Response to Exercise in Patients after Total Surgical Correction of Tetralogy of Fallot

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SUMMARY Heart rate, blood pressure, blood pressure, and electrocardiographic changes, or exercise-induced changes, or exercise-induced changes, were evaluated during upright bicycle exercise in 43 asymptomatic patients, aged seven to 41 years, one to 14 years after total surgical correction of tetralogy of Fallot (TF). One hundred and nine normal subjects between the ages of four and 42 years served as controls. The patient and control groups, subdivided by sex and body surface area (BSA), were similar in height and weight. When comparing males to males and females to females with BSA ≥ 1.2 m², maximal heart rates and working capacities were lower in the patient groups than in the control groups. An inverse relationship was observed between maximal working capacity and age at surgery in both male and female patient groups. By contrast, especially in the males with BSA < 1.2 m², the mean maximal heart rates and working capacities did not differ significantly between the patient and control groups.

Premature atrial or ventricular contractions were recorded in ten of 43 patients (23%) after exercise. Five of these ten patients had multifocal premature ventricular contractions (PVC) and four had unifocal PVC. In the five patients with multifocal PVC, a short burst of ventricular tachycardia occurred in two, coupling in one, and bigeminal rhythm in two. Cardiac arrhythmia was not observed in the control group. Although our current surgical results are excellent, this study suggests that impaired cardiovascular function persists after corrective surgery and that early surgical treatment may be more desirable. Furthermore, additional data suggest that the exercise procedure may be useful in detecting and managing patients who may develop life-threatening arrhythmias following intraventricular surgery.

ADEQUATE RELIEF OF RIGHT VENTRICULAR OUTFLOW TRACT (RVOT) obstruction without the development of significant pulmonary incompetence and closure of the ventricular septal defect are major goals for successful surgical treatment of tetralogy of Fallot. After intracardiac repair, symptoms of hypoxemia and severe exercise intolerance are relieved even in the presence of residual RVOT obstruction, pulmonary valve incompetence, and/or cardiomegaly.1 Despite dramatic symptomatic improvement after surgery for TF, cardiovascular performance at rest2,3 or during exercise4-10 may remain below normal, and major complications such as trifascicular block,11 complete heart block12,13 and sudden death14,15 may occur many years after surgical treatment.

Since ventricular arrhythmia and abnormal cardiovascular responses may occur as a result of physical stress, this study was designed to evaluate noninvasively the heart rate, blood pressure, physical working capacity, and electrocardiogram during strenuous upright bicycle exercise in patients who have had surgical repair of TF. The utility of noninvasive exercise testing in the management of patients who have had intraventricular surgery for congenital heart disease is discussed.
Methods

Patients

Forty-three patients (28 males and 15 females) aged seven to 41 years underwent a continuous controlled graded exercise test one to 14 years after surgical correction of TF. At the time of surgical repair, their ages ranged from three to 35 years. One male was 35 years of age, and the remaining 27 males were between three and 25 years. One female was 25 years of age, and the remaining 14 females were between five and 16 years.

Each patient’s cardiac lesion consisted of a large subaortic ventricular septal defect and severe obstruction of the RVOT. The RVOT obstruction was exclusively infundibular or combined with valvar pulmonic stenosis, with or without hypoplasia of the pulmonary valve ring and arterial trunk. Systolic pressures in both ventricles were equal, with bidirectional or exclusively right-to-left shunting across the ventricular septal defect.

The preoperative electrocardiograms revealed right axis deviation and right ventricular hypertrophy with or without atrial enlargement. Premature ventricular contractions were not documented in any patient prior to total surgical correction. Twenty patients required aorto-pulmonary shunts (2 Potts; 16 Blalock-Taussig; and 2 Waterston) prior to total correction. In those patients with a large pulmonary blood flow through the surgical anastomosis, biventricular hypertrophy was present on the electrocardiogram at the time of total surgical correction.

During intracardiac repair, RVOT obstruction was relieved by infundibulotomy and pulmonary valvotomy in the majority of patients. For adequate relief of the obstruction a pericardial patch was used in 12 patients,1 and an aortic homograft in 7.1-15 In all patients, the ventricular septal defect was closed with a Teflon patch.

At the time of the exercise test, all patients were asymptomatic except one who had palpitations of short duration after mild physical exertion. The resting postoperative electrocardiograms revealed complete right bundle branch block in 35, complete right bundle branch block, and left axis deviation in five and a normal QRS pattern in three patients. Nonspecific T-wave inversion was present in three patients.

The RVOT gradient was measured in 26 of 43 patients at the time of surgery after reconstruction of RVOT or during a postoperative cardiac catheterization. The resting peak systolic RVOT gradient was less than 40 mm Hg in 21 patients and 42 to 67 in five. All patients who were catheterized had an intact ventricular septum. Exercise studies were not performed in any patient during the postoperative cardiac catheterization. Fourteen of the remaining 17 patients had physical signs of mild to moderate pulmonic stenosis with or without incompetence and normal or increased heart size on chest radiograph. A small left-to-right shunt was suspected clinically in one patient. The other three patients had a normal physical examination and cardiac size.

Twenty-six of 43 patients were enrolled in school. Four of these 26 children were considered physically trained because of their active participation in competitive sports. The remaining 17 patients had sedentary types of employment which required mild to moderate amounts of physical exertion.

Controls

One hundred and nine subjects, 68 males and 41 females (aged 5 to 42 years) with normal physical examinations, resting supine blood pressures, and electrocardiograms were the controls. This control group consisted of 42 (39%) randomly selected school children, 49 (45%) children whose cardiac evaluation was normal despite a referral for chest pain, fainting and/or cardiac murmur, and 18 (16%) volunteers. Twelve of the children were considered physically trained athletes because of their active participation in competitive sports. The remaining controls were not engaged in organized physical activity beyond the routine requirements for school and/or employment.

Exercise Test

Both normal and control groups underwent a controlled continuous graded bicycle exercise test. A detailed explanation of the exercise test was given to the subjects and/or parents, and informed consent was obtained. All subjects were stressed in one of three work schedules which were predetermined by body surface area. In this study, the exercise protocol16 (table 1) was a modification of the Goldberg continuous exercise program17 which has been successfully used in the evaluation of cardiac and noncardiac patients.17,18

The initial workload for our program was 200 kg-m/min (lowest workload on Quinton Instruments-Uniwork ergometer Model 884). The workloads were increased at 3 min intervals which facilitated measuring blood pressure and heart rate and permitted an estimation of the highest steady state level for each subject during exercise. The selection of each work schedule according to body surface area allowed grouping of normal subjects with similar physical working capacities as suggested by Bengtsson.19 The challenge in each of the three exercise schedules results in a majority of subjects reaching their maximal voluntary capacity in < 9 min in program I, < 12 min in II, and < 15 min for untrained and < 30 min for highly trained subjects in III. The distribution of the patients and controls in the three work programs is shown in table 2.

Prior to exercise, heart rate, standard 12-lead electrocardiogram and Frank orthogonal leads (X,Y,Z) were recorded in the supine and standing positions with and without hyperventilation. Three electrocardiographic leads were displayed on an oscilloscope and visually observed for arrhythmia for at least 20 min before the exercise procedure. Indirect blood pressure was measured in the right arm if the patient had not had a previous right Blalock-Taussig shunt.

Table 1. The Continuous Graded Exercise Programs (I, II, III)*

<table>
<thead>
<tr>
<th></th>
<th>I (BSA &lt; 1 m²)</th>
<th>II (BSA 1-1.19 m²)</th>
<th>III (BSA ≥ 1.2 m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level</td>
<td>(kg-m/min)</td>
<td>(kg-m/min)</td>
<td>(kg-m/min)</td>
</tr>
<tr>
<td>Level 1</td>
<td>200</td>
<td>200</td>
<td>200</td>
</tr>
<tr>
<td>Level 2</td>
<td>300</td>
<td>400</td>
<td>500</td>
</tr>
<tr>
<td>Level 3</td>
<td>500</td>
<td>600</td>
<td>800</td>
</tr>
<tr>
<td>Increments</td>
<td>100</td>
<td>100</td>
<td>200</td>
</tr>
<tr>
<td>Pedal speed</td>
<td>60-70 rpm</td>
<td>Duration of levels — 3 min</td>
<td></td>
</tr>
</tbody>
</table>

*Three exercise programs were used for three ranges of body surface areas (BSA). The duration of each exercise level was three minutes. If three exercise levels were successfully completed, the workload was increased at 100 or 200 kg-m/min increments until the patient reached his maximal voluntary capacity. (rpm = revolutions per minute).
or brachial arteriotomy. During exercise, in each subject, an attempt was made to achieve a respiratory rate $\geq$ 40 breaths/minute and an increase in pulse pressure with a leveling of systolic blood pressure and heart rate for at least 2 min prior to cessation of active exercise. All subjects attempted to reach these minimal cardiopulmonary responses by maintaining a constant pedalling speed of 60 to 70 rpm during progressive exercise until exhaustion occurred. That level of exercise was considered the maximal voluntary capacity and was used as an endpoint for calculating the maximal working capacity. Blood pressure was measured every one to three minutes. Precordial leads $V_1$, $V_2$, $V_5$, and $V_6$ and Frank orthogonal leads $X$, $Y$, and $Z$ were simultaneously recorded every minute.

After exercise, the subjects were immediately placed in the supine position for the recording of blood pressure, heart rate, and electrocardiogram during a 20-min post-exercise period.

Data Analyses

The maximal working capacity (MWC) was calculated from the workloads (kg-m/min) and the exercise time (in min). The ratios of MWC to body weight (in kg, MWC/kg) and body surface area (in m$^2$, MWC/m$^2$) were calculated for each subject. The maximal blood pressure and heart rate were recorded when the maximal voluntary capacity level was reached. The exercise electrocardiogram was reviewed primarily for rhythm disturbances.

Statistical Analyses

Comparisons of the mean values for heart rate, blood pressure, maximal working capacity, and other measured variables in the control and patient groups were analyzed using Student's $t$-test. The relationship of maximal working capacity indices (MWC/kg and MWC/m$^2$) to each of five variables including age at operation, postoperative years, presence, absence, and duration of an aortopulmonary shunt were analyzed.

Results

These exercise data which are subdivided by sex and body surface area (BSA) or work schedule represent the findings on the initial study from each subject. Interestingly, in the subjects, the respiratory rate exceeded 40 breaths/min with the association of forced high pitch easily audible inspiratory and expiratory breath sounds. All subjects except two patients reached the minimal cardiopulmonary response level. The two patients who failed to achieve the minimal response level had major difficulty in cycling at the required speed. However, these patients developed a heart rate of 140 and 160, respectively, and a significant increase in systolic blood pressure over the resting value. As a result, their exercise data were included in the analysis.

Ages, Heights, and Weights

There were no statistically significant differences between the average ages, heights, and weights of the male patients and controls whose BSA were $< 1.2$ m$^2$ (table 3). The two female patients with BSA $< 1$ m$^2$ were younger and smaller in body sizes than the average values for the respective female control group. Comparing male to male and female to female groups with BSA $\geq 1.2$ m$^2$, the mean ages were higher in the patients than in the controls ($P < 0.01$), yet the mean heights and weights were similar (table 3). All subjects (patient and controls) were then divided into three year age groups and by sex. Within each age group interval, there were no significant differences between the weight and height measurements of the patients and controls.

Operative Ages and Postoperative Years

The average age at corrective surgery was 6.5 years in the patients with BSA $< 1.2$ m$^2$ and 12.7 years in the patients with BSA $\geq 1.2$ m$^2$. The average number of postoperative years was 4.4 and 6.8 years in patients with BSA $< 1.2$ m$^2$, respectively.

Heart Rates and Blood Pressures

The mean resting heart rates in both patient and control groups in each exercise program were comparable. The mean maximal heart rate was lower in the patients (BSA $< 1.2$ m$^2$) than in the controls, but the difference was not statistically significant (table 3). In the males and females with BSA $\geq 1.2$ m$^2$, the mean maximal heart rates differed significantly from the patient to the control group, $P < 0.01$ (table 3). The decreased mean maximal heart rates in the male and female patient groups occurred independently of a previous aortopulmonary shunt.

Although there were notable differences in the patient group means for resting diastolic pressure in males ($< 1.2$ m$^2$) and resting systolic and exercise diastolic pressures in females ($\geq 1.2$ m$^2$), the pulse pressures in the compared patient and control groups increased similarly during exercise (table 3).

Working Capacity

The maximal working capacities (MWC) did not differ significantly between the male patient and control groups whose BSA were less than 1.2 m$^2$. The ratios (MWC/kg and MWC/m$^2$) for the two groups (patient and control) are given in table 3. In the two females with BSA less than 1 m$^2$, the MWC were 500 and 850 kg-m, respectively, as compared to 1663 $\pm$ 197 kg-m (mean $\pm$ standard deviation) for the matched female control group. The test of the patient with an MWC of 500 kg-m was performed 27 months after intracardiac repair. The postoperative cardiac catheterization confirmed the presence of marked pulmonary incompetence with residual RVOT obstruction (25 mm Hg) and right pulmonary artery obstruction (15 mm Hg) at the site of a previous Waterston anastomosis. A dilated main
pulmonary artery and RVOT, combined with a poorly contracting right ventricle, were demonstrated. The ventricular septum was intact. Because of the significant residual defects, surgical treatment was again recommended for reconstruction of the RVOT. Fifteen months after this second operation, on the repeat exercise test, MWC increased to 2000 kg/m² in this patient whose BSA was still less than 1 m².

In the males with BSA ≥ 1.2 m², the mean (± standard error) MWC was 6007 ± 687 kg/m² for the patients and 10,379 ± 799 for the controls (P < 0.01). Similarly, in the females (BSA ≥ 1.2 m²), the mean MWC was 3044 ± 417 for the patients and 6038 ± 636 for the controls (P < 0.01). The ratios of MWC/kg and MWC/m² in these patient and control groups are given in table 3.

The best demonstration of exercise capacity was shown by the larger male subjects. A distribution of MWC within arbitrary weight groups for the males is shown in figure 1. Although marked variations in MWC are seen in the controls within certain weight groups, the larger weight groups tended to have a greater working capacity than the smaller weight groups. Nine of 20 patients had MWC within the normal range. Four of these nine patients with MWC greater than 8000 kg/m² were actively engaged in competitive sports. In these four patients, two had required shunt anastomoses prior to intracardiac repair. A definitive surgical procedure was performed in the other two patients at ages three and 11 years, respectively. Postoperatively, three of four patients had a pericardial patch in the right ventricular outflow tract, with mild cardiomegaly in two. The fourth patient had signs of mild pulmonic stenosis on the physical examination after infundibular resection during surgery.

The relationship between MWC/kg and age at operation was analyzed in the male and female patients with BSA ≥ 1.2 m². An inverse relationship between these two variables was suggested in the male (r = -0.42) and female (r = -0.63) groups. The strength of this relationship was best demonstrated in the group of males who required a previous aorto-pulmonary shunt (r = -0.54) and in the females who did not require a previous aorto-pulmonary shunt (r = -0.80). Further analysis in the males revealed that 6/11 patients had an aorto-pulmonary shunt for 13 to 30 years, whereas six of nine males without a shunt had a corrective operation by age eight years. In the females, four of six patients without a shunt were between ten and 25 years of age at the time of the corrective procedure. Six of seven female patients with a shunt had a definitive correction by age 13 years. These findings suggest that the patient's age at the time of total surgical correction was more important to exercise capacity than the presence or absence of a previous aorto-pulmonary anastomosis. A negligible relationship existed between MWC indices, postoperative years, and duration of shunt except, perhaps, in the males with a previous shunt (r = -0.41).

Exercise Electrocardiogram

The exercise electrocardiogram was reviewed primarily for rhythm disturbance. However, one patient with a normal
Staphylococcal bacterial endocarditis had residual aortic insufficiency from previous episode of *Staphylococcal* bacterial endocarditis.

A typical exercise electrocardiogram in a patient with postoperative complete right bundle branch block is depicted in figure 2. During exercise, premature atrial contractions developed in two patients and persisted after exercise in one. Premature atrial or ventricular contractions were recorded in ten of 43 patients (23%) after exercise. Multifocal premature ventricular contractions (PVC) were recorded in five of the ten patients (50%) and unifocal PVC in four. One of the patients with frequent unifocal PVC after exercise had an occasional pre-exercise PVC which increased in frequency during exercise. Four of the five patients with multifocal PVC had an occasional unifocal PVC pre-exercise. In these five patients with multifocal PVC, a short burst of ventricular tachycardia occurred in two (fig. 3), coupling in one (fig. 4) and bigeminal rhythm in two. The post-exercise ventricular arrhythmia had a left bundle branch block pattern in seven patients and a right and left bundle branch block pattern in two.

During the episodes of ventricular arrhythmia, the patients were asymptomatic and were completely unaware of the rhythm disturbance. A clinical profile of the postoperative patients with post-exercise arrhythmia is given in table 4.

In both male and female control groups, premature atrial or ventricular arrhythmias were not recorded before, during, or after the exercise test.

**Discussion**

This study reveals significant differences in the response to exercise between a normal control population and patients who have had total surgical correction of TF. Although the average ages of the patient groups were greater than the respective controls, especially in patients with BSA ≥ 1.2 m², there were no significant differences in body height and

**FIGURE 1.** Distribution of maximal working capacity (MWC) according to body weight in male patient and control groups. 

**FIGURE 2.** Exercise electrocardiogram (from top, leads V₅, V₆, V₇) in a patient five years after total surgical correction of tetralogy of Fallot. The QRS pattern is compatible with complete right bundle branch block. Heart rate = 220 beats/min; paper speed = 50 mm/sec.

**FIGURE 3.** Post-exercise electrocardiogram (leads V₅, V₆, V₇) in a patient (RM), aged 41 years, five years after total surgical correction of tetralogy of Fallot. Short bursts of ventricular tachycardia were recorded immediately after exercise.
weight measurements. Further numerical analysis of the relationship of age and body size did not indicate that the patients were inappropriately smaller in weight and/or height for age than the controls. These calculations in mean ages of the compared patient and control groups (BSA ≥ 1.2 m²) were affected because the controls were slanted more toward the younger age groups.

In the postoperative patients with BSA less than 1.2 m²,

Table 4. Clinical Profile of Postoperative Patients with Postexercise Arrhythmia

<table>
<thead>
<tr>
<th>No</th>
<th>Sex</th>
<th>Op age (yrs)</th>
<th>Op shunt</th>
<th>Yrs post-op</th>
<th>Pericardial patch</th>
<th>Cardiomegaly</th>
<th>RVOT gradient (mm Hg)</th>
<th>PS/PI</th>
<th>Resting ECG</th>
<th>Post E-ECG</th>
<th>Comments</th>
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<tbody>
<tr>
<td>1</td>
<td>F</td>
<td>16</td>
<td>—</td>
<td>1</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>CRBBB (Occ PVC)</td>
<td>PVC(U)</td>
<td>PVC(U)</td>
</tr>
<tr>
<td>2</td>
<td>M</td>
<td>22</td>
<td>+ (P)</td>
<td>1</td>
<td>+</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>CRBBB</td>
<td>PVC(U)</td>
<td>Transient junctional rhythm immed post-op</td>
</tr>
<tr>
<td>3</td>
<td>M</td>
<td>21</td>
<td>+ (BT)</td>
<td>4</td>
<td>+</td>
<td>—</td>
<td>52</td>
<td>+/+</td>
<td>CRBBB</td>
<td>PAC</td>
<td>Residual peripheral</td>
</tr>
<tr>
<td>4</td>
<td>M</td>
<td>35</td>
<td>+ (BT)</td>
<td>5</td>
<td>+</td>
<td>+</td>
<td>+/+</td>
<td>CRBBB</td>
<td>LAD; OCC PVC</td>
<td>PVC(M)</td>
<td>PVC(M)</td>
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<tr>
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<td>F</td>
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<td>10</td>
<td>10</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>+/—</td>
<td>CRBBB</td>
<td>PAC</td>
<td>Transient CRBBB + LAD immed post-op</td>
</tr>
<tr>
<td>6</td>
<td>F</td>
<td>25</td>
<td>—</td>
<td>13</td>
<td>—</td>
<td>+</td>
<td>+/+</td>
<td>CRBBB</td>
<td>PVC(U)</td>
<td>PVC(M)</td>
<td>VT</td>
</tr>
<tr>
<td>7</td>
<td>M</td>
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<td>—</td>
<td>14</td>
<td>+</td>
<td>35</td>
<td>+/+</td>
<td>CRBBB</td>
<td>PVC(M)</td>
<td>PVC(M)</td>
<td>Transient complete heart block immed post-op</td>
</tr>
<tr>
<td>8</td>
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<td>6</td>
<td>+ (BT)</td>
<td>14</td>
<td>+</td>
<td>20</td>
<td>+/—</td>
<td>CRBBB</td>
<td>PVC(M)</td>
<td>PVC(M)</td>
<td>Brock procedure</td>
</tr>
<tr>
<td>9</td>
<td>M</td>
<td>14</td>
<td>—</td>
<td>8</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>Normal QRS; OCC PVC</td>
<td>PVC(M)</td>
<td>Pre-correction</td>
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<tr>
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<td>+ (BT)</td>
<td>12</td>
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<td>32</td>
<td>—</td>
<td>—</td>
<td>CRBBB</td>
<td>PVC(U)</td>
<td>Transient complete heart block immed post-op</td>
</tr>
</tbody>
</table>

Abbreviations: (—) = not present; (+) = present; (±) = probable; BT = Blalock-Taussig anastomosis; CRBBB = complete right bundle branch block; PVC(U) = premature ventricular contractions; op = operative; P = Potts; PAC = premature atrial contractions; PI = pulmonic incompetence; BS = pulmonic stenosis; RVOT = right ventricular outflow tract; U = unifocal; VT = ventricular tachycardia; Yrs = years.
which consist of those patients who had corrective surgical procedures at a relatively early age, there were no significant differences in maximal heart rates or physical working capacities in comparison to the corresponding control groups. The exceptions were the two females, one of which required a repeat operation because of significant pulmonary incompetence with RVOT obstruction and cardiomegaly. The re-operation undoubtedly contributed to the striking improvement in physical working capacity that was observed during the follow-up exercise test.

In contrast, in those patients with BSA \( \geq 1.2 \, \text{m}^2 \), there were significant differences in maximal heart rates and physical working capacities in comparison to the corresponding controls. The notable exceptions within this male patient group (BSA \( \geq 1.2 \, \text{m}^2 \)) were the normal values in the five patients with body weight less than 56 kg and the four males who were actively engaged in competitive sports (Fig. 1). The remaining male patients failed to show a significantly improved working capacity with increased body weight as demonstrated in the male controls. Each of the four male athletes were cyanotic preoperatively with two requiring a shunt procedure prior to definitive correction. The surgical reconstruction of the RVOT required a pericardial patch in three and an infundibulectomy in one. These definitive procedures were performed by age 13 years in each of the four males. The superior performances in these males as compared to the parent group were perhaps due to the psychological growth and the results of physical training following a relatively early and successful corrective surgical procedure.

Interestingly, an inverse relationship between exercise capacity and age at operation was suggested in the male and female patients, irrespective of the presence or absence of a previous aorto-pulmonary shunt procedure. Additionally, an inverse relationship between exercise capacity and duration of shunt which results in a later age for total correction was suggested in the males (BSA \( \geq 1.2 \, \text{m}^2 \)). The negative relationship between exercise capacity and age at operation was similar to the observations of Streider et al., who also noted an increase in physiological dead space and alveolar-arterial oxygen difference during exercise in patients after corrective surgery for TF.

Several invasive studies have demonstrated left and right ventricular dysfunction in surgically-treated patients. Jarmakani et al. reported that left atrial maximal volume, left ventricular end-diastolic volume, and left ventricular ejection fraction were depressed below normal in children with cyanotic tetralogy of Fallot who were greater than two years of age. After successful shunt procedures or corrective surgery, left atrial maximal volume and left ventricular end-diastolic volume remained less than normal. Similar studies have been done to evaluate right ventricular function. Brodeur et al. measured right ventricular volumes in six patients with pulmonic insufficiency after surgical treatment of right ventricular outflow tract obstruction. An increased right ventricular end-diastolic volume and a decreased ratio of forward stroke volume to end-diastolic volume were present in patients with pulmonic incompetence as compared to patients with isolated pulmonic stenosis. Also, these subjects with pulmonic insufficiency usually had a normal resting right ventricular end-diastolic pressure in the presence of an elevated right ventricular end-diastolic volume.

Jarmakani et al. studied 18 patients with Fallot's tetralogy after aorto-pulmonary anastomosis. Right ventricular end-diastolic volume was normal in patients with hemoglobin less than 16 g% and less than normal in patients with hemoglobin greater than or equal to 16 g%. Right ventricular ejection fraction was significantly less than normal for the entire group. Additional studies by these authors have included patients who had total surgical correction of TF. In 17 patients, right ventricular end-diastolic volumes were normal except in patients who had an outflow tract aneurysm. However, ventricular ejection fraction and stroke index were significantly less than normal in these patients. Jarmakani et al. attributed the decreased right and left ventricular ejection fractions to impaired ventricular function despite clinical improvement after a shunt procedure or surgical correction.

Several investigators have used exercise during invasive procedures to evaluate right and left heart function in patients after surgery for TF. Bristow et al. reported the results of serial cardiac catheterizations with hemodynamics measured during supine exercise in 11 patients, 13 months to seven years after surgical correction of tetralogy of Fallot. The operative ages ranged from three to 20 years with an average of ten.

The incremental changes in cardiac output during exercise were subnormal in some of the patients, as evaluated by the exercise factor. These subnormal changes were attributed to possibly high cardiac output values at rest in the younger patients. Hence these authors felt that a normal relationship existed between oxygen consumption and cardiac output in their patients. Nevertheless, right ventricular end-diastolic pressure did increase abnormally during exercise, suggesting impaired ventricular function.

Epstein et al. studied a similar series of patients during cardiac catheterization at rest and during intense upright exercise. These patients were exercised until the pulmonary artery saturation decreased to 30%. At that exercise level, the mean cardiac output was decreased in the patients as compared to the controls. The low cardiac output during exercise was attributed to an inadequate rise in stroke volume. Additionally, four of six patients who had resting peak right ventricular pressures between 30 and 42 mm Hg increased their right ventricular pressures to a height of 85 to 106 mm Hg during intense upright exercise.

Bjarke studied 18 patients at rest and during exercise. During intense upright exercise, cardiac output was less in the patient group as compared to the normal group. The low cardiac output in their patients was attributed to a small resting stroke volume which did not increase adequately during stress and a fall in stroke volume during heavy exercise. Although the average ages between the patient and control groups (BSA \( \geq 1.2 \, \text{m}^2 \)) differed significantly, it appears that the decreased exercise capacity and maximal heart rate in the larger and older patients cannot be explained on age differences alone. The reason for the inability of our patients to elevate their heart rates to a level comparable to the controls is unclear from our data.

We speculate that the decreased physical working capacity in our patients was probably due to restricted physical activity during the developmental years, decreased
cardiac output because of lower maximal heart rate and stroke volume, and perhaps lack of cardiac rehabilitation after corrective surgery. Although one of our patients had a markedly improved exercise capacity following a second operation for reconstruction of RVOT, at present the effect of significant residual abnormalities after total surgical correction of TF cannot be completely assessed from our data.

Because of the performances of the four male patients who were participating in competitive sports, it is suggested that physical training may assist in significantly improving overall cardiovascular function in these patients. The normal or near normal exercise results in the patients whose BSA is less than 1.2 m² suggest that early surgical treatment may be more desirable in order to minimize cardiac dysfunction in later life.

Although the above abnormalities may exist after corrective surgery, the natural history of tetralogy of Fallot has been significantly altered, and many patients can tolerate moderate amounts of physical stress. Those postoperative patients who have developed significant late conduction abnormalities or near normal exercise function in these patients. The normal or near normal exercise results in the patients whose BSA is less than 1.2 m² suggest that early surgical treatment may be more desirable in order to minimize cardiac dysfunction in later life.

Ten of our 43 patients developed cardiac arrhythmia which was induced or aggravated by exercise as compared to an arrhythmia-free control group. In the patient group ventricular arrhythmias were recorded in the supine position immediately after the patient's maximal voluntary effort. The rapid decrease in heart rate with an augmented breathing pattern and systemic venous return during this immediate recovery period is perhaps a more vulnerable period for the development of rhythm disturbances in these patients. One patient who developed multifocal PVC with brief episodes of ventricular tachycardia had a cardiac arrest eighteen months after the exercise test. Further details on this patient have been reported elsewhere. The aggravation or induction of significant ventricular arrhythmia by exercise in our patients indicated that the graded exercise test is useful in unmasking potentially serious rhythm disturbances which are not apparent at rest. We believe that serious ventricular arrhythmia at rest or induced by exercise in patients after surgical treatment of tetralogy of Fallot increases the risk of sudden death.

Gey et al. reported that oral quinidine was effective in abolishing or diminishing ventricular ectopy induced by maximal exercise testing. Jelinek et al. have advised against the use of antiarrhythmic therapy for sporadic ventricular ectopic arrhythmia because of poor drug response and a high incidence of side effects. Three of our patients had serious postexercise ventricular arrhythmia including one patient who had a cardiac arrest 18 months after the exercise test. We have treated each patient with quinidine, and the postexercise arrhythmia was abolished in one (fig. 4) and markedly decreased in two.

In the patients with postexercise arrhythmia, the average age at the time of total correction was 15.6 years. Canet et al. reported 11 patients who had full thickness biopsies of the right ventricle at the time of corrective surgery. Extensive fibrous, elastic, and collagen tissue invasion of the myocardium was present in patients greater than 4 years of age. Fibrous and collagen tissues involving the intramyocardial coronary vessels and central artery of the sino-atrial node were also observed. Perhaps the abnormal cardiovascular dynamics and ventricular ectopy in the older patients are related to pre-existing myocardial fibrosis and scarring secondary to ventriculotomy and infundibular resection during corrective surgery.

This study documents the usefulness and safety of the exercise procedure in the noninvasive evaluation of patients after total correction of tetralogy of Fallot. Although our current surgical results are excellent, this study has provided important data which indicates that cardiovascular function remains impaired after corrective surgery and that early surgical treatment may be more desirable in order to minimize cardiac dysfunction in later life.

This exercise procedure may be useful in detecting and managing patients who may develop life-threatening arrhythmias after intraventricular surgery. Prior to making any firm conclusions, further studies with adequate longitudinal follow-up must be done in this expanding population.

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Subpulmonary Obstruction in Congenitally Corrected Transposition of the Great Arteries due to Ventricular Membranous Septal Aneurysms

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SUMMARY The clinical, hemodynamic, and angiographic observations, as well as the surgical approach used for repair in three patients with congenitally corrected transposition of the great arteries and ventricular membranous septal aneurysms, are presented. In two of the three patients the membranous septal aneurysm caused subpulmonary obstruction, with 94 and 125 mm Hg systolic gradients. In each patient the aneurysm was demonstrated by angiocardiography, which also showed differences in size and shape with cardiac systole and diastole.

VENTRICULAR MEMBRANOUS SEPTAL ANEURYSMS are commonly found in small, uncomplicated ventricular septal defects. Over the last decade, numerous reports have described the clinical, anatomic, hemodynamic, and angiographic findings associated with these lesions and their possible complications.

In patients with normal ventricular development, atrioventricular (A-V) concordance and normally related great arteries, the aneurysms are often described as incidental findings following angiographic studies and only rarely cause right ventricular outflow obstruction. Ventricular membranous septal aneurysms in patients with transposition of the great arteries (TGA) with and without A-V concordance and ventricular septal defects have been reported rarely. When present, however, these aneurysms usually caused significant subpulmonary obstruction.

Review of the previously described reports indicates that patients with congenitally corrected transposition often display various forms of pulmonary outflow obstruction and when a ventricular membranous septal aneurysm exists, a significant subpulmonary obstruction is present in most patients. The unique anatomic relationship between the pulmonary artery and a ventricular membranous septal aneurysm in patients with transposition of the great arteries with and without atrioventricular discordance explains why subpulmonary obstruction sometimes develops.

The purpose of this report is to present the clinical, hemodynamic, and angiographic findings of three patients with congenitally corrected transposition of the great arteries and ventricular membranous septal aneurysms recently operated upon at the Columbia-Presbyterian Medical Center. In two of the three patients the ventricular membranous septal aneurysm caused significant subpulmonary obstruction. The unique relationship between the ventricular septal defect and the pulmonary valve in these cases makes it likely that ventricular membranous septal aneurysms will result in significant subpulmonary obstruction. We believe that these findings are of special significance at this time when an increasing number of children with various forms of transposition of the great arteries are being referred for surgical correction.

For the purpose of this presentation the authors define congenitally corrected transposition as the congenital cardiac anomaly resulting from atrioventricular discordance and transposition of the great arteries such that both great arteries arise from the inappropriate ventricle.
Response to exercise in patients after total surgical correction of Tetralogy of Fallot.
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