Haemodynamics of exercise in children with isolated aortic valvular disease

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Left ventricular haemodynamics were studied both at rest and during supine exercise in 33 children with isolated aortic valvular disease, either aortic stenosis or aortic insufficiency. In each child cardiac index and stroke index were normal at rest. Exercise response was characterized in 32 patients by an increase in cardiac index without a major increase in left ventricular end-diastolic pressure. Only one patient showed an abnormal exercise response. In each patient with aortic stenosis an increase in peak left ventricular systolic pressure occurred on exercise, while no predictable change occurred among patients with aortic insufficiency. Left ventricular end-diastolic pressure was greater in patients with more severe stenosis or with significant aortic insufficiency.

The exercise response in adult patients with aortic valvular disease has been studied by several authors (Goldberg, Bakst, and Bailey, 1954; Gorlin et al., 1955; Braunwald et al., 1963; Anderson et al., 1969; Lee et al., 1970; Bache, Wang, and Jorgensen, 1971). Many of these reports, however, have described observations in patients with aortic disease coexisting with other types of valvular heart disease, as occurs after rheumatic fever. Only 2 (Lee et al., 1970; Bache et al., 1971) have described observations about exercise in patients with isolated aortic valvular disease.

Limited data are available concerning exercise haemodynamics of aortic valvular stenosis in children. We are aware of only the brief report of Hugenholtz and Nadas (1963) describing exercise response in such patients.

We have studied, by cardiac catheterization, the resting and exercise state of 33 children with isolated congenital aortic valvular disease. The purposes of our study were to define the pump function of the left ventricle in children with aortic stenosis, and to determine the haemodynamic effect of coexistent aortic insufficiency. Such information, defining pressure-flow relations, is needed for proper preoperative and postoperative evaluation and as a background for longitudinal studies of the natural history of aortic stenosis.

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determined as previously described, and a pressure tracing again recorded from the left ventricle to aorta.

Angiography was then performed to define the characteristics of the aortic valve and to determine the presence of aortic regurgitation.

The recordings were analysed for heart rate and systolic and diastolic pressures. The left ventricular end-diastolic pressure was measured after the ‘a’ wave. After superimposing the aortic and left ventricular pressure curves, both the mean left ventricular systolic ejection pressure and mean systolic gradient were determined by planimetry. Aortic valve area (AVA) was calculated according to the formula of Gorlin.

In each patient, the measured and calculated haemodynamic parameters for rest and exercise were compared. On the basis of haemodynamic data and angiographic demonstration of aortic insufficiency, the patients were divided into 4 groups. Group 1: isolated aortic stenosis with AVA > 0.7 cm²/m²; Group 2: isolated aortic stenosis with AVA < 0.7 cm²/m²; Group 3: predominant aortic insufficiency; and Group 4: coexistent aortic stenosis and insufficiency. In group 3, aortic insufficiency was the predominant haemodynamic abnormality in contrast to group 4, wherein only a trace of aortic insufficiency was evident on selective aortography, the stenotic component being the major problem. The mean value of each haemodynamic parameter was calculated for each of the 4 groups, and the groups compared by standard statistical methods.

### Results

The 33 patients were divided among the 4 groups as follows:

- **Group 1**: Aortic stenosis without aortic insufficiency, AVA > 0.7 cm²/m², 10 patients.
- **Group 2**: Aortic stenosis without aortic insufficiency, AVA < 0.7 cm²/m², 10 patients.
- **Group 3**: Aortic insufficiency with aortic stenosis, 6 patients.
- **Group 4**: Coexistent aortic stenosis and insufficiency, 7 patients.

The mean age of the patients in each group was similar (Table). The resting and exercise states were considered comparable, since the heart rate and oxygen consumption were similar for each group.

### Cardiac output

The resting cardiac index was normal in all patients, with no significant difference between the 4 groups. The relation between the oxygen consumption, cardiac output, and arteriovenous oxygen difference was normal in each group (Fig. 1).

In 7 of the 33 patients, the resting cardiac index was greater than 5.0 l/min/m². Because some patients were not in a basal state, the resting values of

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**Table: Comparison of resting and exercise haemodynamic parameters in 4 groups of children with isolated aortic valvar disease (P < 0.05 indicates significant difference between groups 1 and 2)**

<table>
<thead>
<tr>
<th>Haemodynamic parameter</th>
<th>State</th>
<th>Group 1</th>
<th>Group 2</th>
<th>Group 3</th>
<th>Group 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (yr)</td>
<td></td>
<td>11.5 ± 2.5</td>
<td>12.9 ± 1.9</td>
<td>11.8 ± 1.9</td>
<td>11.5 ± 2.8</td>
</tr>
<tr>
<td>LV mean systolic pressure (mmHg)</td>
<td>R</td>
<td>111.3 ± 9.3</td>
<td>137.9 ± 14.1</td>
<td>123 ± 27.8</td>
<td>129 ± 16.7</td>
</tr>
<tr>
<td></td>
<td>E</td>
<td>144 ± 16.6</td>
<td>180.4 ± 20.1</td>
<td>153.8 ± 23.3</td>
<td>162.7 ± 24.6</td>
</tr>
<tr>
<td>LV end-diastolic pressure (mmHg)</td>
<td>R</td>
<td>9.9 ± 1.9</td>
<td>13.9 ± 3.3</td>
<td>15.6 ± 4.6</td>
<td>11.4 ± 2.1</td>
</tr>
<tr>
<td></td>
<td>E</td>
<td>9.5 ± 2.8</td>
<td>13.0 ± 3.0</td>
<td>10.8 ± 7</td>
<td>10.0 ± 4.5</td>
</tr>
<tr>
<td>Mean systolic gradient (mmHg)</td>
<td>R</td>
<td>19.3 ± 12.1</td>
<td>45.2 ± 14.8</td>
<td>31.6 ± 19.8</td>
<td>32 ± 17</td>
</tr>
<tr>
<td></td>
<td>E</td>
<td>43.1 ± 16.3</td>
<td>69.7 ± 19</td>
<td>36.1 ± 21</td>
<td>54.4 ± 24.3</td>
</tr>
<tr>
<td>Oxygen consumption (ml/min/m²)</td>
<td></td>
<td>157 ± 15</td>
<td>167 ± 13</td>
<td>169 ± 15</td>
<td>165 ± 14</td>
</tr>
<tr>
<td></td>
<td>R</td>
<td>157 ± 15</td>
<td>167 ± 13</td>
<td>169 ± 15</td>
<td>165 ± 14</td>
</tr>
<tr>
<td></td>
<td>E</td>
<td>709 ± 24</td>
<td>742 ± 15</td>
<td>713 ± 71</td>
<td>646 ± 108</td>
</tr>
<tr>
<td>AV oxygen difference (vol. %)</td>
<td></td>
<td>3.8 ± 0.4</td>
<td>3.8 ± 0.5</td>
<td>4.4 ± 0.9</td>
<td>3.6 ± 0.8</td>
</tr>
<tr>
<td></td>
<td>R</td>
<td>3.8 ± 0.4</td>
<td>3.8 ± 0.5</td>
<td>4.4 ± 0.9</td>
<td>3.6 ± 0.8</td>
</tr>
<tr>
<td></td>
<td>E</td>
<td>9.3 ± 1.3</td>
<td>9.7 ± 1.2</td>
<td>10.0 ± 0.8</td>
<td>8.1 ± 1.6</td>
</tr>
<tr>
<td>Heart rate (beats/min)</td>
<td></td>
<td>81.9 ± 15</td>
<td>82.8 ± 13</td>
<td>79 ± 11</td>
<td>82 ± 16</td>
</tr>
<tr>
<td></td>
<td>R</td>
<td>81.9 ± 15</td>
<td>82.8 ± 13</td>
<td>79 ± 11</td>
<td>82 ± 16</td>
</tr>
<tr>
<td></td>
<td>E</td>
<td>141.3 ± 23</td>
<td>144 ± 23</td>
<td>130 ± 8</td>
<td>141 ± 11.9</td>
</tr>
<tr>
<td>Cardiac index (l./min/m²)</td>
<td></td>
<td>41.0 ± 8.0</td>
<td>43.3 ± 0.6</td>
<td>3.8 ± 0.5</td>
<td>4.4 ± 0.9</td>
</tr>
<tr>
<td></td>
<td>R</td>
<td>41.0 ± 8.0</td>
<td>43.3 ± 0.6</td>
<td>3.8 ± 0.5</td>
<td>4.4 ± 0.9</td>
</tr>
<tr>
<td></td>
<td>E</td>
<td>7.5 ± 1.2</td>
<td>7.3 ± 1.2</td>
<td>6.6 ± 0.6</td>
<td>7.8 ± 1.2</td>
</tr>
<tr>
<td>Stroke index (ml/beat/m²)</td>
<td></td>
<td>52.1 ± 11.9</td>
<td>52.6 ± 7.6</td>
<td>—</td>
<td>53.1 ± 7.7</td>
</tr>
<tr>
<td></td>
<td>R</td>
<td>52.1 ± 11.9</td>
<td>52.6 ± 7.6</td>
<td>—</td>
<td>53.1 ± 7.7</td>
</tr>
<tr>
<td></td>
<td>E</td>
<td>52.7 ± 8.5</td>
<td>51.9 ± 7.9</td>
<td>—</td>
<td>54.5 ± 8.5</td>
</tr>
<tr>
<td>Aortic valve area (cm²/m²)</td>
<td></td>
<td>1.1 ± 0.4</td>
<td>0.6 ± 0.1</td>
<td>—</td>
<td>0.8 ± 0.2</td>
</tr>
<tr>
<td></td>
<td>R</td>
<td>1.1 ± 0.4</td>
<td>0.6 ± 0.1</td>
<td>—</td>
<td>0.8 ± 0.2</td>
</tr>
<tr>
<td></td>
<td>E</td>
<td>0.9 ± 0.2</td>
<td>0.6 ± 0.2</td>
<td>—</td>
<td>0.8 ± 0.2</td>
</tr>
</tbody>
</table>

* = P < 0.05 between Groups 1 and 3.
R = rest; E = exercise.
Haemodynamics of exercise in children with isolated aortic valvular disease

Cardiac index

I./min/m²

4-2

0°-2

A-V difference

m102/l00ml

b

8

KYI

o

AS>07cm²/m²

AS<07cm²/m²

AS+AI

AI+ AS

x

O

C

C) -

E

400 80

400

1200

V02 ml/min/m²

1000

FIG. 1 Comparison of mean cardiac index and mean arteriovenous oxygen difference with oxygen consumption (VO₂) for 4 groups of children with aortic valvular disease. Values for rest and exercise are connected. All values are similar to those reported in normal children (Sproul and Simpson, 1964).

both cardiac index and oxygen consumption were often greater than predicted for normal. The values are, however, similar to those reported in normal children (Sproul and Simpson, 1964).

With exercise, both the cardiac index and oxygen consumption rose in each patient, and the relation between these 2 variables was normal in 32 patients (Fig. 2). In Case 17 with an indexed AVA of 0.4 cm²/m², the response to exercise was abnormal. In this patient, the cardiac index increased only from 3.6 L./min/m² to 4.2 L./min/m² on exercise, while the oxygen consumption rose from 152 to 476 ml O₂/min.

No significant difference was found in the comparison of the exercise cardiac indices between the

FIG. 2 Relation of oxygen consumption and cardiac index upon exercise in 33 children. Shaded area represents normal limits (Donald et al., 1955). Exercise response adequate in all but 1 patient.

FIG. 3 Comparison of peak LV-aortic gradient and cardiac index in 20 patients with aortic stenosis (left) and 13 patients with associated aortic insufficiency (right).
4 groups. Group 3 (predominant aortic insufficiency), however, showed a smaller rise in exercise cardiac index than the other groups. Because of the number of patients with high resting cardiac indices the calculated exercise factor was not of value to us in assessing cardiac function. The stroke index was similar in each group and showed no significant change on exercise.

Cardiac pressures

Among the groups (1 and 2) with isolated aortic stenosis a systolic gradient existed between the left ventricle and aorta. The mean systolic gradient in group 2 (45.2 ± 14.8 mmHg) was significantly greater than in group 1 (19.3 ± 11.1 mmHg P < 0.05).

The mean systolic gradient increased on exercise in each patient with isolated aortic stenosis. There was again a significant difference between groups 1 and 2 (43.1 ± 16.3 mmHg vs. 69.7 ± 14.8 mmHg P < 0.05).

In each patient with isolated aortic stenosis, both the gradient and cardiac index increased on exercise (Fig. 3). There appeared to be no predictable increase in magnitude of gradient upon exercise. Patients in group 4 showed increases similar to those of groups 1 and 2. In each patient of group 3, the cardiac index rose on exercise in all but 1; the gradient also increased. In these 2 groups (3 and 4) there was even a greater variability of the left ventricular-aorta gradient on exercise because of the coexistence of aortic insufficiency.

The resting left ventricular end-diastolic pressure was significantly greater in patients with more severe aortic stenosis than in those with milder stenosis.
and oxygen consumption, the pressure rose from 13 to 17 mmHg.

Comparison of the exercise changes in LV end-diastolic pressure and stroke index revealed an abnormal response in 3 patients (Fig. 5). The stroke index fell and end-diastolic pressure rose on exercise in 2 patients with aortic valve areas of 0.5 cm²/m² and in 1 with an area of 0.9 cm²/m². Case 17 was one of the 3 patients with abnormal response. The other 2 patients showed a normal exercise response as indicated by other measured parameters.

Among the patients with aortic insufficiency (group 3) the LV end-diastolic pressure was significantly raised (15.6 ± 4.6 mmHg) as compared to the patients with mild aortic stenosis (9.9 ± 1.9 mmHg). On exercise, however, LV end-diastolic pressure fell to 10.8 ± 2.7 mmHg (Fig. 6). This change in pressure was significant (P < 0.05) and suggested that the increased resting LV end-diastolic pressure was related to raised LV end-diastolic volume from aortic regurgitation rather than abnormalities of the myocardium. Patients with minimal aortic insufficiency (group 4) were comparable to group 1, in regard to both resting and exercise LV end-diastolic pressure.

In each patient the pulmonary arterial pressures were normal at rest and remained so after exercise.

Discussion

With the development of prosthetic aortic valves, increasing numbers of patients with aortic valvular disease have undergone haemodynamic study. These investigations have included observations of both the resting and exercise states and have primarily been of older patients with calcific or rheumatic aortic disease (Anderson et al., 1969; Goldberg et al., 1954; Gorlin et al., 1955; Hancock and Fleming, 1960; Lee et al., 1970). In contrast to the large experience with aortic disease in adults, relatively little is known about the haemodynamics of exercise in children with aortic stenosis. Most studies of children with aortic stenosis report data only of the resting state or describe correlations between haemodynamic and clinical data. Hugenholtz and Nadas (1963) briefly reported exercise data in aortic stenosis, but otherwise we could find no information related to exercise response in children with aortic valvular disease.

Our purpose was to define the resting and exercise haemodynamics and to study the pump function of the left ventricular myocardium in children with aortic stenosis. Such data will assist the postoperative haemodynamic assessment of children undergoing aortic valvular surgery by permitting more precise evaluation of operative results. Furthermore, since the natural history of aortic stenosis is largely unknown (Campbell, 1968; Friedman, Modlinger, and Morgan, 1971), the reported data will be useful in determining the impact of the stenosis on the left ventricular myocardium.

Two deficiencies are evident in most reports of exercise in patients with aortic stenosis. Frequently coexistent valvular heart disease has been present in the reported patients. This additional lesion may critically affect the haemodynamics yielding an imprecise view of aortic stenosis. Secondly, the gradient across the aortic valve has often been determined by comparing left ventricular and brachial arterial pressures. Whereas at rest the brachial arterial pressure contour may be similar to the central aortic pressure, on exercise the considerable systolic amplification of the pulse wave occurs in the peripheral arterial system (Samet, Bernstein, and Litwak, 1961). The gradient and therefore magnitude of stenosis could be falsely lowered in this way.

In our study we excluded patients with cardiac anomalies other than those of the aortic valve. Furthermore, we carefully classified the patients separating those with isolated aortic stenosis from those with coexistent aortic insufficiency. In each of our patients we used central aortic pressures for determination of left ventricular-aortic systolic gradient.

In 32 of our patients with congenital aortic valvular anomalies, the cardiac pump function appeared normal as assessed by comparison of exercise to resting haemodynamic variables. In the other patient, cardiac function was abnormal. The cardiac output rose only slightly on exercise and inappropriately to the oxygen consumption. The stroke index fell, and LV end-diastolic pressure rose. The coexistence of aortic insufficiency, either mild or moderate, did affect the exercise response in our patients.

Therefore, according to the parameters measured in our children with congenital abnormalities of the aortic valve, cardiac pump function appeared normal. This is in contrast to reported data of adults with aortic stenosis.

Studies of adult patients with aortic stenosis have shown no consistent increase in mean aortic systolic blood flow during exercise. In comparison this parameter increased in each of our children. Similarly, no increase in gradient on exercise, despite an increase in aortic flow, has been described in adult patients with aortic stenosis (Anderson et al., 1969). The gradient increased on exercise in each of our children with aortic stenosis, but the increase in gradient was variable, and not predictable. Thus, for any given patient, it is difficult to predict the
exercise gradient from knowledge of the resting cardiac output and gradient.

Previously, Friedman and Braunwald (1968) reported that patients with aortic valve area of less than 0.7 cm²/m² showed an abnormal exercise response, but this has not been our experience. Braunwald et al. (1963) reported abnormal exercise response in adult patients with moderate and severe aortic stenosis. The contrast between these data in adults and our data in children yields information about the natural history of aortic stenosis. The abnormal response in older patients suggests that the chronic effects of augmented afterload upon the left ventricle may lead to abnormal pump function.

Our children also differed from adults regarding LV end-diastolic pressure. In a series of adult patients with isolated aortic stenosis, Bache and co-workers (1971) found no relation between LV end-diastolic pressure and severity of aortic stenosis. In contrast we did find a tendency for raised LV end-diastolic pressure in children with more severe aortic stenosis. Though we have not measured LV end-diastolic volume in our patients, we assumed that it was normal or near normal, since the patients showed normal cardiac size on thoracic roentgenograms. Thus, the raised LV end-diastolic pressure in the presence of normal pump function most likely reflects altered LV myocardial compliance secondary to myocardial hypertrophy, rather than myocardial fibrosis. This view is supported by the finding of a normal relation between end-diastolic pressure and stroke index.

Mild coexistent aortic insufficiency had no effect on the haemodynamics in our patients. Among those with major aortic insufficiency the exercise response was also normal, but showed 2 differences from patients with isolated aortic stenosis. The resting LV end-diastolic pressure was raised in the presence of major aortic insufficiency, and fell on exercise in each of our patients, as was described by Lewis, Bristow, and Griswold (1970) in patients with aortic insufficiency and normal LV function. Furthermore, no consistent change occurred in LV aortic gradient.

We believe that measurement of the haemodynamics of exercise in patients with aortic disease adds a valuable parameter to the evaluation, particularly since the exercise gradient cannot be accurately predicted from the resting values. Exercise data also permit evaluation of cardiac pump function, which may be abnormal reflecting myocardial changes. Data derived from such studies have assisted us in decisions concerning operation, and in anticipating the functional results.

References


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