Pulmonary Function in Adults with Intracardiac Septal Defect

By C. R. Woolf, M.D.

DYSPEA is an important cause of disability in adults with atrial or ventricular septal defect. In spite of this, there have been few studies of pulmonary function in these patients. McIlroy and Apthorp measured ventilation, gas mixing, gas diffusion, and the mechanics of breathing in 13 patients and Ayres, Kozam, and Lukas reported on the mechanics of breathing in nine patients. In other reports, the diffusing capacity of the lungs has been the main consideration.

In the present investigation pulmonary function was studied in relation to dyspnea and pulmonary artery pressure in 45 patients with intracardiac septal defect.

Material and Methods

The 45 patients ranged in age from 15 to 53 years, with a mean age of 29 years. There were 22 men and 23 women. Atrial septal defect was present in 28 patients, ventricular septal defect in 15 patients, and both abnormalities were present in two patients. In all cases, the diagnosis was confirmed by cardiac catheterization and only patients with isolated intracardiac septal defect were included in the study. In 31 cases the pulmonary vascular resistance was calculated from the measured pulmonary blood flow, a mean pulmonary arterial pressure, and a pulmonary wedge pressure. In 14 cases the pulmonary blood flow was estimated from a knowledge of the pulmonary: systemic flow ratio. The pulmonary vascular resistance was arbitrarily considered significantly raised if the value was greater than 3 units (240 dynes sec. cm.\(^{-5}\)). The pulmonary vascular resistance was less than 3 units in 27 patients and greater than 3 units in 18 patients.

Many aspects of pulmonary function were examined although not all tests were performed on all patients (table 1). The techniques used for measuring ventilation, lung volumes, gas mixing, oxygen consumption, pulmonary diffusing capacity, and the resting mechanics of breathing have been described.

The arterial oxygen saturation was recorded by ear oximeter during a 1-minute 30-step test and during a treadmill exercise test in which the patient walked for 5 minutes at one mile per hour at a 4 per cent grade. During the fifth minute of treadmill exercise simultaneous measurements were made of minute volume of respiration, oxygen consumption, pulmonary diffusing capacity, and the mechanics of breathing. Compliance and work of breathing were measured from pressure-volume loops and total nonelastic resistance by the method of Frank, Mead, and Ferris. A mild exercise was used so that even severely disabled patients could complete the test.

Dyspnea was graded as slight, moderate, or severe. Slight dyspnea was considered present if the patient said that he was able to walk with normal people of his own age and build on the level but was unable to keep up on hills or stairs, or on severe exertion. Moderate dyspnea was present if the patient was unable to keep up with normal people on the level but was able to walk slowly at his own speed on the level for at least a mile. Severe dyspnea was present if the patient was unable to walk more than 100 yards on the level without rest or was breathless on talking or dressing. There were 30 patients with slight dyspnea, eight with moderate dyspnea, and seven with severe dyspnea.

Results

The clinical abnormalities in the patients are listed in table 2. Orthopnea was an occasional complaint and paroxysmal nocturnal dyspnea occurred in three patients. The physical examination of the lungs was usually normal, even in patients with moderate or severe dyspnea. Basal crepitations were heard in only two patients, although sibilant rhonchi were present in eight cases. Hepatomegaly was occasionally present but increased jugular venous pressure and peripheral edema were each noted only once.

The relationships between dyspnea, pulmonary artery pressure, and pulmonary vascular...
The relationship between dyspnea, mean pulmonary artery pressure, and pulmonary vascular resistance. Symbols with a surrounding circle indicate patients with pulmonary vascular resistance greater than 3 units. Symbols without a surrounding circle indicate patients with a pulmonary vascular resistance of less than 3 units.

Resistance are shown in figure 1. All but one of the patients with moderate or severe dyspnea had a mean pulmonary artery pressure greater than 25 mm. Hg; this raised pressure was due to high pulmonary blood flow in some cases and to high pulmonary vascular resistance in others. However, many patients with high pulmonary artery pressure and high pulmonary vascular resistance had little dyspnea. There was no relationship between the level of the pulmonary artery pressure or

Table 1

<table>
<thead>
<tr>
<th>Pulmonary function tests</th>
<th>Slight</th>
<th>Moderate</th>
<th>Severe</th>
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<tbody>
<tr>
<td>Forced vital capacity</td>
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<tr>
<td>Residual volume</td>
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<td>Total lung capacity</td>
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<tr>
<td>Forced expiratory volume (1 sec.)</td>
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<td>Maximum voluntary ventilation (free)</td>
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<tr>
<td>Single breath oxygen</td>
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<td>7-minute oxygen washout</td>
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<tr>
<td>Resting</td>
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<td>Diffusing capacity</td>
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<td>Exercise</td>
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<td></td>
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<tr>
<td>Resting</td>
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<tr>
<td>Mechanics of breathing</td>
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<tr>
<td>Exercise</td>
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<tr>
<td>Minute volume, oxygen consumption, and</td>
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<tr>
<td>ventilatory equivalent on exercise</td>
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<tr>
<td>Fall of arterial oxygen saturation on exercise</td>
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the level of the pulmonary vascular resistance and the degree of dyspnea. For example, there were six patients with the Eisenmenger syndrome, of whom two had slight, two had moderate, and two had severe dyspnea.

Most patients had little difficulty in ventilation. For example, the forced expiratory volume (1 second) was less than 70 per cent of the total forced vital capacity in only three of 29 patients. The forced vital capacity, lung volumes, forced expiratory volume (1 second) and maximum voluntary ventilation all showed similar results in the three dyspnea groups. Gas mixing was always normal. Diffusing capacity at rest was nearly always normal and showed no relationship to dyspnea.7

The fall of arterial oxygen saturation during exercise did not separate the dyspnea groups (fig. 2). During the treadmill exercise test the oxygen consumption was similar in all three groups and the groups were not differentiated by the diffusing capacity during exercise, which was nearly always within normal limits even in severely disabled patients.7 An abnormally raised minute volume of ventilation during exercise was the rule in the severe dyspnea group but this was found also in many of the patients who complained of only slight dyspnea (fig. 3).

There was no relationship between grade of dyspnea and resting compliance, nonelastic resistance, and work of breathing. During exercise, compliance was similar irrespective of dyspnea grade (fig. 4) but total nonelastic resistance and work of breathing tended to be higher in the more severely dyspneic patients (figs. 5 and 6). Although the mechanics of breathing did not differentiate the three dyspnea groups, many patients irrespective of

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**Table 2**

<table>
<thead>
<tr>
<th>Number of Patients in Each Dyspnea Group and the Relationship of Dyspnea to the Symptoms and Signs of Cardiac Failure</th>
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<tbody>
<tr>
<td>Dyspnea</td>
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<tr>
<td>Total number</td>
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<tr>
<td>Orthopnea</td>
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<tr>
<td>Paroxysmal nocturnal dyspnea</td>
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<tr>
<td>Crepitations</td>
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<tr>
<td>Rhoehi</td>
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<tr>
<td>Raised jugular venous pressure</td>
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<tr>
<td>Edema</td>
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<tr>
<td>Hepatomegaly</td>
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</tbody>
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**Figure 3**

The relationship between dyspnea and minute volume during treadmill exercise. The dotted lines are one standard deviation about the mean of a control group of 40 normal subjects.

**Figure 4**

The relationship between dyspnea and pulmonary compliance during treadmill exercise. Fifteen normal subjects are included for comparison.

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Dyspnea related to minute volume and work of breathing during treadmill exercise. Symbols without a surrounding circle indicate patients with slight dyspnea. Symbols with a surrounding circle indicate patients with moderate or severe dyspnea.

Minute volume of ventilation and work of breathing during exercise have been related in figure 7. An abnormally high minute volume alone and high work of breathing alone were not necessarily related to dyspnea. However, a minute volume greater than 18 L. per minute per M.² and a work of breathing greater than 2 Kg.M. per minute occurring together distinguished the moderate and severe dyspnea groups, from the slight dyspnea groups, there being only two exceptions.

What is the stimulus causing excessive hyperventilation during exercise in many patients with intracardiac septal defect? Such hyperventilation might result from a low compliance causing an exaggeration of the Hering-Breuer reflex. No relationship was demonstrable between minute volume of respiration and compliance during exercise. It seemed reasonable that the hyperventilation should be related to fall of arterial oxygen saturation during exercise but no direct correlation could be demonstrated. Although patients with a significant fall of arterial oxygen saturation (greater than 4 per cent) always had an abnormally high minute volume of ventilation, there were others with similar hyperventilation who showed little or no fall of the arterial oxygen saturation.

A possible explanation for the excessive ventilation during exercise is suggested from...
an analysis of the relationship between minute volume of respiration and diffusing capacity (fig. 8). In the patients with intracardiac septal defect who had abnormally high minute volumes only a normal diffusing capacity was achieved. In other words, in these patients, for any given diffusing capacity the ventilation required was considerably greater than in most normal subjects. This suggests that there is some difficulty in obtaining the increased oxygen required by exercise, and this difficulty is overcome by hyperventilation.

This relatively low pulmonary diffusing capacity may be due to thickening of the alveolar-capillary membrane or to an abnormality of ventilation-perfusion relationships where there might be well perfused but poorly ventilated alveoli or poorly perfused but well ventilated alveoli. In favor of a generally altered alveolar-capillary membrane is the relationship between compliance and diffusing capacity during exercise significant at the 1-per cent level by t test (fig. 9). As compliance decreases diffusing capacity also becomes less. Moreover, there is a relationship between total nonelastic resistance and diffusing capacity during exercise, also significant at the 1-per cent level (fig. 10). As the total nonelastic resistance rises, the diffusing capacity falls.

The alveolar-capillary membrane is usually reported as normal in patients with intracardiac septal defect but changes have occasionally been described. It might require special attention to show lesions, such as edema, which might cause a low compli-
The raised total nonelastic resistance might be due to partial obstruction in alveolar ducts or respiratory bronchioles from edema or a minute excess of alveolar fluid. These multiple airway obstructions would decrease ventilation in tiny peripheral areas but blood flow through these areas need not be interrupted. This would lead to decrease in effective area of blood-gas interface, apart from also increasing venous admixture.

These suggested pathologic abnormalities may be due to a raised pulmonary artery pressure being transmitted to at least the proximal end of the pulmonary capillaries and causing exudation of fluid into the alveolar-capillary membrane and into the alveolus itself. Evidence in favor of this is the relationship (by t test significant at the 1-per cent level) between mean pulmonary artery pressure and total nonelastic resistance on exercise, the two rising together (fig. 11). There is no statistically significant relationship between mean pulmonary artery pressure and compliance during exercise. Eight of the 11 patients with compliance of less than 0.1 L./cm., however, had a mean pulmonary artery pressure greater than 30 mm. Hg. No significant relationships could be shown between the mechanics of breathing during exercise and pulmonary vascular resistance or pulmonary:systemic flow ratio.

It is therefore suggested that raised pulmonary artery pressure is the important factor in initiating lung damage in patients with intracardiac septal defect. This raised pressure is significant, even when due to high flow in the absence of raised pulmonary vascular resistance. In many patients the raised pressure causes edema of the alveolar-capillary membrane and exudation of fluid causing obstruction in the smallest air passages. These abnormalities are reflected by a low compliance and raised total nonelastic resistance. The pulmonary abnormalities result in difficulty in maintaining oxygen requirements but this is compensated by excessive hyperventilation that would probably cause an increased alveolar oxygen tension. This hyperventilation masks a low diffusing capacity. In some cases the hyperventilation is probably related more directly to a fall of arterial oxygen saturation on exercise where a right-to-left shunt is present. In patients with moderate or severe dyspnea this abnormal hyperventilation during mild exertion, irrespective of its basic cause, is associated with a high work of breathing, this dual abnormality separating them from the patients with only slight dyspnea on exercise.

Summary

Pulmonary function has been assessed in 45 patients with atrial or ventricular septal defect. Moderate and severe dyspnea occurred almost exclusively in patients with high pulmonary artery pressure irrespective of whether this was due to high pulmonary blood flow or high pulmonary vascular resistance.

Evidence is presented suggesting that this raised pulmonary artery pressure causes lung damage shown by a low compliance and high nonelastic resistance. These findings suggest an abnormal alveolar-capillary membrane and an abnormality of ventilation-perfusion relationships, which in turn cause a relatively low pulmonary diffusing capacity requiring excessive hyperventilation on exercise to maintain oxygen requirements. In patients with moderate or severe dyspnea, the abnormally high minute volume of ventilation during mild exertion is associated with a high.
work of breathing, the dual abnormality separating them from patients with only slight dyspnea on exertion.

Acknowledgment

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References


Empirical Induction

"Empirical induction" in the natural sciences proceeds from a particular series of observations of a certain phenomenon to the statement of a general law governing all occurrences of this phenomenon. The degree of certainty with which the law is thereby established depends on the number of single observations and confirmations. This sort of inductive reasoning is often entirely convincing; the prediction that the sun will rise tomorrow in the east is as certain as anything can be, but the character of this statement is not the same as that of a theorem proved by strict logical or mathematical reasoning.

In quite a different way mathematical induction is used to establish the truth of a mathematical theorem for an infinite sequence of cases, the first, the second, the third, and so on without exception.—Richard Courant and Herbert Robbins. What is Mathematics? An Elementary Approach to Ideas and Methods. England, Oxford University Press, Tenth Printing, 1960, p. 10.
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