A Hemodynamic Study of Left Ventricular Aneurysm

By Michael D. Klein, M.D., Michael V. Herman, M.D., and Richard Gorlin, M.D.

Appendix in collaboration with H. Westcott Vayo, Ph.D.

SUMMARY

Thirteen patients with left ventricular aneurysm due to coronary heart disease were studied by left heart and coronary sinus catheterization, including cineventriculography and measurement of ventricular mechanics and energetics at rest, and in some subjects, during either isoproterenol infusion or supine leg exercise. Eight patients had an aneurysm estimated to comprise greater than 20% of the left ventricular surface area, associated with increased left ventricular end-diastolic volume and pressure and mean systolic force. Average isometric rate of pressure rise and mean fiber shortening velocity and distance were uniformly decreased. Five patients had an aneurysm, estimated to comprise less than 15% of the left ventricular surface, associated with normal or nearly-normal left ventricular end-diastolic volume and pressure and mean systolic force. Average isometric rate of pressure rise was normal, but fiber shortening velocity and distance were moderately depressed. Stroke output and cardiac output were reduced in both groups.

Aneurysms exhibited either paradoxical systolic expansion or apparent lack of motion (akinesis), or both. A theoretical analysis presented indicated that when approximately 20 to 25% of left ventricular area is inactivated by any pathological process, the degree of shortening distance required of the myofiber to maintain stroke volume exceeds physiological limits, and cardiac enlargement (Starling mechanism) must ensue to maintain adequate ejection of blood.

The magnitude of the salutary response of isoproterenol coupled with an increase in mechanical efficiency during catecholamine infusion suggested that myocardial catecholamines were depleted with additional aggravation of heart failure in this disease.

Additional Indexing Words:
Isoproterenol Congestive heart failure Coronary disease
Cardiac dilatation Catecholamines

Left ventricular aneurysm was first described in the eighteenth century.1 In 1816, Cruveilhier2 attributed ventricular aneurysm to myocardial fibrosis, although its association with coronary thrombosis was not generally appreciated until a century later.3 It was not until Tennant and Wiggers4 showed paradoxical motion in acutely ischemic myocardium that the physiological implications of a ventricular injury became apparent. Subsequently, Murray described systolic paradoxical expansion of acutely infarcted myocardium and correlated this with diminished cardiac output and falling blood pressure.5

The importance of wall compliance in determining paradoxical motion was studied in dogs with experimentally created aneurysms of differing expansile characteristics.6 Variation in size of aneurysms has been studied by means of left ventricular function curves.7

From the Cardiovascular Research Laboratory, Department of Medicine, Peter Bent Brigham Hospital and Harvard Medical School, Boston, Massachusetts.

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Aneurysms created from homologous dog bladder tissue (30 to 60-ml capacity) depressed stroke output by an average of 31%. Cardiac and stroke outputs could be maintained at control levels only with considerable elevation of diastolic filling pressure. Clinically, the hemodynamic importance of the size and compliance of an aneurysm has also been suggested by the remarkable postoperative reduction in left ventricular filling pressure in patients undergoing aneurysmectomy.

Much less is known concerning the way in which myocardial infarction relates to the genesis of aneurysm. Lowe and Love devised mathematical models indicating that acute infarction and the ensuing liquefaction necrosis predisposed to localized increase in myocardial tensile stress. According to this view, formation of aneurysms is determined primarily by the amount of local wall thickness actually necrosed, and only to a lesser extent by the total surface area involved in the infarct. Such reasoning has been invoked to help explain the high incidence of aneurysm at the apex where wall thickness is less than in basal portions of the left ventricle.

Ventricular performance is the end result not only of location, size, shape, and wall compliance of the aneurysm itself but also of the reserve of the remaining viable muscle which in turn will be greatly influenced by the extent, location, and nature of the coronary artery disease present.

To assess the interrelationships of some of these factors, 13 cases of ventricular aneurysm due to proven coronary artery disease were studied by selective cine coronary angiography and cine left ventriculography, in addition to left heart and coronary sinus catheterization.

Methods

Of 13 patients, four patients had apical aneurysms; eight had anterior aneurysms, and one patient had an inferior aneurysm. All had extensive coronary artery disease with involvement of the principal, and at least one subsidiary, vessel to the aneurysmal area. Clinical and pathological details of these patients are reported as part of a larger series. Catheterization of the left ventricle was performed through multiple-hole closed-tip catheters. Selective left and right coronary cineangangiography was carried out via the Sones technique. Myocardial blood flow was measured using the 85Kr indicator method, with instillation of the indicator either into the left ventricle or directly into the coronary artery with sampling from a catheter in the coronary sinus.

Thermodilution left ventricular end-diastolic volumes (LVEDV) were measured in three subjects. The error in computing LVEDV was less than 3% for the ejection fraction and stroke volume applicable to this group of patients. LVEDV was also calculated angiographically in all cases, based on uniplanar modification of the methods of Arvidsson and Dodge and associates. Ventriculograms were taken in the 30° right anterior oblique projection with a set x-ray tube-to-table top distance; the center of field distortion was less than 5%.* Cardiac apex level (assumed to be midventricular) was estimated and subsequent cine films of a grid calibrated with 1-cm markings were made at this level. At the time of data analysis, the projected distance of this grid image was adjusted until actual and projected measurements were matched to provide life-size, projected left ventricular silhouettes. A second method of calibration employed adjustment of the projected width of the catheter filmed in the middle of the left ventricle to its actual width. Area (A) of the end-diastolic opacified image was obtained by planimetry. The long axis (L) (apex to aortic valve) was measured directly. Average width (W) was then calculated from the equation for area of an ellipse, where

\[ W = \frac{4A}{\pi L} \]

LVEDV was then derived assuming the ventricle to approximate an ellipsoid of revolution: LVEDV = \[4/3\pi \left( \frac{W}{2}\right)^2 \cdot \frac{L}{2}\].

Angiographic determination of heart volume was confined to LVEDV because this value agreed closely with similar measurements calculated from thermodilution technique (fig. 1). End-systolic volume (LVESV) was calculated by subtracting stroke volume (SV) from LVEDV. SV was computed by dividing the cardiac output of indocyanine-green dye by heart rate. Cardiac output was measured just prior to the cineventriculogram with constant monitoring of pressure and pulse.

Whenever the aneurysm profile appeared as a distinct projection on the cineventriculogram,

*C. General Electric Image Intensifier System.
the volume of aneurysm was estimated separately from total LVEDV. The ratio of the aneurysmal volume to total LVEDV was determined by idealizing each aneurysmal silhouette to that of a hemisphere. If an aneurysm were confined solely to the lateral wall or midventricular septum, it would not be apparent in the projection used. However, if one were present, it would only magnify the abnormalities already described.

Pressures were recorded on a Sanborn 560 polybeam photographic recorder. Zero reference level was 10 cm above the level of the catheterization table.

Left Ventricular Function

Left ventricular function was assessed according to the following parameters:

**Average Isovolumic Rate of Rise of Pressure** ($\Delta p/\Delta t$)

$$\Delta p/\Delta t = \frac{L V_{el} - LVED}{t_{el} - t_{ed}}, \quad (1)$$

where

$L V_{el} =$ left ventricular end-isometric pressure (aortic valve opening), mm Hg,

$LVED = $ left ventricular end-diastolic pressure, mm Hg,

$t_{el} = $ left ventricular end-isometric time, sec,

$t_{ed} = $ left ventricular end-diastolic time, sec.

Only this average measurement and not true $dp/dt$ was calculated because ventricular pressures were recorded through a catheter-manometer system, and thus subject to unassessed artifact which might invalidate instantaneous, but not necessarily average measurements. No patient had mitral insufficiency, and end-isometric pressure varied within a narrow range (60 to 80 mm Hg).

**Left Ventricular Stroke Work Index** ($LVSW$)

$$LVSW \ (g \cdot m/ht/m^2)_{20} = \frac{(1.36) \ (Psm) \ (SI)}{100}, \quad (2)$$

where

$Psm = $ left ventricular systolic mean pressure, mm Hg

$SI = $ stroke index, ml/m^2

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Mean Systolic Force (Fsm)

\[ F_{\text{sm}} \ (\text{dynes}) = 4\pi r_{\text{sm}}^2 \times P_{\text{sm}} \times 1332 \text{ dynes} \]  

where 
\[ r_{\text{sm}} = \text{mean systolic radius, cm.} \]

Mean Circumferential Fiber Shortening

Distance (MCSD), cm = \[ 2\pi (r_{\text{ed}} - r_{\text{es}}) \]  

Rate (MCSR), cm/sec = \[ 2\pi \frac{r_{\text{ed}} - r_{\text{es}}}{\text{sep}} \]

where 
\[ r_{\text{ed}} = \text{end-diastolic radius, cm} \]
\[ r_{\text{es}} = \text{end-systolic radius, cm} \]
\[ \text{sep} = \text{systolic ejection period, sec.} \]

Mean Systolic Ejection Rate (MSER)

\[ \text{MSER} \ (\text{ml/sec/m}^2) = SI/\text{sec}. \]

Utilizing the cineventriculographic ejection pattern from end diastole to end systole and equating this pattern with stroke volume as determined by indicator dilution, the change in ventricular volume during systole was determined at intervals of 33 msec (1 cine frame), in a patient with aneurysm, and at 16-msec intervals in a normal subject. By modification of equations 3 and 4, curves for instantaneous force and fiber shortening during systole were derived.

Myocardial arteriovenous oxygen difference was determined manometrically (ml/L). Myocardial oxygen extraction, oxygen consumption and myocardial mechanical efficiency were calculated.

Each patient was studied at rest; observations were made during infusion of isoproterenol (1-4 \( \mu \text{g/min} \)) in 10 subjects. Hemodynamic measurements were made during the fifth minute of supine exercise on a bicycle ergometer on four occasions.

Hemodynamic data are given in tables 1 to 3.

Results

Increased Left Ventricular End-Diastolic Pressure

In eight of 13 subjects, left ventricular end-diastolic pressure (LVEDP) was elevated, ranging from 18 to 30 mm Hg. LVEDV was consistently increased 160 to 300 ml/m² or one and one-half to three times normal (100 ± 20 ml/m²) (fig. 2).

Mean \( \Delta p/\Delta t \) was subnormal in most of these subjects, ranging from 480 to 1000 mm Hg/sec with an average of 635 (normal

\[ 1,200 \pm 200 \text{ mm Hg/sec}^* \]. The left ventricle shortened an average of 5% of initial or end-diastolic circumference (normal 15 ± 5%). Despite increased heart size (fig. 3), this pronounced limitation in circumferential shortening resulted in marked reduction in average stroke output (28 ml/m²), and hence cardiac output (2.0 L/min/m²). Residual fraction (LVESV/LVEDV) varied from 0.77 to 0.87 (normal 0.56 ± 0.06). Estimated end-systolic volume was markedly increased.

Systolic force was increased to an average of 39 \( \times 10^6 \) dynes/beat (normal 18 \( \times 10^6 \)). MCSD and MCSR averaged 1.1 cm and 4.0 cm/sec, respectively, both markedly subnormal. Sequential force-time and fiber shortening-time curves in one patient with apical aneurysm were compared with data from a normal subject (fig. 4). There was a marked delay in time-to-peak force and a fiber shortening rate one third that of the normal at nearly all points during systole. Contractile element velocity, which equals fiber shortening velocity at the time of peak force, was markedly depressed compared with findings in the normal subject.

*Calculated directly from pressure curves of 25 subjects with no demonstrable heart disease following diagnostic catheterization. This is comparable to slopes calculated from data of Gleason and Braunwald obtained with intracardiac manometer.
### Table 1

**Left Ventricular Dynamics and Energetics at Rest**

<table>
<thead>
<tr>
<th>Case</th>
<th>Heart rate (per min)</th>
<th>Cardiac index (l/min/m²)</th>
<th>Stroke index (ml/m²)</th>
<th>Pressure (mm Hg)</th>
<th>Volume (ml)</th>
<th>Aneurysm, Vol. (%)</th>
<th>Mean systolic ejection rate (ml/sec)</th>
<th>βp AΔ (mm Hg/sec)</th>
<th>Coronary flow (ml/100g/min)</th>
<th>Oxygen consumption (ml/100g/min)</th>
<th>Mechanical efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>74</td>
<td>1.8</td>
<td>25</td>
<td>120</td>
<td>390</td>
<td>130</td>
<td>33</td>
<td>92</td>
<td>520</td>
<td>73</td>
<td>7.9</td>
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<tr>
<td>2</td>
<td>69</td>
<td>1.8</td>
<td>27</td>
<td>90</td>
<td>418</td>
<td>50</td>
<td>12</td>
<td>95</td>
<td>900</td>
<td>67</td>
<td>7.1</td>
</tr>
<tr>
<td>3</td>
<td>68</td>
<td>1.6</td>
<td>23</td>
<td>83</td>
<td>505</td>
<td>125</td>
<td>25</td>
<td>95</td>
<td>550</td>
<td>57</td>
<td>6.8</td>
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<tr>
<td>4</td>
<td>70</td>
<td>2.2</td>
<td>31</td>
<td>106</td>
<td>485</td>
<td>135</td>
<td>28</td>
<td>97</td>
<td>560</td>
<td>80</td>
<td>6.4</td>
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<td>5</td>
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<td>2.6</td>
<td>35</td>
<td>98</td>
<td>580</td>
<td></td>
<td>144</td>
<td>480</td>
<td>75</td>
<td>9.5</td>
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<tr>
<td>6</td>
<td>79</td>
<td>2.1</td>
<td>26</td>
<td>97</td>
<td>235</td>
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<td>81</td>
<td>450</td>
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<tr>
<td>7</td>
<td>72</td>
<td>2.1</td>
<td>29</td>
<td>119</td>
<td>340</td>
<td></td>
<td>96</td>
<td>630</td>
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<tr>
<td>8</td>
<td>83</td>
<td>2.3</td>
<td>28</td>
<td>138</td>
<td>300</td>
<td>50</td>
<td>16</td>
<td>100</td>
<td>1000</td>
<td>88</td>
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<td>86</td>
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<td>23</td>
<td>110</td>
<td>260</td>
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<td>13</td>
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<td>100</td>
<td>165</td>
<td>10</td>
<td>6</td>
<td>146</td>
<td>1000</td>
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<td>155</td>
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<td>2.3</td>
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<td>123</td>
<td>192</td>
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<td>5</td>
<td>77</td>
<td>1450</td>
<td>76</td>
<td>9.1</td>
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<tr>
<td>13</td>
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<td>1.8</td>
<td>26</td>
<td>121</td>
<td>190</td>
<td>10</td>
<td>5</td>
<td>96</td>
<td>52</td>
<td>7.1</td>
<td>19</td>
</tr>
</tbody>
</table>
Regional contributions to ejection were determined in another subject with apical aneurysm. As shown in figure 5, one can analyze temporal motion in any given minor axis and also estimate the contribution to systolic ejection of shortening along that minor axis per centimeter of length along the major axis. Note the relatively uniform emptying in the

Table 2

**Left Ventricular Mechanics**

<table>
<thead>
<tr>
<th>Patient</th>
<th>Mean systolic force (dynes X 10^6)</th>
<th>Mean circumferential fiber shortening</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Distance (cm)</td>
<td>Rate (cm/sec)</td>
</tr>
<tr>
<td>Increased left ventricular end-diastolic pressure</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>44</td>
<td>0.8</td>
</tr>
<tr>
<td>2</td>
<td>30</td>
<td>1.1</td>
</tr>
<tr>
<td>3</td>
<td>32</td>
<td>0.8</td>
</tr>
<tr>
<td>4</td>
<td>40</td>
<td>1.1</td>
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<td>1.3</td>
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<td>6</td>
<td>21</td>
<td>1.4</td>
</tr>
<tr>
<td>7</td>
<td>34</td>
<td>1.6</td>
</tr>
<tr>
<td>8</td>
<td>36</td>
<td>2.2</td>
</tr>
<tr>
<td>Normal left ventricular end-diastolic pressure</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>26</td>
<td>1.7</td>
</tr>
<tr>
<td>10</td>
<td>17</td>
<td>1.9</td>
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<tr>
<td>11</td>
<td>22</td>
<td>1.3</td>
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<tr>
<td>12</td>
<td>22</td>
<td>2.3</td>
</tr>
<tr>
<td>13</td>
<td>18</td>
<td>2.1</td>
</tr>
<tr>
<td>Mean ± SEM</td>
<td>30 ± 2.4</td>
<td>1.5 ± 0.13</td>
</tr>
<tr>
<td>Normal</td>
<td>17</td>
<td>4.0</td>
</tr>
</tbody>
</table>

Table 3

**Effects of Isoproterenol on Aneurysm**

<table>
<thead>
<tr>
<th>Effect on</th>
<th>Rest</th>
<th>Isoproterenol</th>
<th>Mean</th>
<th>Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heart rate (per min)</td>
<td>76</td>
<td>Isoproterenol</td>
<td>96</td>
<td>±7</td>
</tr>
<tr>
<td>Cardiac index (L/min/m²)</td>
<td>Rest</td>
<td>Isoproterenol</td>
<td>2.0</td>
<td>±0.3</td>
</tr>
<tr>
<td>Stroke index (ml/beat/m²)</td>
<td>Rest</td>
<td>Isoproterenol</td>
<td>3.2</td>
<td>±0.5</td>
</tr>
<tr>
<td>Left ventricular systolic mean pressure (mm Hg)</td>
<td>Rest</td>
<td>Isoproterenol</td>
<td>117</td>
<td>±22</td>
</tr>
<tr>
<td>Left ventricular end-diastolic pressure (mm Hg)</td>
<td>Rest</td>
<td>Isoproterenol</td>
<td>11</td>
<td>±23</td>
</tr>
<tr>
<td>Mean systolic ejection rate (ml/sec/m²)</td>
<td>Rest</td>
<td>Isoproterenol</td>
<td>91</td>
<td>±12</td>
</tr>
<tr>
<td>Coronary flow (ml/100 g/min)</td>
<td>Rest</td>
<td>Isoproterenol</td>
<td>67</td>
<td>±14</td>
</tr>
<tr>
<td>O₂ consumption (ml/100 g/min)</td>
<td>Rest</td>
<td>Isoproterenol</td>
<td>95</td>
<td>±19</td>
</tr>
<tr>
<td>Mechanical efficiency (%)</td>
<td>Rest</td>
<td>Isoproterenol</td>
<td>137</td>
<td>±33</td>
</tr>
</tbody>
</table>

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normal subject. In the patient with apical aneurysm, nearly all ejection occurred from an augmented contraction of the base of the heart. Stroke volume was further enhanced in the subject with aneurysm because ejection began from a larger initial or end-diastolic radius.

Normal Left Ventricular End-Diastolic Pressure

Five patients manifested normal or borderline elevated LVEDP, together with normal or only slightly augmented LVEDV (fig. 2). Fsm was normal in four of these patients, but both MCSD (1.3 to 2.3 cm) and MCSR (4.6 to 7.8 cm/sec) were moderately depressed (table 2). Again, the limited decrement in chamber size during systole resulted in a low average stroke output (24 ml/m\(^2\)) as well as cardiac output (2.0 L/min/m\(^2\)). Mean Δp/Δt averaged 1130 mm Hg/sec (range 850 to 1450).

Volume of Aneurysm in Relation to Volume of Left Ventricle

The size of the aneurysm could be estimated separately from total LVEDV in 10 patients. No detectable change in size was seen throughout the cardiac cycle in eight, while in two, paradoxical expansion was observed. Left panel (fig. 6) shows that the volume of the left ventricle increased with the volume of the aneurysm. In center panel the ratio of surface area of aneurysm to surface area of the left ventricle in diastole is plotted against LVEDV. LVEDV was 150 ml/m\(^2\) or
LEFT VENTRICULAR ANEURYSM

Figure 4

Force and fiber shortening rate (FSR) curves (during a single cardiac beat). The arrow signifies fiber shortening velocity at the point of maximal systolic force. The broken lines define ejection period. See text.

Figure 5

Regional contribution to stroke output. For this demonstration, a cylinder was assumed and base-to-apex shortening ignored. This relationship was expressed as \( \Delta V = 2\pi L r \Delta r + b \), where \( \Delta V \) = change in volume; \( L \) = long axis; \( r \) = minor hemi-axis; \( \Delta r \) = change in minor axis; \( b = 2\pi L (\Delta r) \). The right anterior oblique projection of the calibrated left ventricular silhouette is shown for a normal patient (N) and for a patient with aneurysm (A). The major axis runs from bisected base of aortic valve to apex. Length of minor hemi-axes, that is, \( N_1, 2, 3, 4 \), was measured from calibrated consecutive cine frames and plotted as length (ordinate) versus time in systole (abscissa). Note the uniform motion of all hemi-axes of the normal heart with uniform ejection at both apex and base of 10 ml/cm of length along the long axis, respectively. Note the lack of motion of the apex of the aneurysmal heart (\( A_1, 2, 3, 4 \)) with increased motion at the base (\( A_1, 4 \)). This resulted in ejection of 20 ml/cm length along the major axis at base, but only 2.5 ml/cm of length at apex.

more in the five patients in whom aneurysm-to-chamber surface area ratio exceeded 20%. The volume was normal in four of five subjects with small aneurysms (11 to 15% ratio). The right panel shows surface area ratio plotted against LVEDP. EDP exceeded normal limits in all subjects with inactive surface area exceeding 20%. Figure 7 shows a similar result when aneurysm-to-chamber volume ratios are plotted against LVEDP.

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Figure 6

Relationship between size of aneurysm and left ventricular end-diastolic volume (LVedv) and pressure (LVedp). Size of aneurysm is expressed both as a volume and as a ratio of surface area of aneurysm to surface area of end-diastolic left ventricle. Note the increase in both LVedv and DVedp with increase in surface area ratio beyond 20%.

Figure 7

Relationship between aneurysm volume as the percentage of total left ventricular volume and left ventricular end-diastolic pressure. Size of aneurysm and height of end-diastolic pressure tended to vary together.

Effect of Isoproterenol and Exercise

Isoproterenol infusion (1 to 4 µg/min) reduced elevated LVEDP to normal or near-normal values and increased stroke volume an average of 49% (fig. 8). Stroke work increased (fig. 9) more than myocardial oxygen consumption (table 3), and myocardial efficiency was augmented from 5 to 13% in six

Figure 8

Stroke volume plotted against left ventricular end-diastolic pressure. Isoproterenol infusion produced an increase in stroke volume and decrease in end-diastolic pressure in virtually all subjects. By contrast, exercise increased end-diastolic pressure with little change in stroke volume.
instances. Mean systolic ejection rate rose in all patients from 53 to 92% (normal increment, 47%).

Left ventricular end-diastolic pressure rose an average of 25 mm Hg at rest to 37 mm Hg during exercise. Left ventricular systolic mean pressure rose from 90 to 105 mm Hg. The response of stroke work and volume are depicted in figures 8 and 9.

Discussion

Wiggers24 considered ventricular contraction to result from sequential activation of fractionate units of myocardium. This may be termed "myocardial synergy."* Wiggers also suggested that disease in a local region of the heart could disturb the effectiveness of contraction through interruption of coordinated effort. Harrison26 has recently amplified this concept, and the word "asynnergy" has been applied to uncoordinated ventricular contraction.

Such disorders of ventricular systolic motion have yet to be quantified in a clinical setting. The present discussion confines itself to an analysis of two specific types of asynnergy seen as a consequence of ventricular aneu-

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*Myocardial synergy may be defined as the cooperative and sequential contraction of heart muscle mass in such a way as to produce maximum effective work at a minimum cost of energy.

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Figure 9

Stroke work plotted against left ventricular end-diastolic pressure. The directional findings are similar to those in figure 8.

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wall and prevent its expansion. The nonexpansile properties of the wall were frequently confirmed during cardiac surgery. A rigid aneurysm may act to “splint” the normal heart wall during contraction and thus to dissipate the inward vector of circumferential shortening. Although the aneurysm often did not appear to bulge during systole, there may have been parallel, and therefore, imperceptible elastic stretch at the border of the aneurysm where it joined normal muscle. Thus, there may be a continuum between pure dyskinesia and pure akinesis as mechanical defects.

Surface Area of Aneurysm

When the myocardium in an aneurysmal area functions improperly or has been replaced by fibrosis, local tension development and fiber shortening are restricted or absent. Stroke volume will then fall. In order to maintain constant stroke volume, myocardial fibers extrinsic to the aneurysm must increase their extent of shortening. A quantitative expression of the progressively increasing fiber shortening requirements, resulting from a progressively increasing akinetic ventricular surface, has been derived in the “Appendix” and is displayed graphically in figure 10 (see also fig. 13). In our own cases and in the model,27 when aneurysmal area approached 20 to 25% of the surface area of the left ventricle, the extent of shortening required of the remaining functioning heart began to exceed physiological limits (approximately 30% of maximum initial muscle length). As a consequence, stroke volume must fall. This situation may be further aggravated by two considerations.

1. The involved area may not only be nonfunctioning, but also may expand paradoxically. Because of the translocation of blood during systole, this will further increase the mechanical burden resulting from any given amount of immobile surface.

2. The functioning muscle itself is often affected, to varying degrees, with the underlying ischemic process and may be unable to compensate effectively. In this series, the coronary arteries supplying the contracting portions of the myocardium were free of obstructive disease in only five of the 13 cases.

Site of Aneurysm

No hemodynamic effect of the site of aneurysm per se was immediately apparent in this small series.

Other Possible Mechanisms Adversely Affecting Stroke Volume

1. Mitral Incompetence. This was not observed in this group of patients.

2. Atrioventricular Asynchrony. Normal papillary muscle function is considered important, not only to close the mitral valve, but also to prime isovolumic contraction. Several aneurysms were so situated, possibly as to interfere with anterior papillary muscle function.

3. Asynchrony. The temporal sequence of contraction influences ventricular performance, but asynchrony was not identified in these patients.

Quantification of Myocardial Involvement in Relation to Cardiac Dilatation

Left ventricular end-diastolic volume was markedly increased when the aneurysm comprised 20 to 25% of the ventricular surface area.* This fact had broad implications. For the first time it has been possible to quantify the degree of heart disease leading to ventricular dilatation. Just as a critical mitral or aortic valve size exists beyond which transvalvular flow cannot be increased owing to physiological limitations in pressure-generating capacity,28 so a critical aneurysm size exists beyond which stroke output cannot be maintained because of physiological limitations in myocardial fiber shortening capacity. Figure 10 illustrates that when 20 to 25% of ventricular surface area becomes akinetic, dilatation must ensue if the limits of fiber

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*This obtains whether or not the aneurysm is saccular with a volume of its own and is primarily a measure of the burden placed on normally active muscle.
shortening of healthy muscle are not to be exceeded.*

*Assuming the left ventricle to have a spherical configuration of a given end-diastolic size with radius \( r \), then stroke volume can be designated as \( dV = 4\pi r^2 \text{dr} \). If \( \text{dr} \) (shortening) is exceeded, \( dV \) (stroke volume) can be maintained by increase in initial length, \( r \). The larger heart can now deliver a given stroke volume with less fiber shortening.

**Inadequacy of Hemodynamic Compensation**

*Increased End-Diastolic Volume*

According to the Frank-Starling hypothesis, increased ventricular size should lead to increased stroke volume and effective work. This did not occur. Composite shortening equalled only 5% of initial length, and hence, stroke volume was reduced although the left ventricle was large. Actually, since large areas of ventricular surface area remained virtual-

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**Figure 10**

*Relationship between percentage of circumferential shortening and per cent of inactive muscle (expressed as percentage of left ventricular surface area). The horizontal lines define average range and maximal degree of fiber shortening. The curve to the left defines the degree of shortening necessary in a normal-sized left ventricle expelling 45 ml/m². Note that 17% shortening is required if all muscle is active (0 on abscissa). As progressively more muscle is inactivated, the degree of shortening finally exceeds physiological limits. This is reached when inactive muscle comprises about 20% of surface area. Stroke volume can no longer be maintained. The second curve indicates that a normal degree of shortening can deliver only a small stroke volume from this ventricle with 20% limitation. A normal stroke volume at this same degree of muscle inactivation can only be maintained by increase in end-diastolic volume as in the third curve (EDV = 200). Finally, even such an increase in volume does not permit delivery of a normal stroke volume if shortening is now impaired. This latter state was commonly observed in this series.*
ly immobile throughout systole, regional changes in circumferential fiber shortening of healthy muscle ranged from 6 to 12%; this was still far less than the 12 to 18% observed in normal subjects at rest. Figure 5 indicates quantitatively how the lack of regional contraction and resultant compensation elsewhere in the heart affected ejection. Despite ventricular dilatation acting geometrically to expel more blood for the same degree of shortening and also to augment contraction, myocardial decompensation was clearly evident. Herein lies a fundamental problem: The very increase in heart size occasioned by dilatation and deformation of the aneurysm increases the radius of curvature of the ventricle and, hence, myocardial systolic tension requirements (average two to two and a half times normal), but only a portion of the myocardium is available to respond to increased stretch. The effects of afterload* to inhibit ejection may have exceeded the effects of preload* to increase it.

**Effects of Cathecholamines**

Myocardial performance is normally augmented by catecholamines with positive inotropic action, either liberated from cardiac sympathetic nerves or circulating in the blood. There results an increase in minute and stroke output with usually a fall in left ventricular end-diastolic pressure. Isoproterenol produced similar effects in these patients with congestive failure due to aneurysm, but the effects were quantitatively more marked than those seen in normal subjects, or patients with heart disease but not in failure. In fact, by contrast, in some patients with coronary heart disease without failure, administration of catecholamines resulted in actual deterioration in cardiac performance. Paradoxically, the salutary effect did not appear to be dependent on the state of coronary supply to the unaffected myocardium. Six of 10 patients had extensive obstruction in all branches of the coronary system.

The magnitude of the beneficial effect may have been due to transient repletion of myocardial catecholamine content which has been shown to be reduced in heart failure. Reduction in catecholamine content can also deprive the myocardium of a crucial compensatory mechanism for effects of disease. This may have contributed to the low output state of these patients with aneurysm. Isoproterenol increased myocardial consumption of oxygen in normal man, but with no change in mechanical efficiency. In patients with aneurysm and heart failure, however, the rise in left ventricular oxygen consumption was proportionally less than in patients with normal hearts, with resulting calculated increase in efficiency. Cathecholamine increased energy cost predominantly by marked augmentation in shortening velocity, which occurred in both groups of patients. In the aneurysm group, however, isoproterenol induced a simultaneous marked reduction in cardiac size (and mean systolic force), so that the fraction of energy cost ordinarily related to systolic tension development was reduced.

**Theoretical Force-Velocity-Length Considerations**

Muscular contraction is currently described in terms of the Hill model: a contractile element (CE) in series with an undamped series elastic element (SEE), which has a force-dependent stiffness. Muscle contraction involves stretching of the SEE by the CE during force generation (isometric contraction), and subsequent shortening of the fiber during continued CE shortening (auxotonic contraction). A fundamental characteristic governing contraction is the inverse force-velocity relationship at any given length.

A dilated left ventricle requires increased wall tension to maintain a given pressure. Less contractile element shortening, however, is required because the force-dependent SEE is stretched faster and more blood is ejected per unit shortening at a larger size. Not only is the absolute force increased in

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*Afterload = ventricular wall tension during systole generated by interaction of ventricular ejection and outflow resistance; preload = end-diastolic tension existing within the myocardial wall just prior to activation.*

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the patient with aneurysm and cardiac dilatation, but the time course of the systolic load is shifted (fig. 4). Unlike the normal left ventricle where force begins to decline about 80 msec after inception of systolic ejection, the ventricle with aneurysm labors with a progressively increasing force throughout two thirds of systole. This is further aggravated if, in addition, the aneurysm acts as a compliant series elastic element. At the same time instantaneous volume, and therefore, fiber length are decreasing (however little), as blood is ejected from the heart. Consequently, the ventricle shifts to progressively less effective force-velocity curves, and contractile element velocity is further inhibited. Therefore, the prolonged time course of the systolic load associated with ventricular aneurysm will tend to reduce CE shortening and power, quite apart from the absolute elevation in mean systolic force.

The course of force development depends on the speed of onset of active state as well as the CE-SEE interrelationships. For heart muscle, the onset and decline of the active state are time-dependent with maximum intensity attained at, or shortly before, the point of maximum isometric force and with a slow subsequent decline. The active state has been assessed in terms of velocity of shortening and correlated with time elapsed between resting and peak isometric tension, and equated with maximum dp/dt, the rate of isometric pressure change.

Although no measurements of dp/dt were available in the present series, the average rate of rise of isovolumic left ventricular pressure was calculated. Striking reductions in ∆p/∆t, seen particularly in patients with large aneurysms, signified a reduced average rate of tension development of the composite left ventricle. This could have arisen from any of the following factors: (1) the series’ elastic effect of slackness of the aneurysm; (2) variation in regional instantaneous wall tension resulting in contraction in one area and expansion in another; and (3) reduction in the maximally achieved intensity of the active state.

Appendix

The model of ventricular aneurysm developed below presupposes that interaction between areas of myocardium intrinsic and extrinsic to the aneurysm itself can best be described by arbitrary division of the ventricular wall surface into a totally noncontracting (akinetie) region and a remaining portion with perfectly normal fiber shortening potential. It is recognized that the contractile properties of supposedly normal myocardium may, in fact, be somewhat altered because of insufficiencies in local coronary blood supply and local myocardial fibrosis. To simplify analysis, the ventricular chamber has been assigned the shape of a sphere, though it more normally resembles a prolate spheroid, or in the case of a given aneurysm, a somewhat more complex geometric form.

Figures 11 and 12 illustrate a chamber of given left ventricular end-diastolic volume (LVEDV) with a corresponding radius, r. The angles θ and φ are the central angles, whose vertices are at the center of the sphere, subtended by the diameter of a circular patch or the sides of a rectangular patch of akinetic myocardium. During systole, ventricular size diminishes concentrically.
trically (θ and φ remaining constant), save for that portion of the ventricular surface immobilized by aneurysm. Left ventricular end-systolic volume (LVESV) will have a corresponding radius of r excepting that portion of the ventricular surface determined by θ which remains fixed at end-diastolic length, r, from the center of the chamber.

Mathematics of the Circular Case

Assume stroke volume to be constant:

\[ SV = LVEDV - LVESV = \alpha \] on the basis of the spherical model adopted (1)

\[ LVEDV = \frac{4}{3}\pi r^3, \]

\[ LVESV = \left(\frac{2}{3}\pi r^3 \left(1 - \cos \frac{\theta}{2}\right) + \frac{4}{3}\pi r'^3\right) - \left(\frac{2}{3}\pi r^3 \left(1 - \cos \frac{\theta}{2}\right)ight) \]

\[ \alpha = \left[ \frac{2}{3}\pi \left(1 + \cos \frac{\theta}{2}\right) \right] \times (r^3 - r'^3). \]

Equation 4 gives a relation between r, r', θ and α which can be used to solve for any one of them when the other three are known. If equation 4 is solved for θ, then it is possible to find the area (A) of an immobile zone on the surface of the end-diastolic sphere:

\[ A = 2\pi r^2 \left(1 - \cos \frac{\theta}{2}\right). \]

The percentage of total end-diastolic surface so immobilized or inactive can be found from the relation:

\[ \text{(% inactive muscle)} \]

\[ \text{PIM} = \frac{2\pi r^2 \left(1 - \cos \frac{\theta}{2}\right)}{4\pi r^2} \times 100 \]

\[ = \frac{1}{4}\left(1 - \cos \frac{\theta}{2}\right) \times 100. \]

Mathematics of Rectangular Case

By similar reasoning, it is possible to determine the percentage of inactive muscle for rectangular aneurysms.

\[ \text{PIM} = r^2\phi/4\pi r^2 \times 100 = \phi/\pi \times 100. \]

Example: From equation 6 various areas are determined for various PIMs and a given r. Since α, θ, and r are known, equation 4 may be solved for the different end-systolic radii. A computer was programmed for average normal human values with LVEDV = 100 ml/m^2 and SV or α = 45 ml/m^2. PIM was varied in 1% increments from 0 to 50%. Percentage shortening of muscle extrinsic to the immobile aneurysm was determined as:

\[ \text{PSM (% shortening of muscle)} = 100 \left(1 - \frac{r'}{r}\right). \]

Figure 13 shows the interrelation of PIM to PSM for two curves representing aneurysms of different configuration, that is, circular versus rectangular. The salient features are that with PIM greater than 20 to 25% (depending on actual shape of aneurysm), ventricular enlargement must occur to ensure physiological values of PSM if SV is to be maintained.

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Myocardial Architecture—Harvey, 1628

All Anatomists have observ'd with Galen, that the body of the heart is made with several draughts of fibers streight, thwart, and crooked, but in a heart, being boyld, the structure of the fibers is found to be otherwayes.

For all the fibers in the walls and in the inclosure are circular, as they are in a Sphincter, but those which are in the tendons stretched out in length, are crooked; so it comes to pass that when all the fibers are contracted, it happens that the top is brought to the bottom by the tendons, and the walls are inclosed in a round, and the heart is contracted every way, and the ventricles strengthened. Wherefore since the action of it is contraction, we must needs imagin that the function of it is to thrust blood out into the arteries.—The Anatomical Exercises of Dr. William Harvey; De Motu Cordis 1628; De Circulatione Sanguinis 1649 (first English text). Edited by Geoffrey Keynes. London, The Nonesuch Press, 1653, p. 114.
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