The Effects of Work on the Pulmonary Circulation in Mitral Stenosis

By Harald Eliasch, M.D., Geoffrey Wade, M.B., M.R.C.P. and Lars Werkö, M.D.

In an attempt to understand more fully the hemodynamic effects in mitral stenosis, the vascular response to effort was studied in 12 cases. It was found that pulmonary arterial pressures rose, but did not necessarily parallel changes in the pulmonary “capillary venous” pressure (pcv), suggesting that the response pattern may be modified by secondary pulmonary vascular change. Further, in some studies, pulmonary “capillary venous” pressures were found to rise initially and then fall despite continuing work, emphasizing the necessity to choose work of such a degree and duration that a steady state may be obtained.

In 1946 Bloomfield and co-workers, by passing a catheter into the pulmonary artery, demonstrated the presence of pulmonary hypertension in mitral stenosis, while Hickam and Cargill in 1948 showed that this pressure rose on exercise. The ability to measure the pulmonary “capillary venous” pressure and permitted a fuller understanding of the circulatory dynamics in mitral stenosis. The response to effort in patients with this condition is an important part of the clinicopathologic picture, and the purpose of this paper is to present changes in pressures and flow on graded work which occurred in 13 studies made on 12 cases of mitral stenosis.

Material

Patients were selected at random, and all had typical signs of mitral stenosis. No patient was in right heart failure at the time of the study. Functional grouping and clinical data are summarized in table 1.

Technic

All cases were studied in the morning, recumbent, and in the postabsorptive state. The pulmonary artery was catheterized. The pulmonary “capillary venous” pressure (pcv) was recorded, using the technic described by Lagerlöf and Werkö. An indwelling needle was placed in the brachial artery. All pressures were recorded with the Tybjaerg-Hansen and Warburg manometer, mean pressures being recorded by electrical filtration. Cardiac output was determined by the direct Fick method. Total plasma volume was estimated with Evans blue dye. The mean circulation time and cardiopulmonary blood volume were calculated. Vascular resistances were calculated with the usual formulas.

All basal estimations were made following a period of 30 minutes rest. Work was then performed on a bicycle ergometer with the patient in supine position. Pressures were first recorded after the legs had been raised to the pedals but before work actually commenced. Work was performed over a period of 10 to 20 minutes and was of a degree well within the patients capabilities (approximately 70 Kg. per minute). Pressures were recorded at frequent intervals throughout the period of work. The catheter was left in the pulmonary capillaries as long as seven minutes and then withdrawn into the pulmonary artery. Cardiac output and cardiopulmonary blood volume by dye method were estimated two minutes before cessation of work. Work was not stopped for the purpose of pressure and flow estimations.

Further pressure recordings were made 5 to 15 minutes after cessation of work, in some cases in the pulmonary capillaries as well as in the pulmonary artery. Cardiac output by the Fick method was also estimated in most cases. Finally, on withdrawal, pressures were recorded in the right ventricle and the right auricle.

Results

Cardiac Output. On commencing work the pulse rate invariably rose, an approximately constant rate being obtained after periods of one to four minutes.

The basal oxygen consumption ranged between 123 and 168 ml. per minute per square meter of surface area, rising on effort to between 187 and 286 ml. per minute per square
The basal A-V oxygen difference did not exceed 5.5 volumes per hundred cc., at rest, but increased on effort to a pathologic extent in six studies (greater than 6.8 volumes per 100 cc. at an oxygen consumption less than 400 ml. per minute per square meter of surface area)2).

The resting cardiac indexes were from 2.5 to 4.7 liters per minute, rising on effort in seven studies and not changing significantly in six. In three of these latter studies the A-V oxygen difference remained within normal limits.

**Pulmonary Pressures.** In studies Nos. 311 and 331 the pulmonary “capillary venous” pressure was within normal limits, both at rest and on effort. In the other studies the resting pulmonary “capillary venous” pressure was abnormally high, ranging between 13 and 25 mm. Hg. The response to effort was of three types: (a) In studies Nos. 306a, 315 and 316 an initially high pulmonary “capillary venous” pressure (25, 23 and 25 mm. Hg, respectively) did not increase further. (b) In studies Nos. 321, 324, 337 and 338 a moderately increased pulmonary “capillary venous” pressure (14, 18, 19 and 16 mm. Hg, respectively) rose further on effort, remaining at a constant level throughout the duration of work. (c) In studies Nos. 320, 322, 332 and 334 a moderately elevated resting pulmonary “capillary venous” pressure (13, 14, 19 and 21 mm. Hg, respectively) rose sharply after two to three minutes work, falling again to a level which was constant during the remaining period of work. In two of these studies it fell back to the basal value, but was above this level in the other two (figs. 1 and 2).

The resting pulmonary arterial pressures (PA) were within normal limits in only one study (No. 311), and there was no significant rise on effort. In all other studies there were varying degrees of pulmonary hypertension at rest, the pressures increasing further on effort. This increase affected the systolic more than the diastolic pressures with a consequent increase in pulse pressure in all but one study.

**Pulmonary Pressure Gradient.** Figure 3 shows graphically the changes in pulmonary arterial mean—pulmonary “capillary venous” pressure gradient occurring on effort. In four cases with a basal pulmonary “capillary venous” pressure below 20 mm. Hg the gradient did not change significantly. In the remaining cases the mean pulmonary arterial pressures rose more than the pulmonary “capillary venous” pressures. This increase in gradient tended to

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**Table 1.—Summary of Clinical Data**

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TABLE 2.—Pressures and Flow at Rest, on Effort and on Recovery

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<th>Pulmonary arterial pressure</th>
<th>PCV mean</th>
<th>Brachial arterial pressure</th>
<th>Pulmonary Resistance (dynes sec. cm⁻¹)</th>
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B = Basal  
E = Effort  
R = Recovery  

(Pressures in mm. Hg; referred to 5 cm. below the sternal notch.)
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be greatest in those studies with a high resting pulmonary "capillary venous" pressure; in four studies a considerable rise in pulmonary arterial mean pressure occurred in the absence of a rise in pulmonary "capillary venous" pressure. greatest in those with a high resting pulmonary "capillary venous" pressure.

**Cardiopulmonary Blood Volume.** Under basal conditions the cardiopulmonary blood volume was within normal limits in all studies. In only two studies was there a significant change

![Diagram](http://circ.ahajournals.org/)

**Fig. 2.** Simultaneous recording of pulmonary "capillary venous" pressure, respiration, electrocardiogram and phonocardiogram at rest, after two minutes' work and after seven minutes' work. In the third tracing brachial arterial pressure is also recorded.

**Pulmonary Resistance.** The pulmonary arteriolar resistance varied widely in different studies. In Nos. 311, 331, 332 and 338 the resting values were within normal limits and did not rise on effort. In the remaining studies the basal values ranged between 84 and 678 units and up to 1050 units on effort. The changes in resistance paralleled the alteration in pulmonary arterial mean-pulmonary "capillary venous" pressure gradient, tending to be on effort (Nos. 331 and 332), both showing an increase.

**Systemic Circulation.** The changes observed in the systemic circuit were small. A slight rise in arterial pressure occurred in six studies; there was no change in six, and in one study there was a slight fall.

**Recovery.** On recovery flow and pressure approximated the basal values in most studies. In No. 321 (fig. 4) and No. 337 the pulmonary
"capillary venous" pressure fell considerably below the basal value, and this was accompanied in No. 337 by a fall in the pulmonary arterial mean pressures, although the pulmonary arterial mean-pulmonary "capillary venous" pressure gradient was increased. Abnormally low pulmonary arterial pressure values on recovery were also observed in study No. 332, but a simultaneous pulmonary "capillary venous" recording was not available. In the latter studies there was no significant change in cardiac output.

**FIG. 3.** The relation between pulmonary "capillary venous" mean and pulmonary arterial pressure at rest and on effort. Closed circles = at rest, X = on effort.

**DISCUSSION**

The correct assessment of the circulatory response to effort depends on the work being of such a degree and duration that a steady state can be achieved. This is fundamental, for unless a steady state is achieved, not only is the direct Fick method, and consequently all calculations involving the cardiac output, invalid, but the pattern of pressure response may also be changing. For this reason light work for a period of 10 to 20 minutes was adopted. That a steady state was probably achieved was shown by a constant pulse rate and steady pressures after the fifth minute of work in all studies. Further, estimations of oxygen consumption and cardiac output after the fourteenth and eighteenth minute of work in two studies showed no significant change.

It is also desirable that the resting figures should be obtained under basal conditions.
Despite all precautions the pulse rate was high and the arteriovenous oxygen difference low in studies Nos. 332 and 338. Finally, it is preferable not to use morphine-containing drugs in premedication, since they may themselves be a cause of pulmonary hypertension.19

The limited rise in flow on effort in advanced cases of mitral stenosis was pointed out by Mea-kins and co-workers in 1923.11 In seven of the present studies the rise was inadequate, as shown by an abnormally great arteriovenous oxygen difference in relation to the oxygen consumption. In study No. 332 an unchanged cardiac output was accompanied by a normal arteriovenous oxygen difference of 5.1 volumes per 100 cc. As the resting figures in this study were probably not obtained under basal conditions, this response was not necessarily abnormal.

Although there is considerable evidence showing that in normal subjects and in patients with auricular septal defects the pulmonary "capillary venous" pressure is a good index of left auricular pressure,1, 4, 12-14 the relationship may not be maintained in mitral stenosis. The pathologic changes known to occur in the lungs in mitral valvular disease16-17 must play a part in conditioning the pattern of the pulmonary "capillary venous" pressure response to effort by disturbing pressure-volume relationships. The increased degree of dyspnea proportional to the amount of effort with possible changes in the intrapleural pressures may also be concerned.

In two studies the response to effort was normal, the pulmonary "capillary venous" pressure rising only to 12 and 13 mm. Hg, respectively. Presumably in these cases there was no significant rise in left auricular pressure, and the pressure-volume relationships of the pulmonary capillary bed were not abnormal at the level of the output. In five studies the pulmonary "capillary venous" pressure rose promptly and remained elevated. It is possible that this was due to a corresponding rise of the left auricular pressure, but doubt is cast on this explanation by the behavior of the pulmonary "capillary venous" pressure in the four studies shown in figure 1. It is possible that transitory imbalance between right and left ventricular outputs is responsible for the early rise and later fall in pulmonary "capillary venous" pressure, but some increase in the distensibility of the lung following a period of increased congestion cannot be excluded.18 Slowly developing arteriolar vasoconstriction may also be possible, for although the existence of active vasomotor mechanisms is by no means certain,19-21 recent studies suggest that they may occur.22-24 Other factors to be considered are a slow redistribution of blood in the lungs, the development of right ventricular failure and an excessively short diastolic filling time. It is unlikely that these two latter factors were concerned in the reported studies. All patients were ambulant and had shown no signs of peripheral congestion at work levels higher than those of the study. Also, if failure had developed in the course of the study, it is unlikely that a steady state would have been achieved. A shortened diastolic filling time played no part, for the heart rate was not more rapid during the first three minutes of work than it was later.

Uncertain though the factors underlying changes in pulmonary "capillary venous" pressure are, the results emphasize the necessity to maintain effort for a period longer than four to five minutes.

In two studies there was a significant rise in cardiac output without any change in pulmonary "capillary venous" pressure, a finding at variance with results reported by other workers.25 The explanation may lie in the fact that these workers used greater loads and recorded pressures and flow after only two to three minutes work. Under these circumstances a steady state could not have been achieved. Further, these workers recorded pressures and flow during different three minute work periods, which were separated by an interval of rest. Results obtained in this laboratory (not reported in this study) suggest that under these conditions, there may not be a similar vascular response pattern at the same work and output levels.

With the exception of one study, in which all pulmonary pressures were normal throughout, there was a varying degree of resting pulmonary hypertension increasing further on ef-
fort. In two studies rises of 8 and 12 mm. Hg in the pulmonary capillaries were accompanied by a parallel rise in pulmonary arterial mean pressure and a fall in pulmonary arteriolar resistance. In four studies a large increase in pulmonary arterial pressures occurred in the absence of any change of pulmonary “capillary venous” pressure, the resistance rising considerably. In the remaining studies there was a varying rise in pulmonary mean arterial pressure and always an increase in resistance.

Although there is a good correlation between the resting pulmonary “capillary venous” pressure and the degree of pulmonary arterial pressure rise on effort (fig. 3), this rise could not itself be dependent on the rise in pulmonary “capillary venous” pressure alone, for this may remain constant, and the highest pulmonary “capillary venous” pressure levels were recorded in studies where only a moderate rise in pulmonary arterial pressure was observed. The secondary pathologic changes known to occur in mitral valvular disease cause a great reduction in the diameter of the arterioles and probably also an increase in the elasticity modulus. In such a system small changes in blood volume may cause large changes in pressure, and there need be no change in pulmonary “capillary venous” pressure. Such changes in volume may be too small to be detected by the available methods of estimating cardiopulmonary blood volume.

In these reported studies all gradations of response of the pulmonary arterial pressures to effort are seen, and generalizations on changes in pulmonary arteriolar resistance would seem to be unjustified. That the greatest pulmonary arterial pressure rise should be seen in those studies with a high resting pulmonary “capillary venous” pressure is to be expected, for pathologic change in the pulmonary vessels are most probably secondary to increases in the pulmonary venous pressure.

It is possible that in certain cases of mitral stenosis, where the secondary pulmonary vascular changes are extreme, the limited ability of the cardiac output to rise on effort may not be directly dependent on the orifice of the mitral valve, but rather on the degree of pulmonary arteriolar narrowing.

Summary

1. The vascular response to graded work was studied on 13 occasions in 12 cases of mitral stenosis.
2. The degree and duration of work was such that a steady state was obtained. The importance of this is discussed.
3. The cardiac output rose significantly in seven studies and remained unchanged in six. In four of these studies in which it rose, the rise was inadequate to meet the tissue demands as judged by the arteriovenous oxygen difference.
4. Pulmonary “capillary venous” pressures remained within normal limits in two studies. In the remaining studies the changes fell into three groups: (a) a high resting pulmonary “capillary venous” pressure rose no further on effort; (b) a moderately high resting pulmonary “capillary venous” pressure rose during the initial two to three minutes of work, and remained at this level until work was stopped; (c) following an initial rise the pulmonary “capillary venous” pressure fell again after two to four minutes and remained constant thereafter.
5. Resting pulmonary pressures were high in all but one study. On effort pressure rose further, but this rise was not necessarily dependent on a rise in pulmonary “capillary venous” pressure.
6. In some studies the pulmonary arteriolar resistance remained normal; in others it was greatly increased. Those cases in which the increase in resistance on work was greatest showed no change in pulmonary “capillary venous” pressure.
7. The significance of these results is discussed in relation to the pathologic changes known to occur in the pulmonary vessels and also to changes in the cardiopulmonary blood volume. It is suggested that secondary vascular changes play a large part in conditioning the pattern of the response to effort.

Acknowledgments

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REFERENCES


5. Criteria for the Classification and Diagnosis of Heart Disease, ed. 4. New York, New York Tuberculosis and Health Association, 1940.


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