80</td>
<td>27</td>
<td>10</td>
<td>28</td>
<td>18</td>
<td>23.0</td>
<td>—</td>
<td>120/78.92</td>
<td>698</td>
</tr>
<tr>
<td>M.P.</td>
<td>55 F</td>
<td>1.62</td>
<td>2.23</td>
<td>75</td>
<td>30</td>
<td>9</td>
<td>25</td>
<td>18</td>
<td>21.5</td>
<td>—</td>
<td>104/64.74</td>
<td>624</td>
</tr>
<tr>
<td>G.R.</td>
<td>32 M</td>
<td>1.87</td>
<td>0.80</td>
<td>100</td>
<td>8</td>
<td>8</td>
<td>67</td>
<td>25</td>
<td>46.0</td>
<td>100/7</td>
<td>115/90.95</td>
<td>442</td>
</tr>
<tr>
<td>Nonvalvular heart failure</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>W.O'B.</td>
<td>57 M</td>
<td>1.90</td>
<td>1.38</td>
<td>100</td>
<td>14</td>
<td>21</td>
<td>28</td>
<td>27</td>
<td>27.5</td>
<td>75/29</td>
<td>68/42.50</td>
<td>680</td>
</tr>
<tr>
<td>G.D.</td>
<td>42 M</td>
<td>1.63</td>
<td>1.29</td>
<td>112</td>
<td>12</td>
<td>7</td>
<td>43</td>
<td>30</td>
<td>36.5</td>
<td>100/42</td>
<td>100/75.85</td>
<td>650</td>
</tr>
<tr>
<td>R.W.</td>
<td>38 M</td>
<td>1.80</td>
<td>2.32</td>
<td>130</td>
<td>18</td>
<td>20</td>
<td>35</td>
<td>23</td>
<td>29.0</td>
<td>105/25</td>
<td>110/75.85</td>
<td>856</td>
</tr>
<tr>
<td>J.McE.</td>
<td>28 M</td>
<td>1.75</td>
<td>1.75</td>
<td>120</td>
<td>15</td>
<td>11</td>
<td>28</td>
<td>25</td>
<td>26.5</td>
<td>110/30</td>
<td>118/80.94</td>
<td>694</td>
</tr>
<tr>
<td>M.L.</td>
<td>40 M</td>
<td>1.98</td>
<td>1.34</td>
<td>66</td>
<td>20</td>
<td>15</td>
<td>45</td>
<td>26</td>
<td>35.5</td>
<td>—</td>
<td>155/100,115</td>
<td>656</td>
</tr>
<tr>
<td>S.C.</td>
<td>44 M</td>
<td>2.02</td>
<td>1.42</td>
<td>70</td>
<td>20</td>
<td>5</td>
<td>28</td>
<td>20</td>
<td>24.0</td>
<td>115/19</td>
<td>125/100,115</td>
<td>573</td>
</tr>
<tr>
<td>R.F.</td>
<td>38 M</td>
<td>1.80</td>
<td>2.32</td>
<td>138</td>
<td>17</td>
<td>3</td>
<td>28</td>
<td>24</td>
<td>26.0</td>
<td>121/32</td>
<td>126/94,104</td>
<td>641</td>
</tr>
</tbody>
</table>

Abbreviations and symbols are the same as those used in table 1.

### Table 3

**Summary of Hemodynamic Parameters in Normal Patients and in Congestive Heart Failure**

<table>
<thead>
<tr>
<th>Age, yr</th>
<th>BSA</th>
<th>CI</th>
<th>HR</th>
<th>SI</th>
<th>RA&lt;sub&gt;m&lt;/sub&gt;</th>
<th>PA&lt;sub&gt;m&lt;/sub&gt;</th>
<th>LA&lt;sub&gt;m&lt;/sub&gt;</th>
<th>P&lt;sub&gt;D&lt;/sub&gt;</th>
<th>LV (s/d)</th>
<th>SA (s/d, m)</th>
<th>Blood volume</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal patients</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>25.9</td>
<td>1.86</td>
<td>3.34</td>
<td>77.0</td>
<td>45.0</td>
<td>3.3</td>
<td>13</td>
<td>8</td>
<td>10.5</td>
<td>124/8.8</td>
<td>125/77.94</td>
</tr>
<tr>
<td>SE (±)</td>
<td>3.1</td>
<td>0.05</td>
<td>0.14</td>
<td>3.9</td>
<td>2.9</td>
<td>0.4</td>
<td>0.7</td>
<td>0.7</td>
<td>0.7</td>
<td>4.5/0.9</td>
<td>4.3/2.8/3.9</td>
</tr>
<tr>
<td>Heart failure associated with mitral stenosis</td>
<td></td>
<td></td>
<td></td>
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<td></td>
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<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>43.7</td>
<td>1.60</td>
<td>1.73</td>
<td>102.5</td>
<td>19.7</td>
<td>10.3</td>
<td>49.8</td>
<td>25.8</td>
<td>37.0</td>
<td>115/8</td>
<td>115/78.89</td>
</tr>
<tr>
<td>SE (±)</td>
<td>3.2</td>
<td>0.08</td>
<td>0.27</td>
<td>19.9</td>
<td>4.6</td>
<td>0.8</td>
<td>9.7</td>
<td>3.7</td>
<td>6.3</td>
<td>—</td>
<td>3.4/4.1/10.4</td>
</tr>
<tr>
<td>Nonvalvular heart failure</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>41.0</td>
<td>1.84</td>
<td>1.69</td>
<td>105</td>
<td>16.9</td>
<td>11.7</td>
<td>33.6</td>
<td>25.0</td>
<td>29.3</td>
<td>104/29</td>
<td>115/81.93</td>
</tr>
<tr>
<td>SE (±)</td>
<td>3.6</td>
<td>0.06</td>
<td>0.19</td>
<td>3.6</td>
<td>4.6</td>
<td>3.0</td>
<td>3.1</td>
<td>1.3</td>
<td>1.9</td>
<td>6.5/3.1</td>
<td>10.7/8.9/6</td>
</tr>
</tbody>
</table>

Abbreviations and symbols are the same as those used in table 1.

se = standard error of mean.
(mean, 29.3 mm Hg) were approximately three times the normal mean value. In the six patients in whom it was measured, the left ventricular end-diastolic pressure was significantly elevated, averaging 29 mm Hg. Systemic pressures were normal in five patients. In one patient, W.O'B., there was systemic hypotension, while in another patient, M.L., mild systemic hypertension was observed.

The CBV averaged 679 ml/m² while the PBV averaged 292 ml/m². Both mean values did not differ significantly from the normal. However, in one patient, R.W., the values for CBV and PBV were significantly augmented.

For the group, relative pulmonary vascular compliance averaged 10.3 ml/m²/mm Hg which was less than one half the normal mean value. The mean pulmonary vascular resistance was 248 dynes • sec cm⁻². However, in three instances, it was normal, and in three it was moderately elevated. In only one patient did values for pulmonary vascular resistance exceed 480 dynes • sec cm⁻².

**Discussion**

**Validation of the Method**

The potential sources of error in this method of measuring PBV have been described in detail by Dock and associates¹⁰ and in previous communications from this laboratory.¹¹,¹² Of particular concern is the problem of uneven blood flow through the lungs which may produce changes in both rate of blood flow and mean transit time as measured by the indicator-dilution method. For example, in the presence of heart disease, indicator which traverses an area of slow flow velocity may arrive tardily at the sampling site. This will prolong the downslope of the indicator-dilution curve and increase the Tm(PA-BA). Thus, if cardiac output does not change, the CBV would be larger than if the indicator had traveled more rapidly through a normal pulmonary vascular bed.

Another problem would arise if the indicator injected into the pulmonary artery were lost from the circulation, as would occur if it escaped through pulmonary capillary walls, or if it returned to the systemic venous system through bronchopulmonary venous anastomoses. The area under the dilution curve would be reduced. In this instance the cardiac output calculated from this curve would be larger than that derived from a left atrial injection of dye. If Tm(PA-BA) remained constant, the calculated CBV would again be larger.

The occurrence of either possibility would result in a larger calculated PBV since the volume of blood between the left atrium and the systemic artery would not be affected. Such possibilities would tend to minimize our results, not exaggerate them. Furthermore, if indicator were lost from the lungs during its primary circulation, one would expect to find a systematic difference in the measurement of blood flow derived from curves following pulmonary artery injection compared to those following left atrial injection. Such was not the case.

In contrast, if areas within the lung contain blood with such sluggish flow that it never mixes with the indicator, this fraction would not be included in the calculated CBV. This would produce a falsely low PBV. Whether or not such a hypothetical or pathophysiological state or both exist in the presence of chronic pulmonary venous hypertension is uncertain. Harris and Heath¹³ have described medial hypertrophy and intimal fibrosis of both pulmonary arteries and veins as characteristic lesions of pulmonary venous hypertension. In their experience, extensive and complex arterial "dilatation" lesions were not encountered. It would appear from the pathological findings of these authors and in the presence of high pulmonary artery pressure observed during hemodynamic studies, that the possibility of severe stagnation of the blood in the pulmonary vascular bed is probably not an important source of error.

The use of the computerized program in our study provided an added safeguard. Each indicator-dilution curve was scrutinized for stability of base line. Rigid limits were set in the program such that deviations of the base line greater than 3% of full-scale deflec-
tion were rejected. Likewise, points used in the determination of the exponential downslope were accepted only if they deviated from a true exponential by less than 2% of the peak concentration value of the curve. The exponential downslope was determined from at least 5 points, and the best fit was calculated by the computer using a least mean square fit. These criteria were fulfilled in all curves recorded from patients with normal hemodynamics as well as in all curves recorded from patients in heart failure in this study.

Furthermore, this method is sensitive enough to detect larger than "normal" PBVs in many patients with mitral stenosis of class III functional capacity.\textsuperscript{14}

The Normal Pulmonary Blood Volume

Before adequate interpretation of PBV and CBV changes in patients with heart failure can be undertaken, the magnitude and variability of such measurements in normal subjects and in patients with normal hemodynamics must be assessed. In our 12 patients in the latter category, PBV averaged 271 ml/m$^2$ (SE, ± 10.0) or 7.36 ml/kg of body weight, while CBV averaged 596 ml/m$^2$ (SE, ± 25.7). Few other studies of the PBV in relatively normal subjects are available in the literature. Dock and associates\textsuperscript{10} investigated four patients with normal hemodynamics by utilizing simultaneous injections of two different indicators. The mean value for PBV was 246 ml/m$^2$ (ranging from 219 to 269 ml/m$^2$) and for CBV was 568 ml/m$^2$ (ranging from 415 to 691 ml/m$^2$). Five normal subjects were studied by McGaff and associates\textsuperscript{15} employing sequential injections of indocyanine green. The mean value for PBV was 230 ml/m$^2$ (SE, ± 13.6) or 6.44 ml/kg of body weight.

Utilizing a single injection of indicator into the inferior vena cava followed by simultaneous sampling from the pulmonary artery and the left atrium, deFreitas and co-workers estimated PBV in 26 subjects of whom 21 were normal and five had systemic hypertension. As these authors mentioned, this technique for estimating PBV probably includes most of the left atrial volume as well. Control PBV determinations in 19 patients prior to polyvinylpyrrolidone infusion averaged 295 ml/m$^2$ (SE, ± 16), while control PBV determinations in 14 patients prior to peripheral venous pooling averaged 277 ml/m$^2$ (SE, ± 22).\textsuperscript{16}

It would appear, therefore, that our average values for PBV and CBV in patients with normal hemodynamics are reasonable and within the range of error noted by others.

Criteria for Congestive Heart Failure

Crucial to the interpretation of the data in this study is the question of what constitutes congestive heart failure. It has been previously stressed that while overt signs and symptoms of heart failure are invariably accompanied by clear-cut hemodynamic derangements, the converse is not necessarily true.\textsuperscript{17} For example, following appropriate treatment, the clinical manifestations of cardiac decompensation may clear completely; yet underlying hemodynamic abnormalities may persist at rest or become manifest during mild exercise.\textsuperscript{17}

All five patients with mitral stenosis in heart failure had radiological evidence of pulmonary venous congestion with engorged vascular roots and interstitial edema. The sixth patient, F.S., was studied during an episode of acute pulmonary edema.

Among the seven patients with nonvalvular heart failure in this series, three (W.O’B., G.D. and R.W.), presented all the clinical criteria of pulmonary congestion as well as clinical and hemodynamic criteria of biventricular failure. The criteria constituting evidence for heart failure in the four remaining patients were less complete, but still impressive. All of the hemodynamic criteria for cardiac decompensation were present, that is, very low minute and stroke output, moderate pulmonary hypertension, and marked elevations in left atrial and left ventricular end-diastolic pressures. However, none of the patients was orthopneic or had evidence of pulmonary edema by clinical or radiological examination. Despite this, the histories were
compatible with recent heart failure, and all had various combinations of findings which indicated fluid retention and poor myocardial performance. These signs included tachycardia, narrowed pulse pressures, accentuated pulmonic closure, gallop rhythm, pulsus alternans, elevated venous pressure, and a positive hepatojugular reflex. In two of these patients (J.McE. and R.F.), acute digitalization resulted in dramatic decreases in left and right ventricular end-diastolic pressures and significant increases in cardiac index.

**Pulmonary Blood Volume in Patients with Mitral Stenosis in Heart Failure**

While there has been a wide variability in the clinical material studied, patterns of hemodynamic alterations in mitral valve disease, particularly with respect to changes in PBV, have gradually evolved. Although Dock and associates\(^1\) noted considerable overlap in values for PBV, they were able to correlate elevations in left atrial mean pressure with significant increases in PBV. They also noted that markedly elevated pulmonary vascular resistance was associated with smaller pulmonary blood volumes than would have been expected from the pressure-volume relationship seen in patients with low pulmonary vascular resistance. McGaff and co-workers\(^1\) found appreciable increases in the PBV of patients with clinically and hemodynamically significant mitral stenosis, compared to values found in five normal subjects. Their observations were in agreement with those reported by Dock and associates.

On the other hand, Varnauskas and co-workers\(^1\) did not find a direct correlation between PBV and left atrial mean pressure. In their study, however, the mean value for PBV was 256 ml/m\(^2\) in three class IV patients with rheumatic heart disease involving the mitral valve.

Our own observations upon the variations in PBV in 74 patients with predominant mitral stenosis support and extend the studies of the aforementioned authors. These findings may be summarized as follows: (1) in patients of functional class I and II, the PBV was within normal limits; (2) in patients of class III, significant elevations in mean PBV were encountered; and (3) in patients of class IV, the mean PBV was within the normal range.\(^1\)

In general, concordant changes in PBV and in pulmonary capillary blood volume (Vc) were noted in patients with mitral valve disease. Measurements in 56 patients with mitral valve lesions studied in our laboratory revealed that in class III patients both mean PBV and Vc were usually elevated, whereas in class IV patients both parameters were normal or reduced.\(^1\) Similar findings for Vc in patients with mitral valve disease have been reported by other workers.\(^2\) In the present study, Vc and PBV were determined in patient G.R. The values for each were significantly below normal, being 191.6 ml/m\(^2\) and 135 ml/m\(^2\) respectively.

Resistance to flow in the pulmonary vascular bed may be controlled principally at a localized level such as the pulmonary arterioles. As has been pointed out by Milnor and associates,\(^7\) this may have little effect upon the capacitance function of the pulmonary vascular bed which resides largely in the pulmonary capillary and venous systems. Thus, pulmonary vascular resistance and relative pulmonary vascular compliance need not necessarily be related. Data obtained by these investigators and by ourselves, however, indicate a highly significant inverse correlation between these two parameters.\(^7\) As a group, the patients with heart failure associated with mitral stenosis had the highest mean pulmonary vascular resistance and the lowest mean relative pulmonary vascular compliance.

In these patients, what is the mechanism by which the PBV and Vc remain normal or are reduced? It is well known that with chronic pulmonary venous hypertension, particularly that secondary to mitral stenosis, progressive changes occur within pulmonary blood vessels. Pathophysiological features of these alterations may be outlined as follows:\(^12\) (1) medial hypertrophy, intimal proliferation, and fibrosis of pulmonary arteries and veins which increase with the dura-
tion of pulmonary venous hypertension; (2) interstitial fibrosis, distention of pulmonary lymphatics, and increased lymphatic drainage from the lungs; (3) superimposition of thrombosis-in-situ and thromboembolism; and (4) redistribution of blood flow toward the upper lobes as a result of an increased lower lobe pulmonary vascular resistance associated with interstitial edema.23

Functional vasoconstriction, related in an unknown manner to pulmonary venous hypertension, probably serves to initiate and perpetuate these pathological changes. As a result of these protracted pathophysiological changes, the pulmonary vascular bed becomes considerably restricted from within and without, and right ventricular failure supervenes. This condition is manifested by a decreased cardiac output, markedly elevated pulmonary artery and left atrial pressures, and a nearly normal or reduced PBV and Vc. Under such circumstances, one would expect to find reduced pulmonary vascular compliance and an elevated pulmonary vascular resistance.

Given these circumstances, stresses such as infection, fever, and tachyarrhythmias leading to clinical manifestations of acute pulmonary congestion apparently will result in an inordinate rise in pressure rather than a significant augmentation in PBV. Evidence that such is the case is provided by the six patients whose data are presented in this study. Worthy of reemphasis are the findings in patient F.S. who, while in acute pulmonary edema, had relatively normal PBV (306 ml/m²), but markedly elevated pulmonary artery and left atrial mean pressures (71 and 40 mm Hg, respectively). Further documentation of extreme pressure changes in patients with valvular heart disease studied during acute pulmonary edema is provided from the report of Finlayson and associates from this laboratory.24 In their six patients, the control pulmonary artery mean pressure was 57 mm Hg; during pulmonary edema, 76 mm Hg (three patients); and following recovery, 37 mm Hg (five patients). The pulmonary wedge pressure measured in two patients during pulmonary edema averaged 39 mm Hg.

**Pulmonary Blood Volume in Patients with Nonvalvular Heart Failure**

Correlative studies between right and left heart pressures, PBV and Vc have received scant attention in the past in these patients. In six of our seven patients in this group, the PBV and CBV were normal. Pulmonary artery hypertension in these patients was less marked than in the patients with mitral stenosis. In only two of the seven patients did the pulmonary vascular resistance exceed 240 dynes • sec cm⁻². Relative pulmonary vascular compliance was greater than in the mitral group. In two patients (S.C. and G.D.) in whom PBV and Vc were measured, both values were within the normal range.

How may normal PBV values be explained in these patients? While it is true that many of the pathological lesions noted in pulmonary venous hypertension secondary to left ventricular failure resemble those associated with severe mitral stenosis, the duration of symptoms in the former group of patients, however, was in terms of months rather than of years. Thus, it is reasonable to anticipate less conspicuous pathological changes within the pulmonary vasculature. However, this does not eliminate the possibilities of extravascular fluid accumulations, some interstitial fibrosis, and a significant reduction of flow to dependent portions of the lungs; nor can one be certain that the volume of the pulmonary vascular bed has not been compromised by thromboembolic phenomena.

**Role of the PBV in Congestive Heart Failure**

The data presented in this communication suggest that a revision of the classic concept of the pathogenesis of pulmonary congestion and edema is in order. The basic premise of previous interpretations of both the clinical and pathological manifestations of pulmonary congestion has been an increase in PBV. Our findings indicate, however, that such a change is not a sine qua non of either pulmonary congestion or edema in patients with chronic pulmonary venous hypertension. Since relative
PULMONARY BLOOD VOLUME

Pulmonary vascular compliance is reduced to at least one half the normal value, we believe that significant alterations in the pressure-volume characteristics of the pulmonary vascular bed have occurred in these patients. These changes are compared to pressure-volume characteristics of normal subjects in figure 1. Line A represents the relationship of pulmonary vascular pressure to PBV present in the normal lung in response to two successive exercise loads. During the first exercise period no significant change in PBV, pulmonary artery, or left atrial pressure occurred. When the exercise was repeated, at a greater work load, PBV increased 35% whereas pulmonary vascular pressures did not change. While other data points in normal subjects are not available to extend the curve further to the right, it is probably valid to predict that it would become curvilinear and assume a shape similar to the withdrawal pressure-volume curve obtained in the isolated canine lung studied by Sarnoff and Berglund, that is, at larger PBV, the pulmonary intra-

vascular pressures would be disproportionately greater. It may be that, in patients with normal or nearly normal cardiovascular systems who develop acute left ventricular failure following injudicious use of intravenous fluids or blood transfusion therapy, a larger PBV as well as marked pressure elevations would be present. This hypothesis has received support from experimental observations in the dog recently reported by Levine and associates.

On the other hand, in the presence of chronic pulmonary venous hypertension, the pulmonary vascular bed becomes progressively more restricted by functional as well as structural changes. Pulmonary vascular pressures are elevated compared to PBV. When these patients who are symptomatic but not totally incapacitated, exercise, pressures rise disproportionately (line B, fig. 1). Although only one exercise point is shown, it is probable that the hypothetical curve for these patients bends upward at a lower PBV and a higher pressure than the inflection point of curve A.

Shifted further upward and to the left are the mean resting pressure-volume points of the patients with congestive heart failure included in this paper. The pressure-volume point in patient F.S. during acute pulmonary edema is also indicated. A hypothetical pressure-volume curve for these patients is depicted by line C. We would suggest that the pressure-volume relationships in these patients are such that minor increases in PBV are associated with large pressure elevations in the pulmonary vascular bed. Under these circumstances, pressure elevations rather than augmentation in intravascular PBV dominate the hemodynamic features of heart failure.

Our views regarding the role of the PBV in left heart failure and in mitral stenosis are similar to those expressed by Varnauskas and associates and reiterated by Werko.

From a clinical point of view, it would appear that dyspnea and orthopnea cannot, on the basis of our present knowledge, be construed as specifically related to an elevation in pulmonary vascular volume. We suggest that the crucial operative agents in the pathogenesis of the syndrome of pulmonary

Figure 1

The relationship between pulmonary distending pressure and pulmonary blood volume. Line A shows response of patients with normal hemodynamics to two successive levels of exercise; line B response of patients with significant valvular or primary myocardial disease to exercise, and line C a hypothetical pressure-volume curve derived from data presented in this study; • mean resting value for patients with heart failure associated with mitral stenosis; † mean resting value for patients with nonvalvular heart failure, ▲ value for patient F.S. during acute pulmonary edema. See text for details.
congestion are those which effect changes in pressure as well as those which alter the rate by which fluid can be transferred by this given pressure from the vascular to the extravascular compartment within the lung. Thus, one would predict that changes, if any, in PBV not accompanied by critical pressure elevations would not be associated with clinical features of pulmonary congestion. Such may well be the case in patients with high flow left-to-right shunts. On the other hand, provocative changes in pressure could induce congestive manifestations by the mechanisms postulated above without any significant alteration in intravascular volume. Volume changes, when observed, could thus reasonably be considered a secondary phenomenon, dependent upon the specific pressure-volume characteristics of the pulmonary vascular bed. Furthermore, this hypothesis implies that measures directed toward the treatment of pulmonary congestion and edema will be most effective if they result in a fall in pulmonary intravascular pressures.

Although the concepts presented here add complexity to the understanding of the pathogenesis of heart failure, they serve to emphasize the need for further investigation into the role of the pulmonary blood volume in congestive heart failure.

Summary

By utilizing indicator-dilution techniques, determinations of the pulmonary blood volume (PBV) and central blood volume (CBV) were made in 25 patients during simultaneous right and transseptal left heart catheterization. Of these, 12 patients had normal hemodynamics, six had heart failure associated with mitral stenosis, and seven had heart failure secondary to nonvalvular myocardial disease.

In the normal patients the PBV averaged 271 ml/m² (SE, ± 10.0) and the CBV 596 ml/m² (SE, ± 25.7). The mean value for PBV and CBV in the patients with heart failure associated with mitral stenosis was 235 ml/m² (SE, ± 26.3) and 600 ml/m² (SE, ± 40.9), respectively. Among the patients with nonvalvular heart failure the PBV averaged 292 ml/m² (SE, ± 21.4) while the CBV averaged 679 ml/m² (SE, ± 45.8). In 12 of the 13 patients with heart failure, the individual values for PBV and CBV did not differ significantly from normal. However, in each of the 13 patients pulmonary artery, left atrial, and mean pulmonary distending pressures were significantly elevated, whereas the relative pulmonary vascular compliance was greatly reduced.

These findings indicate that the pressure-volume relationships within the pulmonary vascular bed are greatly altered in the presence of chronic pulmonary venous hypertension. Normal values for PBV were associated with significant pressure elevations in the presence of pulmonary congestion and edema.

It is concluded that in the pathogenesis of heart failure elevations in pulmonary vascular pressures play a dominant role while changes in PBV are of but secondary importance. These findings do not support many of the traditional concepts regarding the role of pulmonary blood volume changes in the pathophysiology of heart failure.

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BERNARD F. SCHREINER, JR., GERALD W. MURPHY and PAUL N. YU

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