

Partition of Blood Flow to the Cutaneous and Muscular Beds of the Forearm at Rest and during Leg Exercise in Normal Subjects and in Patients with Heart Failure

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ABSTRACT

The purpose of this study was to determine the relative effects of various levels of exercise on blood flow to skin and muscle of the resting extremity of normal subjects and the manner in which this distribution is modified by congestive heart failure. Blood flow to the skin and muscle of the forearm was determined plethysmographically with the aid of epinephrine iontophoresis at rest and during supine leg exercise in 12 normal subjects and in 9 patients with failure. In normal resting subjects, forearm blood flow averaged 6.30 ml/min/100 ml, 52% partitioned to muscle and 48% to skin. In the patients, forearm blood flow averaged 2.94 ml/min/100 ml, with 48% to muscle and 52% to skin. In normal subjects performing mild exercise, forearm muscle flow was not significantly changed, but during moderate and strenuous activity it was significantly reduced. Cutaneous blood flow, however, declined early at all levels of exertion. In the normal subjects, cutaneous hyperemia occurred late during moderate exercise but with strenuous exercise, was delayed until after exercise had been discontinued. In contrast, in the patients, forearm muscle blood flow decreased strikingly during leg exercise, cutaneous flow fell and remained depressed during the entire period of exercise, and no postexercise hyperemia occurred. Thus, in congestive heart failure, both the cutaneous and muscle beds of the forearm are abnormally constricted at rest, there is excessive vasoconstriction in both beds during leg exercise, and postexercise cutaneous vasodilation is abolished.

ADDITIONAL KEY WORDS

heat dissipation

sympathetic tone

epinephrine iontophoresis
vasoconstriction

■ It is now clear that during muscular exercise substantial circulatory changes occur in nonexercising parts of the body. There is considerable disagreement, however, concerning the relative distribution of blood flow to

the vascular beds of skin and muscle in the nonexercising limbs. Part of the problem stems from the difficulties inherent in measuring blood flow by plethysmographic techniques during exercise in subjects who are not highly trained (1-4). Until recently, this question had been approached principally by measuring heat exchange (5-7) or changes in skin temperature in the hand (8, 9), venous oxygen saturation of the superficial and deep forearm veins (6, 7, 10, 11), and clearance of radioactive sodium from forearm muscle (6, 7), methods which provide only qualitative information concerning changes in blood flow. Furthermore, blood flow to the hand is

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dramatically influenced by psychic stimuli, and the hand arterioles are capable of only passive dilation (12-14). Therefore, hand blood flow cannot be considered to be representative of skin blood flow in other areas, such as the forearm, in which both active and passive dilation of cutaneous blood vessels can take place (14-17). Despite these limitations in previous studies, two facts seemed clearly evident: (1) vasoconstriction mediated by the sympathetic nervous system appears to occur in the nonexercising limbs (1-9), and (2) there is a need to dissipate the excess heat generated by the increased metabolic activity of the exercising muscles (3, 4, 6, 7, 18).

The purpose of the present study was to characterize the peripheral circulatory response of the resting limbs of normal subjects to varying levels of exercise and of patients with heart failure to strenuous exercise. The latter group was studied because, in the presence of congestive heart failure, the control of the peripheral circulation is of particular importance, since it is responsible for the distribution of a limited total cardiac output to critical areas. In particular, we wished to determine whether the heart failure state altered the balance between the need for heat dissipation and the need to conserve and redistribute the limited cardiac output. To answer these questions, the partition of blood flow to the skin and muscle in the forearm was studied at rest and during leg exercise in normal subjects, and the results were compared with those obtained in patients with congestive heart failure.

Methods

Twelve normal male subjects (ages 19 to 36 years) and 9 patients with congestive heart failure (ages 28 to 44) were studied. The patients with heart failure (3 women, 6 men) all had rheumatic heart disease and were in functional classes II or III according to the New York Heart Association classification. Forearm blood flow was measured simultaneously in both arms with the subjects supine and in the basal, postabsorptive state at a room temperature of 27°C. With the subjects' arms at the level of the sternal angle, forearm blood flow was measured

by the venous occlusion technique (19), utilizing a single strand, mercury-in-rubber strain-gauge plethysmograph, as previously described (20, 21). Circulation to the hand was arrested by inflating a cuff around the wrist for at least 1 minute before the determination of blood flow. Epinephrine iontophoresis was performed on one arm by the technique of Cooper et al. (22) as modified by Collins and Ludbrook (23). This consisted of wrapping the thoroughly cleansed arm in a gauze bandage soaked with epinephrine hydrochloride 1:2000 (pH 4.5). The gauze was covered by aluminum foil, which served as the positive electrode, and was secured by an elastic bandage. The leg served as the negative electrode and was similarly wrapped, except that saline replaced the epinephrine solution. Essentially complete iontophoresis occurred with a current of 20 ma applied for 20 minutes and was assured at the end of the study by noting an average increase in blood flow in the control arm of 81% in response to body heating and only an 8% increase in the treated arm. No increase in heart rate or change in blood flow in the control arm occurred after iontophoresis.

Normal subjects performed mild, moderate, and strenuous leg exercise in the supine position by pedaling a bicycle ergometer at loads of 40, 330, and 1080 to 2240 ft-lb/min, increasing heart rate from 68 to 89, 101, and 128 beats/min, respectively. They were allowed to rest between each level of exertion until forearm blood flow and heart rate returned to control values and were stable. Patients with heart failure were studied at rest and during exercise which they considered to be strenuous but which ranged only from 40 to 330 ft-lb/min, depending on the individual's exercise tolerance. Heart rate increased from 78 to 132 beats/min.

Blood flow was measured every 15 seconds for 2 minutes before exercise. Three blood flow measurements were made and averaged during each of the 6 minutes of exercise. At the completion of exercise, measurements of blood flow were made at 15-second intervals for 10 minutes. Muscle blood flow was assumed to be the flow measured in the arm in which iontophoresis had been performed; skin blood flow was calculated as the difference between the blood flow measurement in the control arm (total forearm blood flow) and the arm on which epinephrine iontophoresis had been performed.

Results

REST

At rest, the blood flow in the control forearm in the normal subjects averaged 6.30 ± 0.58 (SEM) ml/min/100 ml of forearm,

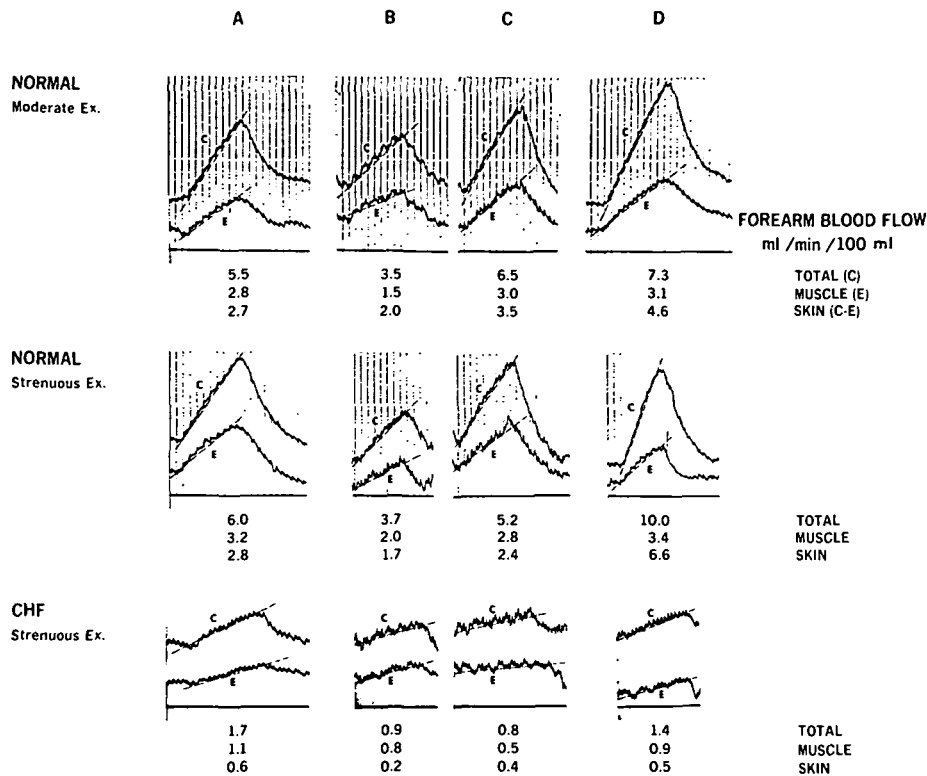


FIGURE 1

Plethysmographic tracings illustrating the response of blood flow in a normal subject performing moderate and strenuous supine leg exercise and a patient in heart failure (CHF) performing strenuous exercise. Tracings were taken at rest (A) and during the first (B) and last (C) 3 minutes of exercise and after exercise (D). In each tracing, C represents the blood flow from the control arm and E the blood flow from the arm on which epinephrine iontophoresis had been performed. Skin blood flow was calculated as the difference between these two measurements (C - E). The severity and duration of exercise are as defined in the text. Ex. = exercise.

while muscle blood flow averaged 3.26 ± 0.22 ml/min/100 ml, and skin blood flow averaged 3.04 ± 0.51 ml/min/100 ml. All of these values were significantly lower in patients with heart failure, averaging 2.94 ± 0.53 ml/min/100 ml ($P < .01$) for total blood flow and $1.40 \pm .09$ ml/min/100 ml ($P < .01$) for muscle flow and 1.53 ± 0.39 ($P < 0.02$) for skin flow. In normal subjects, an average of 52% of the total blood flow was distributed to muscle and 48% to skin. In patients with heart failure, these averages were 48% and 52%, respectively, percents which did not differ significantly from those observed in the normal subjects.

EXERCISE

Normal Subjects.—During the first 3 min-

utes of moderate or strenuous exercise, there was a significant reduction in muscle blood flow in normal subjects (Figs. 1 and 2). The maximum decrease averaged 0.45 ± 0.19 ml/min/100 ml ($P < .05$) and 0.72 ± 0.26 ($P < .05$) ml/min/100 ml from control values for the moderate and strenuous levels of exercise, respectively (Figs. 1 and 2). During the last 3 minutes of exercise the muscle blood flow averaged 106%, 88%, and 96% of control values for mild, moderate, and strenuous exercise, respectively; these values were not significantly different from control. During the postexercise control period, muscle blood flow was also similar to the preexercise control observations.

Skin blood flow during the first 3 minutes of

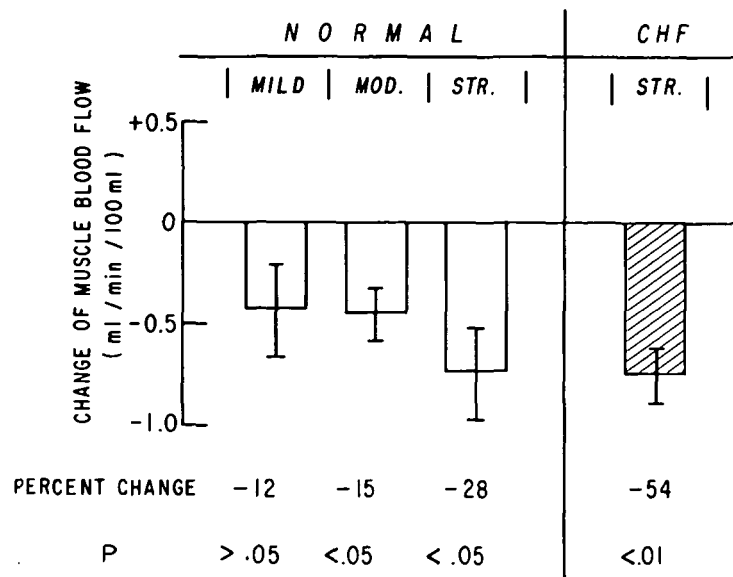


FIGURE 2

Decreases in blood flow in forearm muscle during the first 3 minutes of supine leg exercise. Mod. = moderate; Str. = strenuous; CHF = congestive heart failure.

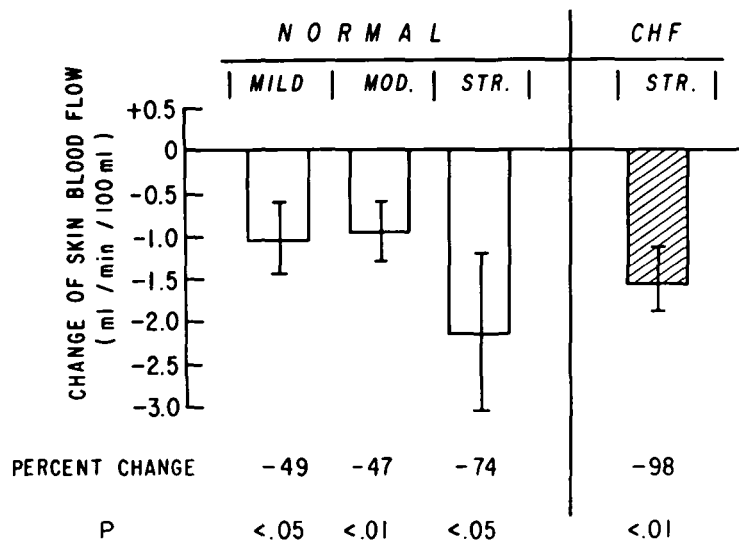


FIGURE 3

Decreases in blood flow in forearm skin during the first 3 minutes of supine exercise. The severity of exercise was as described in the text. Mod. = moderate; Str. = strenuous; CHF = congestive heart failure.

exercise was significantly reduced in normal subjects at all three levels of exertion (Figs. 1 and 3). The maximum decrease during the early period of exercise averaged 1.06 ± 0.39 ,

0.95 ± 0.19 , and 2.16 ± 0.91 ml/min/100 ml, respectively, for mild, moderate, and strenuous exercise. Although during the last 3 minutes of mild exercise, normal subjects tended

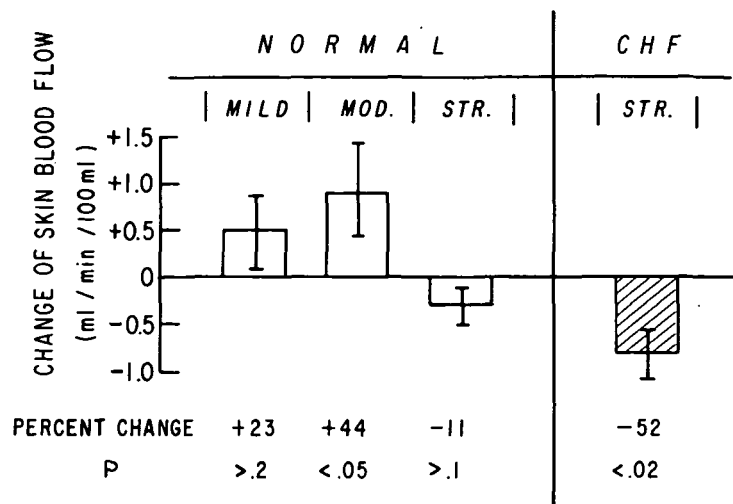


FIGURE 4

Decreases in blood flow in forearm skin during the last 3 minutes of supine leg exercise. The severity of exercise was as described in the text. Mod. = moderate; Str. = strenuous; CHF = congestive heart failure.

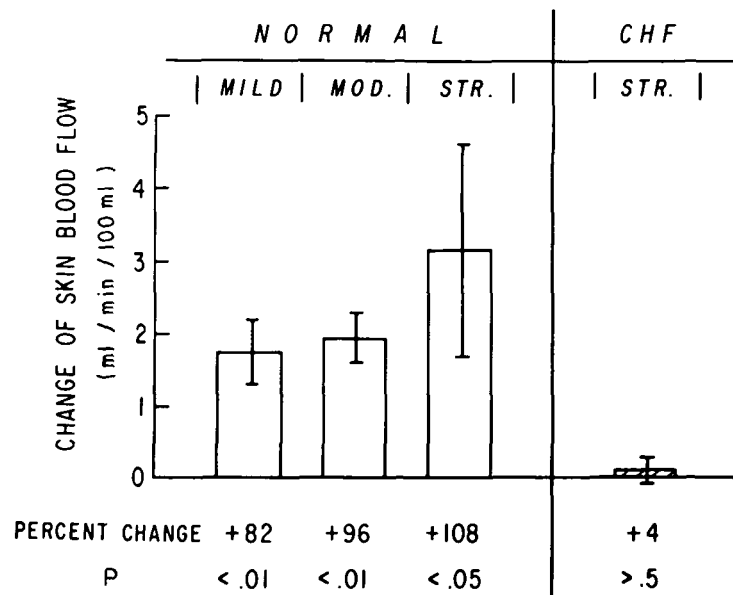


FIGURE 5

Maximum increase in blood flow in forearm skin during the 10 minutes following supine leg exercise. The severity of exercise was as described in the text. Mod. = moderate, Str. = strenuous, CHF = congestive heart failure.

to show an increase in skin blood flow above control resting values, this change was not statistically significant, and it was only with moderate exercise that there was a significant

cutaneous hyperemia ($+0.89 \pm 0.31$ ml/min/100 ml) ($P < .05$) (Figs. 1 and 4). After exercise had been discontinued, skin blood flow consistently increased. The maximum increase

above control values at this time was $+1.76 \pm 0.45$, $+1.96 \pm 0.34$, and $+3.15 \pm 1.46$ ml/min/100 ml for the mild, moderate, and strenuous levels of exercise, respectively (Figs. 1 and 5).

Patients with Heart Failure.—Like normal subjects, patients with heart failure demonstrated a significant reduction of muscle blood flow during the first 3 minutes of leg exercise (-0.76 ± 0.21 ml/min/100 ml) ($P < 0.01$) (Figs. 1 and 2). Blood flow fell to an average of 64% of the preexercise control level during the last 3 minutes of leg exercise and 71% of the preexercise control level during the postexercise period of observation.

Patients with heart failure, like normal subjects, exhibited a significant reduction in skin blood flow during the first 3 minutes of leg exercise, this reduction averaging 1.50 ± 0.39 ml/min/100 ml ($P < 0.01$) (Figs. 1 and 3). However, unlike the normal subjects, in whom cutaneous blood flow rose or was unchanged during the last 3 minutes of exercise, the maximum skin blood flow in the patients with heart failure remained significantly below the preexercise control values (-0.79 ± 0.25 ml/min/100 ml ($P < 0.02$)) at this time (Figs. 1 and 4). Also, unlike the findings in normal subjects, in whom cutaneous vasodilation occurred immediately following exercise, the maximum observed blood flow during the postexercise control period did not differ significantly from the preexercise control value (Figs. 1 and 5).

Discussion

The approximately equal partition of blood flow to the vascular beds of skin and muscle in normal subjects is in agreement with the work of Cooper et al. (22), Edholm et al. (24), and Kontos et al. (25), who used a similar technique of iontophoresis. Blood flow to both skin and muscle was depressed in patients with heart failure, although the distribution between skin and muscle flow did not differ significantly from that in normal subjects. Cooper and associates have stated (22), and we agree, that skin blood flow is highly variable even among normal individuals. Muscle blood flow at rest is a more stable

measurement and better suited for comparison between individuals. The present investigation is the first demonstration that blood flow to resting muscle is reduced in congestive heart failure. We have not defined the relative roles played by augmented sympathetic tone and the increased stiffness of the resistance vessels, which has recently been described in patients with heart failure (21), in producing this decreased muscle blood flow at rest. It is also possible that the observed differences in resting forearm muscle blood flow could be partially accounted for by the differences in sex and physical activities of the two groups.

In the normal subjects during the first 3 minutes of exercise, resting muscle blood flow decreased. It appears that as the stress of exercise increased, the reduction of muscle blood flow became more marked. This finding is consistent with the report of Blair et al. (3), who found that the increase in total forearm vascular resistance paralleled the increase in the severity of exercise. By the technique of selective cutaneous and deep nerve blockade they attributed this response solely to increased muscle vasoconstriction. However, the findings of our study suggest that both the skin and muscle vessels exhibit augmented vascular tone early during exercise. Blair et al. (3), Bishop et al. (6), and Muth et al. (7) have reported an unchanged blood flow in the resting muscles during exercise, but Muth et al. suggested that muscle blood flow might decrease with more stressful exercise. The findings of the present investigation are in accord with this suggestion.

A major finding in our study was that during the latter half of the exercise period, the level of skin blood flow depended on the severity of the exercise. The ability to dissipate heat by increasing skin blood flow became apparent only when normal subjects performed moderate exercise. Presumably, not as much heat required dissipation during mild exercise. More important, it appears that with severe exercise, cutaneous vasodilation and heat dissipation were delayed in normal subjects until after the 6-minute period of exercise had ended. This is consistent with the

premise that with increasing severity of exertion, greater sympathetic vasoconstriction of the cutaneous bed occurred. Late during the course of exercise skin blood flow reflected a summation of the opposing effects of the need to dissipate heat and of generalized vasoconstriction. In any one individual the direction of change depends on which of these opposing influences predominates. The relationship between these two determinants of skin blood flow has not been fully appreciated in the past and serves to explain the variation in the response of the oxygen saturation of the brachial vein which has been observed late during exercise (6).

In patients with congestive heart failure there were significant reductions of blood flow in both muscle and skin in the resting forearm during the first 3 minutes of leg exercise. The degree to which forearm blood flow was reduced was proportionately greater than that seen in normal subjects at levels of exercise which, though strenuous for the patients with heart failure, were mild or moderate when performed by normal subjects. The reduction of muscle blood flow during exercise we observed is consistent with the finding of Muth et al. (7), who showed that patients with heart failure have a decreased clearance of radioactive sodium in forearm muscle during exercise. It would appear that, as in the normal subjects, the severity of exercise is the most important determinant of this vasoconstrictive response, which presumably is mediated by the sympathetic nervous system.

In contrast to the finding in normal subjects, blood continued to be shunted from the cutaneous bed in patients with heart failure, despite the need to dissipate heat during the final 3 minutes of exercise. Furthermore, the stimulus for cutaneous vasoconstriction was not completely eliminated in the patients with heart failure even after exercise had ceased, since they did not have postexercise cutaneous hyperemia. These results help to explain the observation of Donald et al. (10) that axillary venous O_2 content remained depressed in patients with symptomatic heart disease throughout the entire course of exercise.

Although we did not measure heat dissipation from the forehead, scalp, and hands, the studies of Donald et al. suggest that the cutaneous vasoconstriction we observed in the forearm was representative of the entire limb. Thus, patients with heart failure do not appear to generate as much heat as do normal subjects, since they cannot work as strenuously and their very intense sympathetic vasoconstriction prevents them from dissipating this heat from the forearm cutaneous bed in a normal manner. The finding that in patients with heart failure the cutaneous blood vessels do not dilate normally during and after exercise may also explain the heat intolerance often seen in these subjects.

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