Effect of Exercise on the Pulmonary Blood Volume in Patients with Acquired Heart Disease

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In the past, measurements of changes in so-called "central blood volume" during exercise have been inconsistent, both in normal subjects and in patients with cardiovascular abnormalities. Some investigators have found an increase in this volume with exercise in normal subjects while others have not. Likewise, results in patients with mitral stenosis have been conflicting. Rapoport and associates noted an increase in "central blood volume" in patients who could increase their cardiac output but not in those patients in whom blood flow failed to rise. In contrast, other workers did not demonstrate an increase in "central blood volume" despite a rise in cardiac output in such patients. Since many of these inconsistencies may depend upon variations in the volumes measured and in technics employed, the following study was undertaken to define more precisely changes in the actual pulmonary blood volume with exercise.

Material and Methods

Fifteen patients, 14 with valvular heart disease, and one with cardiomyopathy were studied by right heart and transseptal left atrial catheterization. There were seven men and eight women ranging in age from 27 to 54 years. Of the 14 patients with valvular heart disease, eight had pure mitral stenosis, three had a mixed mitral valve lesion, one mitral regurgitation, one aortic incompetence, and one combined aortic stenosis and incompetence. The majority of patients were not severely disabled, five being in class I, four in class II, three in class II-III, and three in class III.

A preceding article in this issue and previous communications from this laboratory have described in detail our technic for right and left heart catheterization and for the inscription of indicator-dilution curves. Limitations of the method and potential sources of error also have been discussed.

With catheters in place in the main pulmonary artery and left atrium and a no. 18 Courand needle in a brachial artery, minute ventilation, and mixed expired oxygen tension were monitored until a relatively steady state was achieved. Indicator-dilution curves were recorded after rapidly sequential injections of indocyanine green into the pulmonary artery and into the left atrium. Immediately thereafter, pulmonary artery, left atrial, and brachial artery pressures were recorded. The patient then performed left leg exercise in the supine position, using a bicycle ergometer. The work load was sufficient to increase oxygen consumption two to three times the resting value. Indicator-dilution curves were repeated between the sixth and twelfth minute of exercise and again were followed by pressure measurements. In three instances the procedure was reversed, the exercise being performed first, followed by a recovery period of 15 minutes. In two patients, measurements were made during periods of control, exercise, and recovery. In three of the 15 patients, indicator-dilution curves were inscribed after injection into the pulmonary artery alone. Thus, there were 12 complete studies of pulmonary blood volume and 15 studies of "central blood volume."

Results

The results are summarized in table 1. In the 12 complete studies there was a statistically significant increase in pulmonary blood volume with exercise ($88.6 \pm S.E. 20.9 \text{ ml./M}^2$). On the other hand, the increase in left atrial to brachial artery volume was not statistically significant ($33.8 \pm S.E. 19.7 \text{ ml./M}^2$). The increase in pulmonary blood volume was associated with a statistically significant
Table 1

Effect of Exercise on Pulmonary Blood Volume

<table>
<thead>
<tr>
<th>Patient</th>
<th>Age, sex</th>
<th>BSA</th>
<th>Diagnosis</th>
<th>Functional classification</th>
<th>Condition</th>
<th>Mean pressures (mm. Hg)</th>
<th>CI</th>
<th>SI</th>
<th>MTT (seconds)</th>
<th>Blood volumes (mL/M.²)</th>
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<td>1</td>
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<td>AI</td>
<td>I</td>
<td>A</td>
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<td>19.6 7.0</td>
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<td>MS</td>
<td>II-III</td>
<td>A</td>
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<td>3.36</td>
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<td>5</td>
<td>54, F</td>
<td>1.58</td>
<td>MS</td>
<td>III</td>
<td>A</td>
<td>25 18 21.5 74</td>
<td>2.18</td>
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<td>4.00</td>
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<td>7.8 7.8</td>
<td>854 854</td>
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</table>

BSA = Body surface area (M.²)  
AI = Aortic insufficiency  
AS = Aortic stenosis  
MI = Mitral insufficiency  
MS = Mitral stenosis  
A = Control  
B = Exercise  
C = Recovery  
PA = Pulmonary arterial

LA = Left atrial  
PD = Pulmonary distending (PA + LA)  
BA = Brachial arterial  
CI = Mean cardiac index (L/min./M.²)  
SI = Mean stroke index (mL/beat/M.²)  
MTT = Mean transit time  
PBV = Pulmonary blood volume  
CBV = 'Central' blood volume

Functional classification according to New York Heart Association
rise in central blood volume (121.9 ± S.E. 29.2 ml./M.²). A positive correlation was demonstrated between the increase in central blood volume and that in pulmonary blood volume (r = 0.68 p < 0.05). In contrast, the increase in central blood volume was not correlated with an increase in left atrial to brachial artery volume (r = 0.44, p > 0.1). These findings are depicted in figure 1.

Figure 2 illustrates the relationship between pulmonary blood volume and distending pressure (average of the mean pulmonary artery and mean left atrial pressures) and shows that, in general, an elevation in distending pressure occurred. In several patients, however, the magnitude of increase in distending pressure was relatively small.

No significant correlation was found between the change in pulmonary blood volume and the change in any of the following parameters: mean pulmonary artery pressure, mean left atrial pressure, mean distending pressure, mean systemic arterial pressure, pulmonary vascular resistance, heart rate, stroke index, stroke work, and mean transit time from the pulmonary artery to the left atrium.

Discussion

During the past decade many attempts have been made to measure the volume of blood between an injection site in the right side of the circulation and a systemic artery. Injection sites have varied from peripheral vein to pulmonary artery and, therefore, the so-called “central” blood volume measured has included variable portions of the venous, right heart, pulmonary, left heart, and systemic arterial volumes. Regardless of the methods employed, changes in volume with exercise frequently have been equated principally to changes in volume within the heart and lungs. Recently, this assumption has been questioned, and the possibility of a significant change in arterial component of this volume has been raised. Other investigations have employed precordial detection of indicator-dilution curves following intravenous injection of 1³¹ radioiodinated human serum albumin in an attempt to limit the volume measured to that
within the heart and lungs.⁹⁻¹⁴ Even this refinement has the limitation of including poorly defined portions of the heart and great vessels within the volume measured.

To our knowledge this study has been the first attempt to document changes in blood volume occurring exclusively within the pulmonary bed during exercise. The potential errors involved have been enumerated and reviewed in detail previously.¹⁰⁻¹³ Exercise, however, magnifies the importance of certain of these factors, especially in patients with acquired heart disease. First, there is the possibility that varying fractions of the left atrial volume are included in the pulmonary blood volume. If increased streaming through the mitral valve and consequently decreased mixing of indicator in the left atrium occurred with exercise, the left atrial to brachial artery volume would decrease and would produce an erroneously large pulmonary blood volume. On the other hand, if exercise increased left atrial turbulence and improved mixing, the left atrial to brachial artery volume would increase, thereby producing a falsely low estimate of pulmonary blood volume. It is impossible to assess the importance of either possibility alone or in concert in the present study. For all 12 patients, the left atrial to brachial artery volume change was insignificant.

It is also possible that as a result of poor mixing or nonmixing of indicator in relatively stagnant blood pools the estimated pulmonary blood volume at rest may be erroneously low. With exercise, the mixing may improve and stagnation decrease so that an augmentation in pulmonary blood volume may be attributable to this factor rather than to a "real" increase in this volume. Since the majority of patients studied had relatively mild disease, we think that the estimation of increases in pulmonary blood volume are valid. For example, patient 3 and patient 4, who had but mild alterations in their cardiovascular dynamics during exercise and in whom functional capacity was unimpaired, developed increases in pulmonary blood volume comparable to that noted in more incapacitated patients. This interpretation is further strengthened by observations on changes in pulmonary blood volume with exercise in another patient, not included in this series, who had no demonstrable cardiovascular abnormality. In this patient, pulmonary blood volume rose from a control value of 204 ml./M.² to 320 ml./M.² with exercise and returned to a value of 201 ml./M.² after a 15-minute recovery period.

Our findings, therefore, strongly suggest a significant increase in pulmonary blood volume during supine exercise. This increase is reflected in a concomitant increase in central blood volume. It may be argued that an increase in pulmonary blood volume with exercise is to be expected because of the elevation in left atrial pressure occurring as a result of mitral valve obstruction or left ventricular disease. Undoubtedly, this well may be an important factor. However, the comparable results obtained in patients with minimal disease, and in the normal patient mentioned above, suggest that the findings may apply in some degree to healthy subjects as well. Certainly, the observations and interpretation of changes in so-called "central" blood volume made by Braunwald and Kelly⁵ in a study of normal subjects would be consonant with our findings in patients with cardiovascular abnormality. Likewise, these previous studies and our results do not support the concept set forth by Marshall and Shepherd⁶ that changes in the "central" blood volume with exercise are due primarily to redistribution of blood within the arterial tree. There was no correlation of cardiac index and pulmonary blood volume at rest. During exercise, when the cardiac index increased 0.6 L./M.²/min. or more, an increase in pulmonary blood volume was almost invariably noted. In general, no significant change was noted in pulmonary artery to left atrial mean transit time.

As shown in table 1, pulmonary blood volume failed to increase with exercise in three patients. In case 1 the increase in blood flow was minimal, despite the presence of only
mild disease. The absence of the usual circulatory response to exercise perhaps accounts for the failure of the pulmonary blood volume to change. The failure of pulmonary blood volume to increase in case 5 may have been related to an unsteady state that culminated in a vasovagal reaction. During the inscription of the indicator-dilution curves with exercise, the main systemic artery blood pressure fell 16 mm. Hg, and the heart rate decreased from 90 to 60 beats per minute. In the ensuing minutes all pressures continued to fall, the mean systemic arterial pressure reaching a low of 54 mm. Hg. Case 12 displayed the greatest shortening of the pulmonary mean transit time of any of the patients studied. The reasons for this degree of shortening remain obscure.

The results of the present study do not localize the site of increase in pulmonary blood volume during exercise to the arterial, capillary, or venous components. Significant increments in pulmonary capillary blood volumes with exercise have been demonstrated by a number of workers.\(^{15-17}\) Whether or not such increases in pulmonary capillary blood volume could completely account for the changes we observed is uncertain.

Exercise induces a greater mean negativity in intrathoracic pressure.\(^{18,19}\) An increase in transmural pressure would result, thereby augmenting pulmonary intravascular volume, provided vascular tone remained unchanged. The rise in left atrial and pulmonary artery pressures and consequently pulmonary distending pressure with this degree of exercise are most likely due to the presence of valvular lesions in these patients. The concomitant rise in these pressures and in the pulmonary blood volume strongly suggest a passive mechanism in the expansion of the pulmonary vascular bed.

**Summary**

The effect of supine exercise on the pulmonary blood volume was studied in 14 patients with valvular heart disease and in one patient with cardiomyopathy. Statistically significant increases occurred in the pulmonary blood volume (88.6 ± S.E. 20.9 ml./M.²) and in the central blood volume (121.9 ± S.E. 29.2 ml./M.²), whereas left atrial to brachial arterial volume remained unchanged. These results support the concept that, with exercise, increases in central blood volume reflect increases in pulmonary blood volume in patients with acquired heart disease. The increase in pulmonary blood volume and in pulmonary distending pressure suggests a passive expansion of the pulmonary vascular bed with exercise.

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**References**


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Training the Doctor of Tomorrow

... When there is a real intellectual interaction between an excellent faculty and a well prepared student body acting as a catalyst, provided in a suitable environment and in an imaginative manner, the product will improve. The faculty should have the capacity to demonstrate their ability to light fires in the human mind because it provides a tremendous impetus to productive scholarship. The faculty should do nothing but promote the imaginative consideration of the various general principles underlying a career in medicine. The proper function of the medical school is the imaginative acquisition of knowledge because a medical school is imaginative and progressive or it is nothing—at least nothing useful.

All courses of study should allow for both diversity and flexibility combined with freedom and discriminating discipline. Any set of courses which insists upon discriminating discipline defeats its own objects by dulling the mind. Any teacher of experience in a graduate school soon notes the dulled minds of those whose education in secondary school and a college has consisted of the requirement of inert knowledge or facts divorced from imagination. Pedants produce dullards.—Chester S. Keefer, M.D. Training the Doctor of Tomorrow, Boston, The Boston Medical Quarterly 12: 87, 1961.
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