Impaired Forearm Oxygen Consumption during Static Exercise in Patients with Congestive Heart Failure

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SUMMARY In this study, the effects of forearm static exercise were determined on local blood flow and oxygen consumption in 15 normal individuals (NL) and their responses were compared with those of ten patients in congestive heart failure (CHF). Forearm blood flow was determined by a plethysmographic technique before and during 15% of maximum voluntary contraction of the forearm. Regional arterial and venous oxygen contents were sampled and forearm oxygen consumption calculated by the Fick principle. At rest, forearm blood flow was less in patients with heart failure than in normal individuals; however, this was compensated for by an increased oxygen extraction, thus maintaining forearm oxygen consumption at a normal level. In contrast, during static exercise, forearm blood flow failed to rise normally with heart failure (NL 9.31; CHF 4.33 ml/min · 100 ml, P < 0.001) and the increased oxygen extraction was not sufficient to maintain a normal forearm oxygen consumption (NL .82; CHF .44 ml/min · 100 ml, P < 0.01). Therefore, patients with congestive heart failure demonstrate regional circulatory and metabolic abnormalities during static exercise that are comparable to those present during dynamic exercise. Because of a limited ability of their skeletal muscle resistance vessels to respond to dilator stimuli, they have an attenuation of their exercise hyperemia which leads to an earlier shift to anaerobic metabolism.

IT HAS RECENTLY BEEN DEMONSTRATED that during forearm dynamic exercise of graded intensity patients with congestive heart failure fail to increase their forearm blood flow to the same level as normal individuals.1 Despite an increased oxygen extraction, these patients failed to achieve the same level of forearm oxygen consumption as normal volunteers exercising at a comparable level. Two problems are encountered in the interpretation of this study. First, the level of exercise was not standardized for the patients' capacities to perform work. Thus, patients with congestive heart failure, though exercising at an absolute level of severity comparable to that of normal individuals, may have been exercising at a greater percent of maximal exertion than their normal counterparts. Second, during dynamic exercise, forearm blood flow can only be approximated because of the marked fluctuations in blood flow noted during intermittent grip exercise.2 During muscular contraction, forearm blood flow falls and during the postcontraction relaxation phase, a hyperemia is seen. Although it has been determined that the plethysmographic blood flow measured during the postcontraction relaxation phase closely correlates with that measured by brachial artery electromagnetic flowmeter, flows obtained plethysmographically are still an estimate of true flow. Therefore, the calculations of forearm oxygen consumption derived from these flows were also an estimate.3

To circumvent these problems, two groups of individuals with and without congestive heart failure were studied during forearm static exercise. In contrast to dynamic exercise, forearm blood flow measured plethysmographically during static exercise is an accurate representation of true blood flow to the forearm.4 Similarly, static exercise can be quantitated in terms of the percent of maximum voluntary effort which can be exerted in gripping a hand dynamometer. In the studies described in this paper, it was determined that patients with congestive heart failure have a similar response to static exercise as to dynamic exercise. The increase in forearm blood flow and oxygen consumption during static exercise was found to be significantly less in a group of patients with heart failure when compared with a group of normal volunteers.

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Methods

Studies were performed in 15 normal individuals between the ages of 18 and 53 and ten patients with congestive heart failure (age range 46 to 59 years). All studies were reviewed and approved by an appropriate institutional committee to evaluate human research and informed consent was obtained in all instances. All patients with congestive heart failure were suffering from valvular heart disease and were in functional class III or IV (New York Heart Association classification). They were studied during a scheduled admission for elective cardiac catheterization. At the time of heart catheterization, they were found to have a depression in their cardiac index (2.03 ± .16 L/min/m²) (mean ± SEM), significant pulmonary hypertension (pulmonary artery peak systolic pressure 55.9 ± 7.0 mm Hg) and systemic and pulmonary venous congestion (right atrial mean pressure: 10.2 ± 1.6 mm Hg; pulmonary artery wedge mean pressure: 23.3 ± 2.8 mm Hg). All patients were studied in the basal postabsorptive state lying supine with the arm elevated to the level of the anterior chest after 30 minutes of equilibration in a 27°C room. Forearm blood flow was measured by the venous occlusion technique with a single strand mercury-in-rubber strain gauge plethysmograph as previously described. Care was taken to exclude the hand from the circulation by the inflation of a wrist cuff for one minute prior to any measurements of flow. Arterial pressure was measured by an indwelling arterial needle inserted into the radial or brachial artery of the contralateral upper extremity and forearm vascular resistance was calculated. The arterial needle was also used for the withdrawal of blood samples for the determination of oxygen content with a Lexington O₂ content analyzer. A 16-gauge intracath catheter was inserted in the antecubital vein of the arm which was to be exercised and the tip advanced to the level of the mid-brachial vein for the withdrawal of mixed venous blood for the determination of whole limb venous oxygen content. From the arterial and venous differences in oxygen content and forearm blood flow, forearm oxygen consumption could be calculated by the Fick principle.

Immediately following instrumentation, the subjects briefly performed a maximum contraction of their forearm using a hand grip dynamometer (Stoelting Co.). This second contraction was repeated and the two values averaged as an indication of the maximum voluntary contraction. Following this, the patients and normal volunteers were allowed to achieve a basal state for fifteen minutes following which 8 to 12 determinations of forearm blood flow were performed and samples of arterial and venous blood were withdrawn for analysis.

Following control determinations, the subjects gripped the dynamometer to achieve a 15% maximum voluntary contraction and held this for four minutes. Forearm blood flow was measured at 15 second intervals during the last minute of contraction and averaged. During the last minute of contraction, samples were drawn for arterial and venous oxygen analysis and the calculation of forearm oxygen consumption. The tension generated by the hand dynamometer was converted into an electrical signal which was recorded for later analysis to insure that the subjects maintained a constant force of contraction. The same electrical signal was displayed on a Hewlett Packard two channel electronic scope which was placed directly in front of the subjects so that they could gauge their effort and precisely control it at the level desired. Full scale on the scope was 20% maximum contractile force. The second channel of the scope was adjusted to 15% of the patient's maximum voluntary contraction to provide a target at which the patients could aim.

Statistical analysis was performed using the Student's t-test for nonpaired data. Results are expressed as mean ± standard error of the mean.

Results

In the normal subjects, forearm blood flow increased from a resting value of 3.54 ± 0.39 ml/min • 100 ml to 9.31 ± 1.27 ml/min • 100 ml during a 15% maximum voluntary contraction (fig. 1). Patients with congestive heart failure demonstrated a lower resting forearm blood flow (2.13 ± 0.22 ml/min • 100 ml, P < 0.005) and a significant attenuation of the forearm hyperemia with static exercise (4.35 ± 0.52 ml/min • 100 ml, P < 0.001). Forearm vascular resistance was insignificantly higher in the patients with congestive heart failure during the resting state (NL 37.6 ± 6.93, CHF 58.8 ± 10.1 mm Hg/ml/min • 100 ml). During forearm static exercise, forearm vascular resistance fell in both groups of subjects and was significantly lower in the normal individuals (NL 15.1 ± 2.38, CHF 28.9 ± 3.56 mm Hg/ml/min • 100 ml, P < 0.005).

Forearm oxygen extraction was greater in the heart failure individuals than in the normal subjects both at rest and during exercise (fig. 2). Oxygen consumption was similar in both groups of subjects at rest (NL 0.19 ± 0.02, CHF 0.16 ± 0.03 ml/min • 100 ml). However, during forearm static exercise, forearm oxygen consumption failed to rise to the same degree in the heart failure subjects as in the normal individuals (NL 0.82 ± 0.12, CHF 0.44 ± 0.06 ml/min • 100 ml, P < 0.01) (fig. 3).

![Figure 1](http://circ.ahajournals.org/)

**Figure 1.** Forearm blood flow determined in normal individuals and patients with congestive heart failure (CHF) during a control resting state and during a 15% maximum voluntary contraction (MVC). Brackets indicate standard error of the mean and P values indicate the level of significance when the normal values are compared with values obtained from heart failure individuals.
Discussion

During dynamic exercise in which the forearm contracts four times per minute, there are significant theoretical problems in calculating forearm blood flow by the Fick principle. First, flow is constantly fluctuating and hence a non-steady state is present. This can be circumvented by prolonged sampling times and averaging data. Fortunately, during static exercise, blood flow rises to a plateau and achieves a steady state. A more accurate determination of forearm oxygen consumption can therefore be obtained and more reliable comparisons between normal and heart failure individuals can be evaluated. These comparisons can only be made, however, if both subjects gripped the hand dynamometer to a precisely-determined percent of maximum contraction. This was insured by allowing the subjects to have a visual presentation of their force of contraction which was accomplished by displaying the signal from the dynamometer in front of the patients. Thus, they were able to precisely regulate their level of contraction and maintain it constant throughout. Further assurance that subjects obtained the target level of force was verified by recording tension from the hand dynamometer.

In these studies, it was again determined that forearm blood flow is reduced in patients with congestive heart failure (fig. 1). There is a compensatory increase in oxygen extraction (fig. 2) which maintains forearm oxygen consumption during the resting state at normal levels (fig. 3). During exercise, however, forearm blood flow fails to rise normally in heart failure individuals (fig. 1) and the increase in oxygen extraction is not sufficient to prevent an attenuation of the normal increase in oxygen consumption that would be expected during static exercise (fig. 3). It should be reiterated that over short periods of time, forearm oxygen consumption is not a measure of the work performed by the individuals as is systemic oxygen consumption since the forearm can function anaerobically.

Thus, the attenuated rise in oxygen consumption at a normalized level of external work strongly suggests that heart failure subjects have gone over to anaerobic metabolism as a source of energy for muscle contraction. The basic mechanism causing this shift to anaerobic metabolism appears to be an inability for forearm blood flow to rise in the heart failure individuals during exercise to the same level as that achieved by normal subjects. Two explanations could account for this attenuated blood flow response, the increased vascular stiffness seen in heart failure individuals and additional vasoconstrictor stimuli in the face of vasodilator effects of exercise.

It has been demonstrated previously that limb resistance vessels do not dilate normally to an ischemic stimulus. The cause of this limited vasodilator capacity is probably related to an increased vascular sodium content and possibly an increased tissue pressure related to interstitial edema. It is possible that similar factors are also operative in the vasodilation accompanying muscular exercise. If this limited vasodilator response results in skeletal muscle hypoxia, it may also be related to the excessive sympathoadrenal response noted when heart failure individuals exercise, probably by stimulating somatic afferent nerves in skeletal muscle. In turn, the excessive vasoconstrictor stimuli to exercising muscle would lead to enhanced oxygen extraction. Whereas metabolic vasodilators generally override neurohumoral vasconstrictor stimuli during maximal muscular exertion, during submaximal exercise norepinephrine can actually reduce skeletal muscle blood flow to the point that skeletal muscle oxygen consumption fails to rise to normal levels during exercise. Thus, both factors, an enhanced neurohumoral sympathetic nervous system tone and a limited metabolic vasodilator capacity, may lead to the exaggerated oxygen debt and early shift to anaerobic metabolism that is characteristic of heart failure patients.

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References

Mitral Valve Area in Combined Mitral Stenosis and Regurgitation

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SUMMARY Eight patients with mixed mitral stenosis and regurgitation underwent hemodynamic and angiographic study prior to mitral valve replacement. The stenotic orifice of the mitral valve was calculated employing the total left ventricular stroke volume by cineangiography as the numerator of the Gorlin Formula. Excellent agreement with the measured orifice of the mitral valve was obtained using a value of 37.9 (0.85 × 44.5) for the constant in the Gorlin formula as recommended by Cohen and Gorlin. Recalculation of this constant independently by our data yielded a value that was almost identical. Regurgitant flows and orifice sizes were calculated for each patient using the same constant as for calculation of the stenotic orifices.

CALCULATION OF THE CROSS-SECTIONAL AREA of the mitral valve by the Gorlin formula is remarkably accurate when the valve is stenotic. It has been emphasized, however, that the calculation underestimates the true size of the valve when mitral regurgitation coexists.1,2 The use of quantitative cineangiography makes it possible to measure diastolic mitral valve flow and hence calculation of the stenotic area as well as regurgitant size of the orifice. Despite this method having been available since 1960,3 such measurements have seldom been made and the value of the constant in the Gorlin formula has never been determined.

This study was undertaken to evaluate the accuracy of calculation of the mitral valve area in patients with mixed mitral stenosis and insufficiency utilizing quantitative cineangiography to obtain the value for flow across the mitral valve in diastole.

Methods

Surgically excised mitral valves were obtained in eight selected patients with mixed mitral stenosis and insufficiency (MS-MR) undergoing valve replacement. Six of the eight patients were operated on less than one week following cardiac catheterization (table 1) and in all but one patient (4), the mitral valve was obtained intact. In this patient, the mitral valve was reconstructed postoperatively. The fresh excised valves were flattened on a plate of glass which fixed them in a standard maximum diastolic position. They were then photographed from the ventricular and atrial aspects alongside a centimeter ruler placed in the plane of the valve orifice (fig. 1). The actual area of the valve orifice was measured by planimetry. The largest planed area

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