Exercise Testing in Children Before and After Surgical Treatment of Aortic Stenosis

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SUMMARY Twenty-three children with valvar or discrete subvalvar aortic stenosis underwent a controlled, progressive bicycle exercise test within 6 months before and 3–30 months after surgery for left ventricular outflow tract obstruction. The patients were divided into three groups according to the preoperative resting gradient of left ventricular to aortic peak systolic pressure: 30–69 mm Hg (group A), 70–99 mm Hg (group B), and ≥ 100 mm Hg (group C). Preoperatively, 19 of 23 patients (83%) developed significant ST depression (≥ 1.0 mm) during exercise, whereas only seven (30%) had abnormal ST depression at rest. Postoperatively, mean exercise-induced ST depression regressed to less than 1 mm in all three groups. In the total population the frequency of ST depression greater than 1 mm was significantly reduced after surgical treatment and mean total work and peak exercise systolic blood pressure were significantly increased within 12 months after surgery. Total work increased significantly in group B within 12 months and in group C within 13–24 months after surgery, but remained unchanged in group A. Peak exercise heart rates were similar before and after surgery in each group. Peak exercise systolic pressures increased after surgery in all three groups, but the mean differences were statistically significant only in group C patients tested 13–24 months after surgery. The results of this study show that exercise testing is useful for quantifying the severity of aortic stenosis and documenting the clinical improvement (or lack thereof) after surgical treatment, and that properly supervised exercise testing can be performed at minimal risk to children with significant aortic stenosis.

THE SEVERITY of aortic stenosis (AS) is primarily determined from data obtained during cardiac catheterization in sedated patients. The risk and conditions under which the procedure is performed render this technique impractical for routine or frequent serial investigations in the young. Significant or progressive AS may escape detection during a cardiac evaluation consisting of a detailed history, careful physical examination, chest radiograph, vectorcardiogram and resting ECG.1–6 The development of another technique that carries minimal or no risk and improves our assessment of the severity of AS is highly desirable.

Exercise-induced ST depression is related to the resting gradient of left ventricular to aortic peak systolic pressure in children with AS.1–7, 9 Preliminary studies suggest that the cardiovascular adaptation to exercise can reveal the severity of AS and the degree of recovery after adequate surgical relief of the obstruction.10

This study was designed to assess the effect of surgical relief of significant left ventricular outflow tract (LVOT) obstruction by measuring total work and recording the exercise ECG and blood pressure in children with valvar or discrete subvalvar AS. The safety features for performing exercise studies in these children are discussed. The results from exercise testing in this population could potentially improve our current management and reduce the risks associated with chronic LVOT obstruction.

Materials and Methods

Patients

Twenty-three patients (19 males and four females) underwent a controlled, progressive bicycle exercise test within 6 months before and 3–30 months after surgical relief of valvar or discrete subvalvar AS. These patients were 5–19 years of age (mean 10.7 years) at surgery. "Isolated" valvar AS was present in 10 patients, valvar AS with trivial incompetence in seven, and discrete subvalvar AS in six (three with associated trivial aortic incompetence). Fifteen patients (65%) had one or more of the following symptoms by clinical history: chest pain, exertional dyspnea, decreased exercise tolerance, syncope and dizziness.

Preoperative chest radiographs were normal in 14 patients (61%) and revealed cardiomegaly or an enlarged left ventricle in nine (39%) and prominence of the ascending aorta in four (17%). The resting ECGs were normal in eight patients (35%) and revealed left ventricular hypertrophy by voltage criteria in 14 (61%) and abnormal ST depression11 in seven (30%). The exercise study was performed on all 23 patients within 3 months (mean 0.88 month) before the preoperative cardiac catheterization. The resting gradients of left ventricular to aortic peak systolic pressure (LV-AO) during the preoperative cardiac catheterization were 30–235 mm Hg (mean 86 mm Hg), with resting peak left ventricular systolic pressures of 130–300 mm Hg. The cardiac indexes were 2.6–7.0 l/min/m² (mean 4.9 l/min/m²) when the LV-AO gradients were measured. The surgery consisted of aortic valvotomy in 17
patients and resection of discrete subvalvar obstruction in six. Immediately after bypass and at normal body temperature, LV-AO gradients and cardiac indexes were measured in 22 of 23 patients. The cardiac indexes were 1.6–6.2 l/min/m² (mean 3.7 l/min/m²) when the postoperative LV-AO gradients were obtained.

Exercise Procedure

The continuous, progressive bicycle exercise protocol described by James et al. was used. The exercise procedure was explained to the patient and parent or guardian and informed consent was obtained. The exercise test was conducted by a physician who monitored and instructed the patient during the test, and coordinated the recording of certain variables such as heart rate, blood pressure and the multipole ECG. Two technicians assisted with primary functions of recording blood pressure and the ECG.

The test was performed on a bicycle ergometer (Quinton Instrument, model 845), with a programmer (model 644) enabling automatic progression through the preselected exercise program. A fifteen-lead ECG (12 conventional leads and Frank orthogonal leads X, Y and Z) was recorded using a multichannel recorder (Siemens Mingograf 62). Heart rate (beats/min) was computed by averaging the interval between the PQ or PR points of two consecutive RR cycles on the ECG recorded at a paper speed of 50 mm/sec. Blood pressure was measured in the right arm in each patient using a programmable, air-compression cuff system (Narco-Biosystem, Inc., PE-300) operated by remote control. The guidelines of the Task Force on Blood Pressure Control in Children were followed for selecting the appropriate size compression cuff.

Before exercise, conventional 12-lead ECGs and Frank orthogonal leads X, Y and Z were recorded with the patient in the supine and standing positions, with and without hyperventilation. Three simultaneous electrocardiographic leads were observed on the oscilloscope for arrhythmia before testing. Heart rate and blood pressure were recorded with the patient in the supine position and while sitting on the bicycle ergometer.

During exercise, each patient pedalled at a constant speed (60–70 rpm) on the ergometer while the work load increased automatically every 3 minutes. Leads V₁, V₅, V₆, II, X and Y were simultaneously recorded every minute. The remaining nine leads were frequently scanned for alterations of the ST segment. Heart rate was recorded every minute and blood pressure every 1–2 minutes. At the peak level of exercise, the ECG, blood pressure, heart rate and exercise time were recorded.

The exercise test was discontinued if one or more of the following signs or symptoms appeared: (1) serious cardiac arrhythmia; (2) ST depression ≥ 3.0 mm; (3) inappropriate decrease in systolic pressure, i.e., 20 mm Hg or more or to a level less than resting systolic pressure; (4) exhaustion; and (5) chest pain, dizziness or pallor.

After exercise, blood pressure, heart rate and electrocardiographic recordings were taken with the patient in the supine position, immediately and 1, 3 and every 5 minutes for a total of 20 minutes.

Data Analyses

Total work was calculated as the sum of the products of work load (in kilogram-meters [kg-m]/min) and exercise time at each level reached in the exercise program. The ECG was analyzed for (1) ST depression ≥ 1.0 mm for 60 or more msec below a baseline that connects the PR or PQ junction of three to five consecutive P-QRS-T complexes in any lead to peak performance; (2) distribution of the ST depression; and (3) cardiac arrhythmia.

The exercise results were divided into three groups using the preoperative resting LV-AO gradient: 30–69 mm Hg (mean 53 mm Hg) in nine patients (group A); 70–99 mm Hg (mean 72 mm Hg) in seven patients (group B); ≥ 100 mm Hg (mean 141 mm Hg) in seven patients (group C). Serial exercise data (ST-segment depression, total work, peak exercise heart rate and blood pressure) were analyzed in 19 of 23 patients who had a preoperative study within 6 months (mean 2.9 months) before surgery, as well as a follow-up study within 24 months after surgery. Of the four patients not included in this serial data analysis, two had an initial follow-up study more than 24 months after surgery and two developed complete left bundle branch block after surgery.

Statistical Analyses

Pre- and postoperative mean values for amplitude of ST depression, total work, peak exercise heart rate and systolic blood pressure were calculated and analyzed using the paired t test. The frequency of ST depression before and after surgery was analyzed using the chi-square test.

Results

LV-AO Gradient Difference Before and Immediately After Surgery

Significant reductions in the mean LV-AO gradients were found immediately after surgery in all the groups (fig. 1). The mean differences in the LV-AO gradients measured immediately after surgery were 40 mm Hg in group A and 113 mm Hg in group C. In group B, six of the seven patients had gradients measured immediately after surgery. In these six patients, the mean LV-AO gradient difference was 49 mm Hg, or 64 mm Hg when the one patient with an increased gradient after surgery was excluded. The latter patient in group B had a preoperative LV-AO gradient of 70 mm Hg and a cardiac output of 1.9 l/min. After surgery, this patient’s LV-AO gradient increased to 100 mm Hg and cardiac output increased to 3.3 l/min. Aortic valve replacement was not considered appropriate in view of the patient’s age (6 years) and the small aortic valve ring.
End Points of Exercise

Twenty-three patients had a preoperative study, as well as follow-up studies within 3-30 months after surgical treatment. The frequency of end points used for discontinuing a test in the preoperative and initial postoperative studies is shown in Table 1. Some patients developed more than one of these end points during the test. Preoperatively, chest pain and dizziness were provoked by exercise in groups B and C. No symptoms were noted in group A. Postoperatively, no symptoms were observed during exercise in any group.

Before surgery, exhaustion and ST depression ≥ 3.0 mm were the two most frequent signs signaling the end of an exercise test in groups A and B (LV-AO gradients < 100 mm Hg). One patient in group A developed frequent premature ventricular complexes and the test was stopped. In group C (LV-AO gradient ≥ 100 mm Hg), ST depression ≥ 3.0 mm was the most frequent reason (71%) for halting the exercise test.

After surgery, exhaustion was the end point of the exercise test in 22 of 23 patients. The remaining patient had exercise-induced ST depression of 3.0 mm 10 months after aortic valvotomy and has not had a subsequent study.

Exercise ECG

The following exercise results were obtained from 19 of the 23 patients who had initial studies within 24 months after surgery and did not have complete left bundle branch block postoperatively. The difference between the frequency of exercise-induced ST depression ≥ 1.0 mm in these 19 patients before and after surgical treatment was highly significant (chi-square = 13.47, p < 0.0025). The postoperative frequency of exercise-induced ST depression ≥ 1.0 mm in group A

Table 1. Frequency of End Points for Stopping Exercise Test in 23 Children with Aortic Stenosis

<table>
<thead>
<tr>
<th>Before surgery</th>
<th>After surgery</th>
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<tbody>
<tr>
<td></td>
<td>Group A (n = 9)</td>
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<tr>
<td>Resting LV-AO gradient (mm Hg)</td>
<td>30-69</td>
</tr>
<tr>
<td>Symptoms</td>
<td></td>
</tr>
<tr>
<td>Chest pain</td>
<td>0%</td>
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<tr>
<td>Dizziness</td>
<td>0%</td>
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<tr>
<td>Signs</td>
<td></td>
</tr>
<tr>
<td>Exhaustion</td>
<td>89%</td>
</tr>
<tr>
<td>ST depression (≥ 3 mm)</td>
<td>11%</td>
</tr>
<tr>
<td>Exercise systolic pressure ≤ resting systolic pressure</td>
<td>0%</td>
</tr>
<tr>
<td>Arrhythmia</td>
<td>11% (VE)</td>
</tr>
</tbody>
</table>

*Each child may have had more than one of these end points.

Abbreviations: LV-AO = left ventricular to aortic peak systolic pressure; VE = ventricular ectopy.
was significantly reduced compared with the preoperative frequency (chi-square = 3.43, \( p < 0.05 \)). The frequency was not significantly reduced by surgery in group B (chi-square = 1.46, \( p > 0.10 \)) or in the three patients in group C who had an initial exercise test within 12 months after surgery (chi-square = 2.65, \( p > 0.10 \)). However, there was a significantly decreased frequency of ST depression \( \geq 1.0 \text{ mm} \) in the remaining three patients of group C who were tested 13–24 months after surgery (chi-square = 5.13, \( p < 0.0125 \)).

Before surgery, the percentages of patients with exercise-induced ST depression \( \geq 1.0 \text{ mm} \) were 83% in group A, 71% in group B and 100% in group C. Within 12 months after surgery, the percentages decreased to 33% in group A and 43% in group B. In group C, two of three patients (67%) had ST depression \( \geq 1.0 \text{ mm} \) within 12 months after surgery. In the remaining three patients in group C, one (33%) had ST depression \( \geq 1.0 \text{ mm} \) within 13–24 months after surgical treatment.

The mean amplitude of ST depression in these 19 patients was 1.9 mm preoperatively and 0.8 mm postoperatively (\( p < 0.0025 \)). The mean amounts of ST depression in groups A, B and C before and within 12 months and 13–24 months (group C only) after surgical treatment are shown in figure 2. In group A, the mean amplitude of ST depression during exercise was 1.3 mm before surgery (mean 2.1 months) and 0.6 mm within 12 months (mean 5.9 months) after surgery (0.05 < \( p < 0.10 \)). In group B, the mean amplitude of ST depression was 1.5 mm before surgery (mean 5.2 months) and 0.6 mm within 12 months (mean 8.1 months) after surgery (\( p < 0.05 \)). The six patients in group C had a greater amplitude of exercise-induced ST depression (mean 2.9 mm) before surgery (mean 2.1 months) than patients in group A or group B. After surgery in group C, the mean ST depression was 1.5 mm within 12 months (mean 8.7 months) in three patients (\( p < 0.05 \)) and 0.8 mm within 24 months (mean 21.5 months) in the other three patients (\( p < 0.0025 \)).

Of all the exercise-induced ST depressions of 1.0 mm or more in the 19 patients on the pre- or postoperative exercise study, the slope of the ST segment was upward in 58%, horizontal in 37.5% and downward in 4.5%. Figure 3 shows two patients with significant exercise-induced ST depression of 1.5 mm (fig. 3A) and 3.0 mm (fig. 3B) and an upward-sloping or horizontal ST segment in V6 and/or V5 before surgery. These electrocardiographic tracings show the lead-dependency of the ST segmental changes during exercise. In both children, all abnormal ST segmental changes resolved within 15 months after surgery.

Seventy-nine percent of the pre- and postoperative exercise-induced ST depressions \( \geq 1.0 \text{ mm} \) were recorded in the left precordial leads (V6 or V5). Of these significant ST depressions, 50% were recorded in both left precordial and inferior leads (II, III, aVf and/or Vf). The remaining 21% of the pre- and postoperative exercise-induced ST depressions were recorded in the inferior leads only. No statistically significant differences in distribution of the ST-segment changes were found pre- or postoperatively in groups A, B or C.

Three of the 19 patients (15%) exhibited an arrhythmia during the exercise test. During the preoperative exercise study, one patient had frequent ventricular ectopy that necessitated stopping the test; this patient’s ventricular ectopy was less frequent after surgery. Another patient had occasional ventricular bigeminy during exercise, and a third had occasional ventricular ectopy after exercise at the initial postoperative exercise test. Two patients excluded from the exercise data analysis had complete left bundle branch block after surgical treatment but did not develop arrhythmia during the postoperative exercise studies.

### Total Work and Peak Exercise Heart Rates

In the 16 patients who had an initial follow-up exercise test within 12 months after surgery, the mean

![Figure 2. Mean exercise-induced ST depression before and after surgery in three groups of patients with aortic stenosis: group A, resting gradient of left ventricular to aortic peak systolic pressure (LV-AO) 30–69 mm Hg; group B, 70–99 mm Hg; and group C, \( \geq 100 \text{ mm Hg} \). Means and standard deviations for the amplitude of exercise-induced ST depression are represented by open bars (before surgery) and by hatched bars (after surgery). Preoperatively, the amplitude of ST depression increased as the LV-AO gradient increased. Postoperatively, ST depression regressed to less than 1.0 mm. Levels of significant differences between pre- and postoperative means for the amplitude of ST depression: *\( 0.05 < p < 0.10 \), †\( p < 0.05 \), ‡\( p < 0.05 \), and §\( p < 0.0025 \). Number of patients is given in parentheses.](image-url)
total work was 1702 ± 945 kg·m (± SD) preoperatively and 2975 ± 1921 kg·m postoperatively (p < 0.0125). For group A, total work was 1604 ± 573 kg·m before surgery and 1991 ± 538 kg·m after surgery (p > 0.10) (fig. 4). In group B, all seven patients had a moderate-to-marked increase in total work at their postoperative study as compared with their preoperative study. In this group, total work was 2117 ± 1192 kg·m before surgery and 4378 ± 2140 kg·m after surgery (p < 0.025). Group C had three patients that were tested within 12 months after surgery who did not have a significant change in total work. In this latter group, total work was 1633 ± 1189 kg·m before surgery and 1667 ± 929 kg·m after surgery (p > 0.10). In the remaining three patients in group C who were tested 13–24 months after surgical treatment, there was a significant increase in mean total work to 5050 ± 3808 kg·m (p < 0.025).

The mean peak exercise heart rates before and after surgery were not significantly different in the 16 patients or within any of the three groups (fig. 4).

**Blood Pressure**

The mean peak exercise systolic pressures (± SD) in the 16 patients with an initial postoperative exercise test within 12 months after surgery were 121 ± 22 mm Hg before surgery and 143 ± 33 mm Hg after surgery (p < 0.025). The mean peak exercise systolic pressures before and after surgery in group A were 123 ± 14 and 137 ± 16 mm Hg, respectively (0.05 < p < 0.10) (fig. 5). For group B, mean exercise systolic pressures before and after surgery were 129 ± 28 and 151 ± 47 mm Hg, respectively (p > 0.10). The mean peak exercise systolic pressures in group B during the pre- and postoperative studies were greatly affected by

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**Figure 3.** Pre- and postoperative exercise ECGs in a child with valvar aortic stenosis. When the patient was 10 years of age, the preoperative exercise study revealed J-point depression and 1.5 mm of ST depression, with a rapid (V3) and a slow (V4) upward-sloping segment. When the patient was 11 years of age (5 months after surgery) and at an increased level of exercise, the J point and ST segments were normal. (B) Pre- and postoperative exercise ECGs in a child with valvar aortic stenosis. When the patient was 10 years of age, the preoperative exercise study revealed horizontal ST depression of 3 mm during exercise. When the patient was 11 years of age (15 months after surgery), and at an increased level of exercise, the ST segment was normal, with an increased amplitude of the S wave.
two patients with systolic pressure greater than the ninetieth percentile for age at rest and an exaggerated systolic pressure response during exercise. In group C, the mean peak exercise systolic pressures were 112 ± 18 mm Hg before surgery and 134 ± 17 mm Hg within 12 months after surgery (0.05 < p < 0.10) in three patients and 157 ± 24 mm Hg within 13-24 months after surgery (p < 0.01) in the other three patients (fig. 5).

The mean percentage increases in exercise systolic pressure above the resting levels were 23% for group A and 16% for group B preoperatively, and 32% for group A and 40% for group B postoperatively. In group C, the mean percentage increases in exercise systolic pressure above the resting levels were 7% preoperatively and 20% in the three patients studied within 12 months and 30% in the other three patients postoperatively.

The mean peak exercise diastolic pressures before and after surgery were not significantly different. Mean diastolic pressures tended to increase from rest to exercise in all groups, but the mean changes were not statistically significant.

**Discussion**

This study presents longitudinal exercise data in children with significant AS, 65% of whom were symptomatic by clinical history. After surgery, symptoms resolved, abnormal amplitude and frequency of exercise-induced ST depression regressed and exercise tolerance and systolic blood pressure improved.

**Exercise ECG**

Preoperatively, 19 of the 23 children in this study had significant ST depression during exercise, whereas only seven had abnormal ST-segment changes at rest. In all patients, exercise-induced ST depression returned to the preexercise level immediately after exercise. Only two of these 19 patients had chest pain during exercise, despite the occurrence of significant ST depression. This evolutionary pattern of ST-segment changes in children with AS differs from the pattern in adults with coronary artery disease, in whom exercise-induced ST depression persists or progresses after exercise. After surgery, the frequency and degree of exercise-induced ST depression decreased in our patients. Patients with the highest resting preoperative LV-AO gradients had the greatest change in amplitude of ST depression after surgery. Gradual resolution of significant exercise-induced ST depression was documented in 12 of the 19 patients after surgical treatment. An example of this gradual resolution is presented in figure 6. The resolu-
tion of abnormal ST segments during exercise is thought to be due to a decrease in myocardial oxygen demand after surgical relief of the severe pressure overload to the left ventricle, resulting in increased perfusion of the subendocardial tissue.\textsuperscript{16-18}

Eight patients (42\%) had ST depression $\geq$ 1.0 mm during the initial postoperative exercise study, performed within 2 years after surgery. In four of these eight patients there was no residual LV-AO gradient after surgery, but at their initial postoperative exercise study, which was performed at a mean time of 2.8 months, mild-to-moderate aortic insufficiency was present. It is reasonable that in these patients the ST depression was related to the intensity of exercise relatively soon after surgery, the persistence of significant left ventricular hypertrophy and the associated aortic insufficiency. In the other four patients who did have a residual LV-AO gradient (mean 50 mm Hg), three were in group C and one was in group B. The persistence of abnormal ST depression at a mean follow-up period of 12.3 months in these latter patients may indicate a significant residual gradient.

\begin{figure}
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\includegraphics[width=\textwidth]{figure5}
\caption{Peak exercise systolic pressures before and after surgery in three groups of patients with aortic stenosis (see fig. 2 for definition of groups). The peak exercise systolic pressures tended to increase postoperatively in all three groups. Means and standard deviations for peak exercise systolic pressure are represented by closed circles and bars. Levels of significant differences between pre- and postoperative means for peak exercise systolic pressure: *$0.05 < p < 0.10$, †$p > 0.10$, §$0.05 < p < 0.10$, and ¶$p < 0.01$. Number of patients is given in parentheses.}
\end{figure}

\begin{figure}
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\includegraphics[width=\textwidth]{figure6}
\caption{Preoperative and serial postoperative exercise ECGs in a child with valvar aortic stenosis whose resting gradient of left ventricular to aortic peak systolic pressure was 110 mm Hg. The preoperative exercise study revealed 3.0 mm of ST depression. Six months after surgery the initial exercise test showed 1.5 mm of ST depression. There was no significant exercise-induced ST depression at a similar level of exercise 19 months after surgery.}
\end{figure}
with hypertrophy and/or significant myocardial damage resulting from the preoperative LVOT obstruction.19, 20

The slope of the abnormal ST segments was upward in the majority of children. This finding was dependent on the ECG lead and appeared in some patients as a transitional phase leading to horizontal ST depression. The upward-sloping ST segments with significant depression resolved after surgical relief of the LVOT obstruction (fig. 3A). Resolution of the upward-sloping ST-segment depression (≥ 1.0 mm) after surgery indirectly supports the contention that this criterion is a valid indicator of acute subendocardial ischemia during exercise in children.

Several groups have suggested monitoring only a few selected leads or a modified bipolar lead V5 during exercise.21-24 Although significant ST depression occurred most frequently in lead V5 in our patients, several had ST depression of 1.0 mm or more in left precordial and inferior leads or in the inferior leads only. The presence and distribution of these abnormal ST segments would presumably have been missed if multiple electrocardiographic leads had not been available to scan during the exercise test. Our data, which are similar to those in adults,25 support the use of multilead electrocardiography to increase the yield of abnormal exercise-induced ST depression.

Total Work and Peak Exercise Heart Rates

Mean total work was significantly increased above the preoperative value at the initial postoperative exercise study in the total population. The changes in total work occurred without significant differences in peak exercise heart rates measured before and after surgery (fig. 4). Despite impressive postoperative increases in total work, many children who had adequate surgical treatment failed to attain total work levels expected for their body size when tested up to 2 years after surgery. This suggests that these children may benefit from a rehabilitation program that includes medically prescribed physical training.

Blood Pressure

At the initial postoperative study, the mean peak exercise systolic pressure was greater than the resting systolic pressure and was significantly increased above the preoperative peak exercise systolic pressure in the total population. Normally, the peripheral systolic pressure level is determined by the rate of left ventricular ejection, stroke volume and distensibility of the peripheral arterial walls.26 In LVOT disease, these determinants are abnormally affected, particularly the rate of ejection and volume of left ventricular output.27-28 Abnormal interplay of these determinants is the presumed mechanism for depressed exercise systolic pressure levels in AS. Additionally, a decrease in exercise systolic pressure below the resting level indicates compromise in cardiac output and is a sign of severe cardiovascular distress.

Safety

Several studies have demonstrated that exercise testing can be performed at minimal risk to children with significant AS.1-3, 29-34 We recommend the use of a multilead electrocardiographic system to assist in detecting significant ST-segment changes and evaluating serious arrhythmias. Careful monitoring of systolic pressure will help to signal a decrease in the cardiac output. An evaluation of exercise-induced signs and symptoms and the interpretation of responses during exercise warrant the presence of a physician in the laboratory when testing children with significant AS. This approach, we feel, increases the safety of exercise testing.

Serial Exercise Testing

Two examples of the clinical value of sequential exercise testing are shown in figure 7. Both patients showed improvement in one or more of the measured variables during exercise at their first postoperative study, suggesting a substantial relief of LVOT obstruction. Patient AL continued to improve at his second postoperative exercise test, whereas patient WP showed marked deterioration in total work and in the exercise ECG due to the development of significant aortic valve incompetence within 26 months after aortic valvotomy.

Conclusion

A properly conducted exercise test provides additional information for selecting children, especially those who are asymptomatic, for cardiac catheterization and surgical treatment, as well as for the evaluation of surgical therapy. This study shows that exercise testing is potentially useful in identifying patients with severe AS who were previously judged to have mild LVOT obstruction, in following patients with mild AS determined by cardiac catheterization, and in following patients after surgical relief of significant LVOT obstruction. This study does not show that exercise testing is beneficial and clinically indicated in patients with obvious signs of severe aortic stenosis.

An abnormal exercise profile consisting of signs of cardiovascular dysfunction, myocardial ischemia and exercise intolerance existed in our patients with significant AS with LV-AO gradients as low as 30 mm Hg before surgery. A substantial change toward normal occurred in some patients as early as 3 months after adequate surgical relief of the obstruction. The measured exercise responses, such as significant exercise-induced ST depression, may require many months to resolve completely.

The persistence of the preoperative exercise profile or the lack of a significant change toward normal after surgery suggests significant residual obstruction, cardiovascular dysfunction and/or an associated lesion. Although we cannot establish rigid criteria for surgical treatment based upon this study, exercise testing does assist in the early detection and treatment of children with AS. Therefore, in children without
classic signs of severe obstruction, we recommend serial exercise testing before and after surgery for AS. A significant deterioration in the exercise profile before or after surgery indicates the need for cardiac catheterization and possible surgical treatment.

Acknowledgment

We thank Magdalen A. Anyaebu, Susan Dalton, Vera Naylor, Wayne Mays, and Catherine Sarwar for their technical assistance, and Margaret Dello for typing the manuscript.

References


Figure 7. Serial exercise data before and after surgery in two patients with aortic stenosis. In patient AL, with a resting gradient of left ventricular-aortic peak systolic pressure (LV-AO) of 100 mm Hg, the preoperative exercise study revealed severe depression of the ST segment, total work and peak exercise systolic pressure. Postoperatively, the ST depression regressed to normal at 10 months (a), total work improved at 29 months (b), but peak exercise systolic pressure remained depressed. Patient WP, with an LV-AO gradient of 70 mm Hg, developed dizziness during the preoperative study and had decreased total work. Postoperatively, the LV-AO gradient increased to 100 mm Hg, with an increase in cardiac output; total work was above normal at 9 months (a), but at 30 months (b), total work was severely depressed with progressive ST depression. Open circles represent the expected levels for body size.14
Mechanism for Improved Cardiac Performance with Arteriolar Dilators in Aortic Insufficiency

BARRY H. GREENBERG, M.D., HENRY DEMOTS, M.D., EDWARD MURPHY, M.D., AND SHABUDIN H. RAHIMTOOLA, M.B.

SUMMARY To determine how arteriolar dilation improves cardiac performance in aortic insufficiency, we evaluated the acute effects of hydralazine in 10 patients with chronic severe aortic insufficiency. Control measurements of intracardiac and intravascular pressures, cardiac output and left ventricular volumes were obtained at cardiac catheterization. Hydralazine, 0.3 mg/kg i.v. (maximal dose 20 mg), was administered and all measurements were repeated 30 minutes later. A reduction in systemic vascular resistance from 1264 to 710 dyn-sec-cm⁻² was associated with significant increases in forward cardiac index (2.9 to 5.1 l/min/m²) and stroke volume index (37 to 55 ml/m²). Left ventricular end-diastolic pressure was reduced from 19 to 12 mm Hg. There was a significant reduction in mean arterial pressure (88 to 83 mm Hg) and a significant increase in heart rate (81 to 94 beats/min).

Regurgitant stroke volume was reduced by more than 10 ml/m² in seven patients and for the group was significantly reduced, from 65 to 53 ml/m². Regurgitant fraction was reduced in all patients; the overall reduction from 0.64 to 0.48 was highly significant. Ejection fraction increased more than 0.10 in four patients, by 0.08 in an additional patient and for the group increased significantly from 0.50 to 0.57. Left ventricular end-diastolic volume decreased by more than 25 ml/m² in four patients, by 19 ml/m² in an additional patient and was decreased significantly, from 208 to 190 ml/m², for the group.

Arteriolar dilators improve cardiac performance in aortic insufficiency by reducing the amount of aortic regurgitation and, in some patients, by substantially improving systolic pump function. These data suggest a role for arteriolar dilators in the management of selected patients with aortic insufficiency.

ARTERIOLAR DILATORS have beneficial effects on cardiac performance in a variety of clinical settings. In patients with congestive heart failure, reduced impedance enhances left ventricular emptying and increases stroke volume. In mitral regurgitation, the predominant effect of arteriolar dilation is to redistribute total left ventricular stroke volume in a manner favoring forward stroke volume at the expense of regurgitant flow. In patients with chronic severe aortic insufficiency, arteriolar dilation with hydralazine improves cardiac performance both at rest and during exercise. However, the mechanism responsible for the beneficial effects is uncertain. The present study was designed to evaluate the effects of hydralazine on left ventricular performance, volumes and regurgitant flow in patients with aortic insufficiency.

Methods

Patient Population

Ten consecutive patients with chronic severe aortic insufficiency were studied at diagnostic cardiac imaging.
Exercise testing in children before and after surgical treatment of aortic stenosis.

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