Results of total correction of the tetralogy of Fallot

Long-term haemodynamic evaluation at rest and during exercise

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Postoperative haemodynamic evaluation was performed on 15 patients 7 to 14 years (mean, 11 years) after total intracardiac repair of Fallot’s tetralogy. The average age of the patients at the time of postoperative catheterization was 20 years (range 12 to 29) and they were all asymptomatic. Before operation 11 patients were severely cyanosed and disabled and 4 had mild cyanosis with anoxic spells.

The cardiac output and right heart pressures were measured at rest and after 5 minutes of submaximal exercise on a bicycle ergometer. It was shown that the degree of residual obstruction of the pulmonary outflow tract was slight and that the right ventricular/pulmonary arterial systolic gradient (RV/PA gradient) exceeded 20 mmHg (2.6 kPa) at rest in only 3 patients. The mean cardiac index at rest was 5.4 l min⁻¹ m⁻² which increased to 8.3 l min⁻¹ m⁻² during exercise. The response of the cardiac output during exercise was either normal or supranormal in 14 of the 15 patients. In the remaining patient the response was marginally below the normal range.

Pulmonary valvular regurgitation was present in 8 patients but there was no detectable difference in the cardiac function of these patients compared with patients with competent pulmonary valves.

Six of the patients investigated had also had cardiac catheterizations performed 1 to 4 years after operation. The results of the present study show that remarkably little change has occurred in their haemodynamic status in the intervening years. Though these results are encouraging, further studies are required to determine the eventual outcome of the RV pressure and volume overload.

Total intracardiac correction of the tetralogy of Fallot is now well established as a highly successful surgical procedure (Kirklin and Karp, 1970). The symptomatic and clinical improvement which occurs after operation is usually dramatic. It is not surprising, however, that residual haemodynamic abnormalities have been shown by postoperative catheterization studies (Hallidie-Smith et al., 1967; Soulé et al., 1971; Sunderland et al., 1973; Kaplan et al., 1973; Gersony et al., 1973).

Two main abnormalities have been described:

1. Residual obstruction of the right ventricular outflow tract which is usually mild or moderate in degree.

2. Pulmonary valvular regurgitation, particularly when a prosthetic or pericardial patch is used to enlarge the right ventricular outflow tract and the pulmonary artery.

In a minority of patients the persistence of a shunt through a ventricular septal defect has been shown.

Many of the postoperative studies were done relatively soon after total correction and there is an

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to widen the and in widened other paired with valvotomy. The ventricular suture.

Five patients, 8 male and 7 female, were investigated 7 to 14 years after total correction of Fallot's tetralogy, and in 11 patients the interval was greater than 10 years. Their average age at the time of investigation was 20 years (range 12 to 29 years) and they were all asymptomatic and leading normal lives. They were selected because they were the earliest survivors of the total correction operation in our unit. The purpose and nature of the investigation was fully explained to each patient or parents as appropriate and informed consent for its performance obtained.

Before operation 11 patients were severely cyanosed and 4 had mild cyanosis with anoxic spells. The diagnosis was based on the clinical signs, haemodynamic and angiographic investigation, and the findings were confirmed at operation.

Operation details

Five patients had preliminary palliative operations, viz. a pulmonary valvotomy in 3 and a Blalock anastomosis in 2. At the time of total correction pulmonary infundibulectomy was done in all 15 patients and in addition 8 patients had a pulmonary valvotomy. The ventricular septal defect was repaired with a ‘teflon’ patch in 9 patients and in the other 6 patients the defect was closed by direct suture. The right ventricular outflow tract was widened with a ‘teflon’ prosthetic patch in 7 patients and in 2 of these the prosthetic patch was extended to widen the proximal pulmonary artery.

**Patients and methods**

**Table 1 Postoperative data in 15 patients with tetralogy of Fallot**

<table>
<thead>
<tr>
<th></th>
<th>Rest Mean</th>
<th>Range</th>
<th>Exercise Mean</th>
<th>Range</th>
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<tbody>
<tr>
<td>Mean RAP (mmHg)</td>
<td>5</td>
<td>-1-10</td>
<td>7</td>
<td>1-10</td>
</tr>
<tr>
<td>RVSP (mmHg)</td>
<td>39</td>
<td>22-61</td>
<td>54</td>
<td>23-83</td>
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<td>RVEDP (mmHg)</td>
<td>6</td>
<td>0-13</td>
<td>7</td>
<td>-2-12</td>
</tr>
<tr>
<td>PASP (mmHg)</td>
<td>24</td>
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<td>33</td>
<td>18-49</td>
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<td>PADP (mmHg)</td>
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<td>-1-18</td>
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<td>Mean PAP (mmHg)</td>
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<td>6-26</td>
<td>22</td>
<td>8-33</td>
</tr>
<tr>
<td>RV/PA systolic pressure gradient (mmHg)</td>
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<tr>
<td>PAWP (mmHg)</td>
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<td>4-30</td>
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<td>BA diastolic (mmHg)</td>
<td>84</td>
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<td>101</td>
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<td>PVR (dynes·s·cm⁻²)</td>
<td>87</td>
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<td>Systemic resistance (dynes·s·cm⁻²)</td>
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<td>Systemic arterial oxygen saturation (%)</td>
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<td>86-98</td>
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<td>AV oxygen difference (vol %)</td>
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<tr>
<td>Cardiac index</td>
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<td>8·3</td>
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<tr>
<td>Heart rate (beats/min)</td>
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<td>Stroke volume (ml/beat)</td>
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<td>62-185</td>
<td>100</td>
<td>61-173</td>
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<td>Oxygen consumption (ml min⁻¹ m⁻²)</td>
<td>153</td>
<td>113-192</td>
<td>597</td>
<td>444-755</td>
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**Abbreviations**: RAP, right atrial pressure; RVSP, right ventricular systolic pressure; RVEDP, right ventricular end-diastolic pressure; PASP, pulmonary artery systolic pressure; PADP, pulmonary artery diastolic pressure; PAP, pulmonary artery pressure; PAWP, pulmonary artery wedge pressure; BA, brachial artery; PVR, pulmonary vascular resistance; AV, arteriovenous.

**Conversion factors from Traditional Units to SI Units**: 1 mmHg = 0·133 kPa; 10 dynes·s·cm⁻² = 1 MPa·s·m⁻⁴.
The cardiac content

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simultaneously. The gas samples were analysed for oxygen content by the Scholander micro-method. The cardiac output was measured at rest and during the fifth minute of exercise on a bicycle ergometer. The degree of workload selected for each patient was approximately two-thirds of the predetermined maximum load and it was maintained for 5 minutes. Simultaneous pulmonary arterial (PA) and right ventricular (RV) pressures were recorded at the beginning and at the end of the gas collection.

Electrocardiography

All the patients had complete right bundle-branch block on their electrocardiograms but there was no evidence of left anterior hemiblock or complete atrioventricular dissociation.

Results

The physical characteristics of the patients and haemodynamic results at rest and during exercise are shown in Tables 1 and 2.

Right heart pressures

The mean values for the RV systolic pressure and the RV-PA systolic pressure gradient at rest and during exercise are given in Table 1 and the individual values are shown in Fig. 1 and 2. The RV-PA systolic gradient at rest was 20 mmHg (2.7 kPa) or less in 12 of the 15 patients. An increase in the gradient during exercise was recorded in 14 patients but the increase was < 10 mmHg (1.3 kPa) in 7 patients. The RV-LV peak pressure ratio averaged 0.31 (range 0.16 to 0.42) and there was no significant difference between the patients who had a patch repair of the RV outflow tract and those who did not.

The RVEDP was slightly increased (> 5 mmHg; 0.7 kPa) in 10 patients at rest (Fig. 3). During exercise the RVEDP increased in 10 patients but the increase exceeded 5 mmHg (0.7 kPa) in only 1 patient.

The mean pulmonary artery pressure (PAP) and pulmonary wedge pressures (PAWP) were within

<p>| TABLE 2 Physical characteristics and values for cardiac output, cardiac index, AV O₂ difference, and oxygen consumption at rest and during exercise |
|---|---|---|---|---|---|---|---|
| Case | Age | Sex | BSA (m²) | AV O₂ Differences (vol %) | Cardiac output (l/min) | Cardiac index (l/min⁻¹ m⁻²) | Oxygen consumption index (ml/min⁻¹ m⁻²) |</p>
<table>
<thead>
<tr>
<th>No.</th>
<th>(years)</th>
<th></th>
<th></th>
<th>Rest</th>
<th>Exercise</th>
<th>Rest</th>
<th>Exercise</th>
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<tr>
<td>1</td>
<td>21</td>
<td>M</td>
<td>1.69</td>
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<td>3.8</td>
<td>8.0</td>
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<td>2</td>
<td>24</td>
<td>F</td>
<td>1.49</td>
<td>2.3</td>
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<td>9.9</td>
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<td>M</td>
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<td>8</td>
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<td>M</td>
<td>1.81</td>
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<td>11</td>
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<td>1.71</td>
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<td>18.7</td>
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<td>10.5</td>
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<td>15</td>
<td>25</td>
<td>F</td>
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<td>10.0</td>
<td>5.2</td>
<td>10.2</td>
<td>3.2</td>
<td>6.3</td>
</tr>
</tbody>
</table>

Normal values at rest: (1) AV oxygen difference, 2.4 to 5.7 vol. %; (2) cardiac index, 2.6 to 5.8 l/min⁻¹ m⁻²; (3) oxygen consumption index, 110 to 192 ml/min⁻¹ m⁻². Fuller details are given in a paper by Segeal et al. (1964).
Long-term haemodynamic evaluation of tetralogy of Fallot

正常范围内。在所有患者中，右心室-肺动脉收缩压梯度在休息和运动时均在正常范围内。在1名患者中，PAWP为19 mmHg (2.5 kPa)。PAWP的平均值在休息时也正常，运动时有所下降。

Cardiac index (Table 2)

运动时的平均心指数为5.4 ± 1.91 ml·min⁻¹·m⁻²，高于该实验室的正常范围（2.6至5.81 ml·min⁻¹·m⁻²）在6名患者中。心指数与氧耗之间的关系在运动时低于正常范围在1例患者（Fig. 4）。

休息时，平均心输出量和氧耗均在正常范围内。运动时心输出量和氧耗的增加接近四倍，而平均氧耗差则超过两倍。六个患者的值小于正常心输出量和氧耗的患者。氧耗差与氧耗对于个体的关系在图5中显示。

Stroke volume

运动时，8名患者中氧耗差和氧耗均在正常范围内。运动时氧耗差的平均值和氧耗差的增加超过正常范围的两倍。六个患者的值小于正常心输出量和氧耗的患者。氧耗差与氧耗对于个体的关系在图5中显示。

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Stroke volume

运动时，8名患者中氧耗差和氧耗均在正常范围内。运动时氧耗差的平均值和氧耗差的增加超过正常范围的两倍。六个患者的值小于正常心输出量和氧耗的患者。氧耗差与氧耗对于个体的关系在图5中显示。
substantial fall in stroke index was observed in 2 patients and in 1 of these the RVEDP remained unchanged while in the other the RVEDP increased by 4 mmHg (0.5 kPa). In one further patient the stroke index fell by 8 ml min⁻¹ m⁻² while the RVEDP increased from 1 mmHg (0.1 kPa) to 9 mmHg (1.2 kPa).

Oxygen saturations
The mean arterial oxygen saturation at rest and during exercise was identical (95 ± 3 per cent). Two patients showed a significant reduction of the arterial saturation at rest (90 and 88%). In one of these patients an increase occurred during exercise from 90 to 93 per cent but a further reduction to 86 per cent was observed in the other patient.

Analysis of the right heart blood samples by spectrophotometer revealed no evidence of a left-to-right shunt.

Effects of pulmonary regurgitation
Eight patients had early diastolic murmurs in the pulmonary area and these showed haemodynamic evidence of pulmonary regurgitation (pulmonary artery diastolic pressure within 0 to 2 mmHg (0 to 0.3 kPa) of the RVEDP).

In patients without pulmonary regurgitation the mean RVEDP at rest was 6 mmHg (0.8 kPa) and it was unchanged during exercise. The mean RVEDP at rest was also 6 mmHg (0.8 kPa) in the patients with pulmonary regurgitation and exercise caused a slight increase to 9 mmHg (1.2 kPa). The highest individual value recorded at rest was 13 mmHg (1.7 kPa) in a patient with pulmonary regurgitation (Fig. 3).

The mean pulmonary artery pulse pressure was 19 ± 6 mmHg (2.5 ± 0.8 kPa) in the patients with pulmonary regurgitation compared to 13 ± 5 mmHg (1.7 ± 0.7 kPa) in those without pulmonary regurgi-
immediately. Studies in Fallot’s tetralogy showed that during exercise, the RV/PA pressure gradient increased significantly. However, the increase was not statistically significant (P > 0.05). Minor differences in the cardiac output were observed in the two groups at rest and on exercise. The mean cardiac index at rest in patients with pulmonary regurgitation was 6.1 ± 1.1 min⁻¹ m⁻² increasing to 9.0 ± 1.1 min⁻¹ m⁻² on exercise compared to 4.6 ± 1.1 min⁻¹ m⁻² increasing to 7.6 ± 1.1 min⁻¹ m⁻². These differences were not statistically significant (P > 0.1 rest; P > 0.05 exercise).

Comparison of serial haemodynamic results
The results of the early and late postoperative catheterization studies are compared in Table 3 and they show remarkably little change in the intervening years. The mean RV systolic pressure, RVEDP, RAP, and PA diastolic pressures are identical and there are only minor changes in the RV/PA gradient, PA systolic, PA mean, and PAWP. However, one patient showed a significant increase in the PAWP from 7 to 19 mmHg (0.9 to 2.5 kPa) at rest and from 14 to 30 mmHg (1.9 to 4.0 kPa) during exercise. The effects of exercise were measured in only 3 patients who showed no significant haemodynamic change between the two studies.

The mean cardiac index in the early study was 3.8 ± 0.81 min⁻¹ m⁻² compared to 4.8 ± 1.61 min⁻¹ m⁻² in the later study. The difference is not statistically significant (P > 0.1). The mean AV oxygen difference at rest in both studies was within the normal range and only 1 patient had a value significantly greater than normal during exercise.

Discussion
The majority of haemodynamic studies after total correction for Fallot’s tetralogy have shown a decrease in the RV/PA systolic pressure gradient in later studies compared with measurements made immediately after operation (Kirklin and Karp, 1970; Muraoka et al., 1973). The results of catheterizations performed 5 to 6 years postoperatively compared with 1 year after operation have shown little subsequent haemodynamic change (Gotsman et al., 1969; Bristow et al., 1970). The RV/LV ratio was selected by Hawe et al. (1972) as the most valid indicator of the degree of pulmonary stenosis. They studied 37 patients and showed in 25 patients that the RV/LV ratio decreased between the completion of repair and restudy by 10 to 53 per cent. The ratio was unchanged in 4 patients and in 8 it was increased by 10 to 73 per cent.

In our study the RV/LV peak pressure ratio was 0.31 (range 0.16 to 0.42) and this indicates satisfactory relief of the pulmonary stenosis. It was also noted that the ratio did not differ significantly between patients who had a prosthetic patch in the right ventricular outflow tract and those who did not. Exercise caused an increase in the RV/PA systolic pressure gradient but the increase was slight or trivial in the majority of patients though more intense exercise would probably have shown a further increase (Epstein et al., 1973). Nevertheless, the increase in pulmonary blood flow during exercise was well tolerated. Another important observation was the unchanged RV/PA systolic pressure gradient in the patients catheterized previously. The relatively small increase in the RV/PA gradient during exercise and the constancy of the haemodynamic measurements with the passage of time strongly suggests that the restoration of a normal pulmonary blood flow provides an adequate stimulus for the growth of the right ventricular outflow tract and the pulmonary arteries.

Right ventricular myocardial function
The RVEDP was greater than 5 mmHg (0.7 kPa) in 10 patients and instead of the normal fall during exercise the RVEDP showed a further slight increase. Pulmonary regurgitation is one possible reason for the increased RVEDP but diminished
right ventricular compliance caused by persisting muscular hypertrophy or myocardial fibrosis may also be important. A fall in the stroke volume index and a concomitant increase in the RVEDP during exercise has been interpreted as indicating abnormal right ventricular myocardial function in patients with Fallot's tetralogy after total correction (Joransen and Moller, 1972) and also after pulmonary valvotomy for pulmonary stenosis (Finnegan et al., 1974; Stone et al., 1974). A similar occurrence was observed in 5 patients in the present study. Because of the presence of pulmonary regurgitation and the brevity of the isovolumic period in the right ventricle, it was not possible to derive indices of myocardial contractility (Vmax, Vpm) and therefore a more direct assessment of myocardial contractile function was not made.

Pulmonary hypertension
An increase in the pulmonary vascular resistance has been observed in the early postoperative period in the majority of patients (Albertal, Swan, and Kirklin, 1964) and in some patients thereafter (Lillehei et al., 1964; Hallidie-Smith et al., 1967; Gersony et al., 1973; Kinsley et al., 1974). However, other studies have shown a normal pulmonary vascular resistance and mean pulmonary artery pressures (Gotsman, 1966; Bristow et al., 1970; Epstein et al., 1973; Shah and Kidd, 1966). In our study there was no evidence of pulmonary arterial hypertension at rest or during exercise. The fall in the pulmonary vascular resistance during exercise shows the ability of the pulmonary vascular system to accommodate the increased pulmonary blood flow. This finding lends support to the view that the thrombotic lesions, seen in the pulmonary arteries of cyanotic patients, usually resolve when the pulmonary blood flow increases (Ferencz, 1960).

Pulmonary valvular regurgitation
The problem of pulmonary valvular regurgitation after total correction continues to cause concern as to its ultimate effects on right ventricular function. Though some authors consider pulmonary regurgitation to be the major postoperative problem (Soulić et al., 1971), others have concluded that it appears to be well tolerated (Malm et al., 1963; Gotsman, 1966; Jones et al., 1973; Sunderland et al., 1973).

In our study there was no significant difference in the resting cardiac output or the response to exercise in patients with and without pulmonary regurgitation. The slight increase in RVEDP during exercise was the main difference between the two groups. It appears, therefore, that pulmonary regurgitation is well tolerated but further observation is necessary to determine its ultimate significance because a long-term experimental study of pulmonary regurgitation has shown the development of right ventricular dilatation and hypertrophy and a reduced resting cardiac output (Ellison et al., 1970).

Recurrence of ventricular septal defect
Several authors report that the ventricular septal defect reopens in a small number of patients after total correction (Bristow et al., 1970; Sunderland et al., 1973; Joransen and Moller, 1972). Analysis of the right heart blood samples by spectrophotometer showed no evidence of left-to-right shunting in any of our patients. This does not exclude the presence of a small left-to-right shunt but more sensitive methods of shunt detection were not used by us.

Systemic oxygen saturations
The arterial oxygen saturations were normal in all except 2 patients at rest. One patient had an oxygen saturation of 90 per cent which increased to 93 per cent during exercise. The other patient had an oxygen saturation of 88 per cent and a further decrease to 86 per cent occurred during exercise. This patient was asymptomatic and had a high resting cardiac output, a normal response of the cardiac output during exercise, and a trivial degree of right ventricular outflow tract obstruction (RV/PA systolic gradient at rest = 5 mmHg (0.7 kPa)). The reason for the arterial unsaturation is, therefore, unexplained but it may be attributable to a persistent abnormality of pulmonary blood flow distribution.

Left ventricular function
Abnormal left ventricular function has been reported before and after total correction of Fallot's tetralogy (Jarmakani et al., 1972). The main abnormality described was a decreased left ventricular ejection fraction. Left ventricular function was not studied directly by us but the pulmonary wedge pressure was within normal limits in 14 patients. One patient had a PAWP at rest of 19 mmHg (2.5 kPa) which increased to 30 mmHg (4.0 kPa) during exercise. In the majority of patients, however, the failure to develop pulmonary hypertension and the response of the stroke volume during exercise probably indicates normality of LV function.
Cardiac output
The mean resting cardiac index for the group was 5.41 min⁻¹ m⁻² which is at the upper limit of normal and 6 patients had cardiac outputs above the normal range. Six subjects had a normal response of the cardiac output during exercise and 1 patient was slightly below the normal range. The remaining 8 patients had high cardiac outputs during exercise and this was associated with low AV oxygen differences. Though the patients were generally anxious there was no evidence of hyperventilation during the catheterization procedure or any other reason for the high output state such as anaemia, thyrotoxicosis, or arteriovenous shunting. However, the presence of small left-to-right shunts undetected by analysis of oxygen saturations is a possible explanation.

In normal subjects the response of the stroke volume during exercise is variable; it usually increases or is unaltered but it may fall (Donald et al., 1955). In patients with pulmonary stenosis studied postoperatively, a similar variability was observed (Finnegan et al., 1974; Stone et al., 1974). Another study of patients with pulmonary stenosis showed that in the presence of mild stenosis the stroke volume increased on exercise but when the stenosis was more severe the stroke volume remained constant (Moller, Rao, and Lucas, 1972). In our study the changes in stroke volume during exercise were also variable. The stroke volume increased in 8 subjects and decreased in 7, though a substantial decrease was observed in only 2 patients (38 ml and 27 ml).

The response of the cardiac output during submaximal exercise testing is clearly very satisfactory, but testing during more intensive exercise has shown a consistently reduced response (Epstein et al., 1973). Nevertheless, considering the presence of residual defects such as right ventricular outflow tract obstruction and pulmonary regurgitation, the performance of these patients during exercise is remarkably good. The ultimate effect of the residual abnormalities can only be determined by further clinical and haemodynamic studies.

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