Cardiac Performance Capacity and the Effect of Exercise on Renal Plasma Flow in Aortic Insufficiency

By Thomas B. Gibbons, M.D., Austin Henschel, Ph.D., Henry Longstreet Taylor, Ph.D. and Carleton B. Chapman, M.D.

Maximal oxygen intake and renal plasma flow at rest and in work were measured in normal subjects and patients with aortic valve insufficiency; the tests measure some aspects of cardiovascular function. The lower maximal oxygen intake and renal plasma flow at rest and in work in these cardiac patients indicate a decreased cardiovascular performance capacity even though the patients were asymptomatic and their daily physical activity was not restricted.

Clinical experience has repeatedly demonstrated that aortic insufficiency due to rheumatic fever may exist for many years without causing congestive heart failure. Some individuals with this particular valvular deformity have even distinguished themselves in athletics. One might anticipate from this that cardiovascular performance is impaired little or not at all by asymptomatic aortic insufficiency. It is of interest, however, to examine the circulatory performance characteristics in more quantitative detail and to compare the findings with those in normal persons.

Several lines of approach are suggested by previous functional studies on patients with serious cardiac disease. Diminution of the cardiac reserve and of the renal plasma flow are known to accompany cardiac decompensation with great regularity. Even after compensation is re-established, the resting renal plasma flow is likely to be somewhat low, and there is some evidence that the same phenomenon is present in patients with various types of valvular heart disease who have never been in congestive failure. There is reason to believe, therefore, that subtle changes in cardiovascular function may take place in patients with asymptomatic aortic insufficiency long before overt symptoms and signs of impending cardiac failure supervene. The present study is concerned with the qualitative and quantitative definition of several of these functional changes.

Material

For normal subjects, 11 male university students, aged 20 to 28 years, were employed. The group with asymptomatic aortic insufficiency was composed of 12 men, aged from 20 to 42 years. All 12 had typical high-pitched, early diastolic murmurs which were usually best heard along the left sternal margin. Several also had unimpressive systolic murmurs but none had signs suggestive of other types of valvular heart disease. None had ever suffered from congestive failure and only one (F.H.) had dyspnea on exertion. A 6 foot roentgenogram of the chest in this subject disclosed moderate enlargement of the left ventricle but in the other 11 subjects the cardiac silhouette was normal. Electrocardiograms were normal in all the subjects. The systolic and diastolic blood pressure and pulse pressure at rest for the normal men and the cardiac subjects are presented in table 1.

Method

Determination of the maximal oxygen intake was employed as a measure of cardiovascular performance. This test is based on the fact that at low levels of work there is a linear relation between the intake...
of oxygen and the amount of physical work actually performed. With increasing work loads, a point is ultimately reached at which little or no further increase in the intake of oxygen occurs. This point is termed the point of maximal oxygen intake and its value (expressed as cc. per kilogram of body weight per minute) is, in the absence of respiratory disease, an objective measure of the performance capacity of the cardiovascular system. It does not represent the extreme capacity of the subject to perform physical work, since it is usually possible to increase the work load still further after the maximal intake of oxygen is reached. In the present study the maximal oxygen intake was determined while the subjects ran on a motor-driven treadmill. After a preliminary warm-up period of horizontal walking at 3 miles per hour, the subjects ran for three minutes at 6 miles per hour; the grades were adjusted to the performance capacity of the individual and ranged from 0 to 12.5 per cent. Expired air was collected in a balanced Tissot gasometer for one minute beginning 105 seconds after the start of the exercise. Oxygen and carbon dioxide content of the expired air was determined by the Haldane method. Each subject ran on only one grade on any one day but the grade was increased 2.5 per cent in each exercise period until the maximal oxygen intake was attained.

Renal plasma flow was determined with the subjects in a postabsorptive state employing a modification of the technic originally described by Chasis and associates.\textsuperscript{13} Constant injection of paraminohippurate, both during rest and exercise, was maintained by use of a mechanical injector. The method has been previously described in detail.\textsuperscript{14} To determine the response of the renal plasma flow to exercise the subjects walked on the treadmill at 3 miles per hour and at a grade of either 5 or 10 per cent. Two 16 minute exercise periods separated by a 4 minute rest period were used. Oxygen consumption during each work period was determined to permit calculation of the efficiency of external work performance. The renal plasma flow was also determined for two 20 minute recovery periods following exercise.

Two ballistocardiograms were taken on each of 5 patients with aortic insufficiency; the instrument used was a low frequency, critically-damped ballistocardiograph similar to that described by Nickerson.\textsuperscript{15}

The maximal oxygen intake was determined for the 11 normal men and for 8 cardiac subjects of comparable age, physique and exercise habits. The effect of the heavier work load (3 miles per hour at 10 per cent grade) on the renal plasma flow was measured in the normal subjects and in 5 cardiac patients; 5 subjects with aortic insufficiency were exercised at the lighter work load (3 miles per hour and 5 per cent grade). Their response was compared with previously published data obtained for normal male subjects at the same level of activity.\textsuperscript{11}

**RESULTS**

**Performance Capacity**

The values for the maximal oxygen intake in 11 normal subjects and in 8 subjects with aortic insufficiency are presented in table 2. The mean maximal oxygen intake for the highest grade that each subject ran was 37.1 ± 3.32 cc. per Kg. per minute for the cardiac subjects and 45.3 ± 5.10 cc. for the normal subjects. The difference between the means (8.2 cc. per Kg. per min.) was statistically highly significant ($t = 4.17$; $t$ for .01 = 2.86).

That maximal oxygen intake capacity was actually reached is shown by a comparison of the values for the two highest treadmill grades at which the subjects were tested. For the 11 normal subjects the mean maximal oxygen intake for the lower rate of work was 42.18 cc. per Kg. per min. and for a grade two and one-half per cent higher the mean value was 45.27; the difference of 3.09 cc. per Kg. per min. was not statistically significant ($t = 1.49$; $t$ for .05 = 2.08 and $t$ for .20 = 1.32). Repeat maximal oxygen intake measurements were obtained for 4 of the 8 cardiac subjects. The mean maximal oxygen intake for these 4 subjects was 34.4 and 34.5 cc. per Kg. per min. for the lower and higher of the two grades respectively. The 4 subjects with aortic ins-

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**Table 1.**—Systolic and Diastolic Blood Pressure and Pulse Pressure (in mm. Hg) at Rest for Normal Subjects and Subjects with Aortic Insufficiency

<table>
<thead>
<tr>
<th></th>
<th>Normals</th>
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<th>Cardicals</th>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>S.D.</td>
<td>Range</td>
<td>Mean</td>
<td>S.D.</td>
<td>Range</td>
<td></td>
</tr>
<tr>
<td>Systolic B.P.</td>
<td>119</td>
<td>10.8</td>
<td>102-134</td>
<td>124</td>
<td>8.9</td>
<td>106-130</td>
<td></td>
</tr>
<tr>
<td>Diastolic B.P.</td>
<td>73</td>
<td>7.4</td>
<td>62-80</td>
<td>58</td>
<td>6.4</td>
<td>48-68</td>
<td></td>
</tr>
<tr>
<td>Pulse pressure</td>
<td>47</td>
<td>5.3</td>
<td>38-56</td>
<td>67</td>
<td>5.7</td>
<td>62-75</td>
<td></td>
</tr>
</tbody>
</table>
and the muscular efficiency of performance of the vertical component of the walk were similar for the normal subject and the cardiac subject groups (table 2). However, the oxygen consumption during the walks represented a larger percentage of the maximal oxygen intake capacity in the cardiac subjects than in the normals; an average of 55.8 per cent and 69.5 per cent for the normal subjects and cardiac subjects, respectively.

The mean respiratory efficiency during the work periods was slightly higher in the group with aortic insufficiency. The normal subjects removed, on the average, 47.88 cc. of oxygen from each liter of expired air while the group with aortic insufficiency removed 53.92 cc.; the small difference was not statistically significant.

**Renal Plasma Flow**

The mean renal plasma flow of each individual for the 3 collection periods during rest is graphically presented in figure 1. The 8 normal subjects had an average corrected renal plasma flow of 576 ± 60.5 cc. per minute; 11 determinations on 9 subjects with aortic insufficiency yielded an average of 487 ± 79.9 cc. per minute. The difference of 89 cc. per minute (15.5 per cent) was statistically highly significant (t = 2.78; t for .01 = 2.86).

Both levels of activity employed resulted in a reduction in the renal plasma flow in all the subjects but there was no significant difference between the normal and cardiac subjects in the percentage reduction of the plasma flow. The data are presented in table 3. Although the percentage reduction of renal plasma flow was similar in the 2 groups, the absolute volume of plasma flowing to the kidneys of the cardiac subjects was considerably smaller than in the normal subjects.

The lighter work load (3 miles per hour on a 5 per cent grade) also caused a significant reduction in renal plasma flow in a second group of 5 subjects with aortic insufficiency. The data are included in table 3. The average decrease was 85 cc. per minute in the first work period and 104 cc. per minute in the second work period. The decrease was about 30 cc.

<table>
<thead>
<tr>
<th>Table 2.—Maximal Oxygen Intake</th>
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<tr>
<td></td>
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<tr>
<td></td>
</tr>
<tr>
<td>Max. oxygen intake</td>
</tr>
<tr>
<td>Oxygen, at rest</td>
</tr>
<tr>
<td>Oxygen, 3 m.p.h. 10% grade</td>
</tr>
<tr>
<td>Eff. of work</td>
</tr>
</tbody>
</table>

![Figure 1](http://circ.ahajournals.org/)
per minute less than was obtained in the group of cardiac subjects that walked on the 10 per cent grade.

Although no normal subjects were exercised on the 5 per cent grade in this study a comparison of the data from the cardiac subjects on the 5 per cent grade can be made with data previously obtained on normal young men who walked 3 miles per hour on a 5 per cent grade. The average percentage reduction in renal plasma flow during the first work period was similar (17 and 18 per cent, respectively) for the cardiac and normal subjects; for the second work period the cardiac subjects showed an

<table>
<thead>
<tr>
<th>Table 3.—Renal Plasma Flow</th>
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<tr>
<td>Given in cc. per minute (corrected to 1.73 sq. M body surface) at rest and during two 16 minute walks at 3 m.p.h. on either a 5 or 10 per cent grade for normal subjects and patients with aortic insufficiency.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Grade</th>
<th>Plasma Flow</th>
<th>Reduction, %</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Rest</td>
<td>Work period 1</td>
</tr>
<tr>
<td>Normal,</td>
<td>10</td>
<td>576</td>
</tr>
<tr>
<td>Mean</td>
<td></td>
<td>60.5</td>
</tr>
<tr>
<td>S.D.</td>
<td>10</td>
<td>487</td>
</tr>
<tr>
<td>Cardiac,</td>
<td>79.9</td>
<td>65.5</td>
</tr>
<tr>
<td>Mean</td>
<td>5</td>
<td>480</td>
</tr>
<tr>
<td>S.D.</td>
<td>11.54</td>
<td>55.7</td>
</tr>
</tbody>
</table>

average reduction in renal plasma flow of 26 per cent and the normal group an average reduction of 27 per cent.

The renal plasma flow during the two 20 minute collection periods following the exercise tests varied considerably among the individuals in both the cardiac and normal groups. In most cases, however, the renal plasma flow returned to or exceeded the resting levels at the end of 40 minutes of recovery.

Ballistocardiogram

Analyses were made of the resting ballistocardiograms taken on 5 of the patients with aortic insufficiency. The mean values for stroke volume (145 cc.), cardiac output (9.16 liters per minute), and cardiac index (4.99 liters of blood ejected per square meter of body surface per minute) are much larger than those obtained in 158 normal subjects tested on the same ballistocardiograph (stroke volume 89 cc., cardiac index 2.90 liters per sq. M. per min.)

**Discussion**

The maximal rate of oxygen intake which a person can attain is determined by several factors, the most important being the output of the heart. Contributory factors include the ventilatory capacity of the lungs, the ability of the blood to transport oxygen, distribution of blood to the working muscles and the efficiency of the oxygen unloading mechanism at the tissues. In the normal and cardiac subjects employed in the present study the effect of the contributory factors may be assumed to be approximately equal. In normal young men the maximal oxygen intake (cc. per Kg. per min.) is proportional to physical work capacity and is related to the level of habitual physical activity. The similar exercise habits of the normal and cardiac subjects would preclude a difference in the state of physical training as an explanation for the decreased maximal oxygen consumption. It seems reasonable to conclude, therefore, that the smaller maximal oxygen intake observed in the patients with aortic insufficiency reflects a reduced performance capacity of the heart.

The occasional occurrence of aortic insufficiency in patients possessing considerable athletic prowess is not incompatible with the above conclusion. Several of our own cardiac subjects currently participate in strenuous competitive sports without difficulty. Other factors, such as speed, coordination, and the ability to accumulate an oxygen debt are as important in athletic achievement as is the maximal oxygen capacity.

Others have found the maximal oxygen capacity to be reduced in cardiac patients. Herbst measured maximal oxygen capacity in subjects with various valvular lesions and found that the reduction in maximal oxygen intake paralleled the severity of the heart disease. Harrison and Filcher noted that the presence of mitral stenosis was associated with a particularly
marked impairment of oxygen intake capacity. In functional class IV cardiac patients studied by Knipping\textsuperscript{8} the resting oxygen consumption was identical with the maximal oxygen intake, indicating a complete loss of cardiac reserve. The failure of many authors to express maximal oxygen intake in terms of body weight has hindered comparison of results.

Previous reports bearing on the efficiency of work performance by patients with heart disease are conflicting. Nielson\textsuperscript{20} and Katz and his co-workers\textsuperscript{31} found that cardiac patients consumed more oxygen while performing a set work task than did normal subjects. Peabody and Sturgis\textsuperscript{29} on the other hand, noted an equal oxygen consumption in normal and compensated cardiac subjects performing a set task. The present study indicates that the presence of mild to moderate aortic insufficiency does not significantly increase the oxygen consumption during exercise or decrease the efficiency of work performance, at least if the work load does not exceed the maximal oxygen intake. This is in accord with the view of Simonson and Enzer.\textsuperscript{26}

The significantly lowered resting renal plasma flow is additional evidence that there are measurable functional differences between individuals with compensated aortic insufficiency and normal persons. Heller and Jacobson\textsuperscript{22} have recently observed that the resting renal plasma flow of 5 patients with rheumatic valvular heart disease, functional class I averaged 433 cc., a value that was 29.2 per cent below their normal mean value. Their 5 patients, like those employed in this study, had never been in congestive heart failure.

The similar percentage reduction in renal plasma flow observed in normal and cardiac subjects in response to exercise suggests that the mechanism involved in the shunting of blood from the kidneys during work is concerned primarily with supplying sufficient blood to other tissues, probably the muscles, with less regard for the kidneys' needs.

Interpretation of the ballistocardiograms in aortic insufficiency is difficult and nothing definite can be said about the effective cardiac output. Analysis of the records suggests that in the patients with aortic insufficiency the work of the heart exceeds that in the normal. Calculation of stroke volume yields a mean figure (145 cc.) far in excess of that obtained in normal subjects (89 cc.). It seems probable that part of the difference between these two figures (56 cc.) is due to regurgitation of blood into the left ventricle. From a comparison of cardiac output measured by the acetylene and the roentgenkymographic method, Keys and associates\textsuperscript{23, 24} found an efficiency of the valves of 60 to 90 per cent of normal in patients with aortic insufficiency that were clinically classified as moderate to mild. Bay\textsuperscript{25} estimated that in aortic insufficiency from 15 to 87 cc. of blood flows backwards through the aortic valve after each stroke.

**SUMMARY**

The results of this study demonstrate several abnormalities of the cardiovascular physiology of patients with asymptomatic aortic insufficiency. The performance capacity of the heart is impaired, as reflected by a diminished maximal oxygen capacity. The kidneys are supplied with a subnormal volume of blood both during rest and during exercise. Also, it appears that with the patient at rest, the left ventricular muscle must perform more work than the normal. Other functions tested, such as respiratory efficiency, work performance efficiency, and the resting oxygen consumption do not differ significantly from the normal.

**REFERENCES**


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