Pre- and Postoperative Rest and Exercise Hemodynamics in Children with Pulmonary Stenosis

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SUMMARY
Twenty children with pulmonary valvular stenosis were studied by cardiac catheterization both at rest and during submaximal supine exercise, prior to and following pulmonary valvotomy. The resting and exercise states were comparable preoperatively and postoperatively since cardiac output, heart rate, $A - V$ $O_2$ difference and oxygen consumption were similar. Evidence of improved cardiac function was found postoperatively.

Both the rest and the exercise right ventricular end-diastolic pressure (RVEDP) decreased significantly following pulmonary valvotomy. Preoperatively, 12 of 20 patients showed an increase in RVEDP with exercise; in six of these there was a simultaneous fall in stroke index, indicating impaired myocardial function. No patient showed this response postoperatively.

This indicates that although altered cardiac function can be demonstrated in some children with pulmonary valvular stenosis, it is reversible by pulmonary valvotomy. This is in contrast to studies in adults, and suggests that a factor in the natural history of pulmonary valvular stenosis is the impact of chronically elevated afterload on the right ventricle. Hemodynamic measurements made during exercise provide a useful means of assessing patients with pulmonary stenosis before and after pulmonary valvotomy.

Additional Indexing Words: Right ventricular function, Oxygen consumption, Cardiac index, Stroke index, Myocardial fibrosis, Right ventricular end-diastolic pressure, Pulmonary valvotomy

PULMONARY VALVULAR STENOSIS is a progressive condition in some patients, most likely related to impaired right ventricular myocardial performance secondary to hypertrophy and/or fibrosis. Hemodynamic studies in patients with pulmonary valvular stenosis have shown impaired cardiac function in both children and adults preoperatively and in adults postoperatively. This impaired cardiac function appears to result from changes in the myocardium and occurs more commonly in patients with severe stenosis. It is unknown whether this impaired cardiac function is reversible by operation. Although pre- and postoperative hemodynamic studies in adults with pulmonary stenosis have been reported, these studies do not compare the same patient before and after pulmonary valvotomy.

We have evaluated the resting and exercise hemodynamics of 20 children with moderate or severe pulmonary stenosis before and after pulmonary valvotomy. Suspecting that limitations in right ventricular function may be present preoperatively, it was our intention to demonstrate whether significant hemodynamic changes occurred following pulmonary valvotomy. To our knowledge, there are no comparable reports of hemodynamic findings in children with pulmonary valvular stenosis before and after pulmonary valvotomy.

Materials and Methods
Twenty children with isolated pulmonary valvular stenosis were studied by cardiac catheterization before and after pulmonary valvotomy. There were 13 males and seven females. The patients ranged in age from 5$1/2$ years to 16$1/2$ years at the time of preoperative catheterization, the mean age being ten years. Preoperatively, the clinical, electrocardiographic, and roentgenographic findings were consistent with the diagnosis of isolated pulmonary valvular stenosis. Selective right ventriculography was used to demonstrate...
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the site of stenosis. Fixed infundibular stenosis was not present angiographically, and no patients exhibited evidence of infundibular stenosis on pressure tracings.

Preoperatively, each patient was studied in a resting, fasted state in the supine position. Premedication consisted of morphine and phenobarbital. A Goodale-Lubin catheter was utilized to measure right-sided cardiac pressures, and a Teflon arterial cannula, inserted into the brachial artery, was used to measure systemic arterial pressures. These were connected to P23db Statham strain gauges, and the pressure recorded on an Electronics-for-Medicine DR-12 optical recorder. In each patient, the resting cardiac output was measured by the Fick principle. Expired air was collected in a Collins chain-driven tank over a six minute period and analyzed by the Tissot-Shonander method to determine the rate of oxygen consumption. Midway through the collection, blood samples were drawn simultaneously from the pulmonary and brachial arteries for Van Slyke oxygen analysis. The venous catheter was withdrawn from the pulmonary artery to the right ventricle with continuous pressure recording. Right ventricular end-diastolic pressure (RVEDP) was recorded at low attenuation and the catheter was withdrawn from the right ventricle to the right atrium with continuous pressure recording.

The venous catheter was repositioned in the pulmonary artery and the patient exercised in the supine position using a variable resistance bicycle ergometer with a work load designed to increase the heart rate to between 140 and 160 beats/min. The duration of exercise was from 10-15 min and hemodynamic parameters were measured after a steady exercise state had been achieved for a period of at least four minutes. Cardiac output and right-sided cardiac chamber pressures were again measured.

The recordings were analyzed for heart rate and systolic and diastolic pressures. RVEDP was measured after the "a" wave. Cardiac index and stroke index were calculated from the measured data. Pulmonary valve area was calculated utilizing a modification of the Gorlin formula.

On the basis of an indexed pulmonary valve area less than 0.5 cm$^2$/m$^2$, each of the 20 patients underwent transfemoral pulmonary valvotomy an average of six months following catheterization. In 18 the procedure was performed during inflow stasis and in the other two the pump oxygenator was used for cardiopulmonary bypass in order to close an atrial communication.

Each of the patients was recatheterized one year following operation. Resting and exercise studies were performed in the same manner as that outlined above. The measured and derived data obtained preoperatively and postoperatively were compared utilizing a paired $t$-test.

Results

The mean values for the measured and derived data are shown in Table 1. Statistically significant differences ($P < 0.05$) were present between the rest and exercise states both preoperatively and postoperatively for oxygen consumption, $A-V$ oxygen difference, cardiac index, and heart rate. Therefore, the resting and exercise states, as determined by these parameters, were different physiologically.

Comparing the preoperative to the postoperative data, no significant differences were found during rest or exercise for oxygen consumption, $A-V$ oxygen difference, heart rate or cardiac index. This indicates that the patients had been studied in comparable resting and exercise states before and after pulmonary valvotomy.

The resting cardiac index was greater than 3.0 L/min/m$^2$ in 16 of the 20 patients prior to operation. In the four patients with the most severe pulmonary stenosis (PVA < 0.2 cm$^2$/m$^2$), the cardiac indices ranged from 2.6 to 2.9 L/min/m$^2$. Postoperatively the resting cardiac index was greater than 3.0 L/min/m$^2$ in each of the 20 patients.

The relationship between cardiac index and oxygen consumption during exercise was normal in 18 patients prior to operation (fig. 1). In the remaining two patients, both with severe stenosis, the cardiac index was lower than anticipated for the amount of oxygen consumed. Postoperatively, each patient exhibited a normal relationship between cardiac index and oxygen consumption on exercise.

Both pre- and postoperatively, the right ventricular peak systolic pressure increased from rest to exercise.

### Table 1

<table>
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<th>Hemodynamic Variables at Rest and During Exercise</th>
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Mean ± two standard deviations for measured and derived hemodynamic data. No significant differences between preoperative and postoperative measurements at rest or during exercise for oxygen consumption, $A-V$ oxygen difference, cardiac index, or heart rate. Both the resting RVEDP and the exercise RVEDP decreased significantly following pulmonary valvotomy ($P < 0.05$).

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in each patient. The resting right ventricular systolic pressure following operation was lower than the resting value preoperatively, and the increase in right ventricular systolic pressure occurring with exercise was considerably less in the postoperative patients (fig. 2).

Prior to operation, stroke index showed no significant change from rest to exercise. In contrast, following operation there was a significant increase ($P < 0.05$) of stroke index on exercise (table 1) even though the resting value was the same as that prior to operation.

Three significant changes of $RVEDP$ occurred following pulmonary valvotomy (table 1). The mean resting $RVEDP$ decreased from a preoperative value of $9.6 \pm 3.2$ mm Hg to a postoperative value of $7.1 \pm 2.1$ mm Hg ($P < 0.05$). Secondly, the exercise $RVEDP$ decreased from preoperative value of $12.3 \pm 5.0$ mm Hg to $7.0 \pm 2.2$ mm Hg ($P < 0.05$). Thirdly, prior to operation the average $RVEDP$ rose significantly with exercise, while postoperatively the average $RVEDP$ showed no change from rest to exercise. The direction and magnitude of these changes in $RVEDP$ were also statistically significant ($P < 0.05$). Of the individual responses of $RVEDP$ with exercise prior to operation, $RVEDP$ rose in 12 patients, remained constant in four patients and decreased in the remaining four patients; postoperatively the $RVEDP$ increased in five patients, remained constant in eight patients, and decreased in the other seven patients.

Differences between the preoperative and postoperative states were apparent when the change from rest to exercise of the simultaneously measured stroke index and right ventricular end-diastolic pressure was studied (fig. 3). Preoperatively, 11 patients exhibited an abnormal response. Six of these showed a simultaneous fall in stroke index and rise in $RVEDP$ while five others exhibited a rise of both $RVEDP$ and stroke index. In another patient, although $RVEDP$ fell, stroke index fell 10 ml/beat/m². In the remaining eight patients response was normal.
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Following operation, 17 patients showed a normal change of RVEDP and stroke index with exercise. Three were abnormal, one showing a fall in stroke index without change in RVEDP and two showing a rise in RVEDP without a change in stroke index. No patient who showed an increase in stroke index on exercise preoperatively subsequently decreased the stroke index with exercise following operation; nor did any patient whose RVEDP fell with exercise preoperatively show an increase in RVEDP with exercise postoperatively.

The data of the 12 patients who showed an abnormal relationship between changes in RVEDP and stroke index from rest to exercise prior to operation are shown in figure 4. In five of these, both parameters increased on exercise, and when they were restudied postoperatively the exercise response was normal in each. Six other patients preoperatively showed a rise in RVEDP and a fall in stroke index. Postoperatively these also were in the normal range. In the final patient, RVEDP remained constant, but SI fell by at least 10 ml/beat and there was no change following operation.

Discussion

Hemodynamic measurements obtained at cardiac catheterization can provide useful information concerning myocardial function, particularly when the values obtained at rest and during exercise are compared. Our study was designed to analyze selected hemodynamic parameters in children with severe pulmonary valvular stenosis before and after pulmonary valvotomy to determine if operation improved cardiac function in these patients.

Preoperatively, four of 20 of our patients had cardiac indices less than 3.0 L/min/m², whereas postoperatively each patient had a normal cardiac index. The lower than normal values in four patients prior to operation were related to increased right ventricular afterload which, when reduced by pulmonary valvotomy, was associated with a cardiac index in the normal range. A linear relationship exists between cardiac index and oxygen consumption on exercise; for a given oxygen consumption the cardiac index should exceed a particular value if cardiac function is normal. Preoperatively, two of our patients on exercise exhibited a lower than expected cardiac index for the amount of oxygen consumed. In the remainder, the relationship was normal. Following operation each of the 20 patients showed a normal relationship between these parameters.

Despite these individual differences, the resting and exercise states were comparable in our patients both before and after operation. The following measurements, when compared preoperatively and postoperatively, revealed no significant differences: rest and exercise cardiac index, rest and exercise oxygen consumption, rest and exercise $A - V$ oxygen difference, and rest and exercise heart rate. If the pre- and postoperative states as defined by these parameters were comparable, then the differences in other hemodynamic measurements should define alterations of cardiac function which occurred secondary to pulmonary valvotomy.

We found significant changes in stroke index and RVEDP which help to define improvement in cardiac function. Normally, stroke index increases slightly from rest to exercise. Previous studies in children and in adults with pulmonary valvular stenosis, particularly those patients with severe obstruction, have demonstrated that the stroke index may remain constant or even decrease with exercise. Preoperatively the mean value of stroke index in our patients remained constant from rest to exercise. Following surgery, the mean value of stroke index increased significantly from rest to exercise. This postoperative increase of stroke index with exercise compared with the fixed stroke index preoperatively, indicates improvement of cardiac function related to decrease in right ventricular afterload.

Measurement of RVEDP can also be used as an indicator of myocardial function. Normally, the RVEDP falls during exercise. Conditions causing abnor-
malities of right ventricle compliance or an increase in preload or afterload can lead to no change or an increase in RVEDP with exercise.\(^1\) When comparing the preoperative to postoperative hemodynamics in our patients, the most striking changes were in the RVEDP. Prior to operation, the RVEDP was higher than normal at rest and rose significantly with exercise. Following pulmonary valvotomy, RVEDP was significantly lower both at rest and during exercise.

Study of the simultaneous changes of stroke index and RVEDP from rest to exercise also showed changes following operation. In 11 patients an abnormal response of these two parameters was present prior to operation. In five both stroke index and RVEDP rose prior to operation, while the other six showed a rise in RVEDP and a fall in stroke index. These two measurements returned to normal in each of the 11 patients following pulmonary valvotomy and the resultant decrease in right ventricular afterload.

The mechanisms by which changes in afterload affected the measured changes in stroke index and RVEDP is unknown, since we did not measure right ventricular compliance or right ventricular volume. These changes were perhaps related to a decrease in right ventricular hypertrophy as the afterload fell, but more data are needed.

The natural history of pulmonary stenosis is uncertain. The clinical state appears to progress in some patients, but it is unclear whether this is due to a decrease in the relative pulmonary valve orifice with age,\(^9\) factors altering right ventricular myocardium\(^1,\,2,\,7\) or both. In adult patients with pulmonary stenosis, whether studied preoperatively\(^3,\,8,\,10\) or postoperatively\(^2,\,7\) abnormalities of cardiac function are found frequently, the principal finding being an inability to increase their cardiac output on exercise. Impaired cardiac function secondary to myocardial fibrosis\(^2\) or an adaptation of the circulation leading to more effective oxygen extraction and utilization have been given as explanations for the limitation in cardiac output response to exercise. In contrast to these reports of adults, children with pulmonary valvular stenosis whether before or after operation\(^4\) show an ability to increase their cardiac output with exercise.

Our studies suggest that right ventricular function may be abnormal in patients with pulmonary stenosis and reflect changes in afterload. We feel that changes in the right ventricular myocardium may be a significant factor in the natural history and contribute to progression of severity of pulmonary stenosis. The data derived from the present study indicate that impairment of right ventricular function occurs as early as childhood in patients with severe pulmonary stenosis, but surgical intervention in these children can be followed by significant improvement in cardiac function. This finding is especially significant when compared to findings in adult patients after surgery for pulmonary stenosis, which would indicate that impaired cardiac function in this age group secondary to chronic elevated right ventricular afterload may be irreversible.

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