Central and peripheral circulatory changes after training of the arms or legs

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CLAUSEN, JAN P., KLAUSEN KLAUSEN, BIRGER RASMUSSEN, AND JENS TRAP-JENSEN. Central and peripheral circulatory changes after training of the arms or legs. Am. J. Physiol. 225(3): 675–682. 1973—In two groups of young healthy subjects who performed arm training (n = 5) and leg training (n = 8), respectively, the circulatory response to exercise done with trained and nontrained muscle groups was compared by measurement of heart rate (HR), cardiac output (Q), regional arteriovenous oxygen differences, (axillary and femoral (a-v)O2 diff), hepatic clearance of indocyanine green (ICG clearance), and aortic blood pressure during moderate and heavy submaximal exercise. Arm training caused a pronounced reduction in HR during arm exercise, whereas only a small reduction was seen during exercise performed with non-trained leg muscles. Leg training, however, reduced HR almost equally during leg exercise and arm exercise. After both types of training during exercise with trained muscles, Q and its distribution were unchanged except for central circulatory adaptations. Q and aortic blood pressures were unchanged or slightly reduced. During exercise with non-trained muscles, Q and its distribution were unchanged except during heavy arm exercise after leg training, in which a 10–20% increase in Q and aortic blood pressures occurred. From these findings, it is concluded that alterations in the trained muscles and central circulatory changes both contribute to the effects of physical training on circulation.

The subjects were 13 healthy young men. Signed informed consent was obtained from each of them before initiating the study. None of the subjects had been a recent participant in athletic or exercise programs yielding high maximal oxygen uptakes. Five of the subjects formed an arm-training group. Their mean age, height, and weight were 23 years, 179 cm, and 70.4 kg. The remaining eight subjects formed a leg-training group. Their mean age, height, and weight were 24 years, 179 cm, and 73.9 kg.

At least 2 days before the main study involving catheterization, the physical fitness of each subject was evaluated by observing his response to bicycle-ergometer exercise at several submaximal loads during both arm exercise and leg exercise. On this occasion the circumference of both upper arms was measured before and after a 15-min period of arm exercise on a heavy submaximal workload (heart rate ca. 170 beats/min). In three subjects the maximal oxygen uptake was measured for both types of exercise.

The main study involving catheterization was performed in the morning. The subject had been allowed a light, fat-free meal 1.5 hr before. All catheterizations were performed under local anaesthesia and no premedication was administered. By means of a venous cutdown or by the Seldinger technique, three catheters were inserted permitting sampling of blood from the axillary vein just proximal to the level of the coracoid process of the scapula, from the femoral vein just proximal to the inguinal ligament, and from the abdominal aorta at the level of the second lumbar vertebra.

For tables of individual data, order NAPS Document 02160 from Microfiche Publications, 305 East 46th St., New York, N.Y. 10017, remitting $1.50 for microfiche or $5.00 for photocopies.
After a 30-min rest period the different variables utilized in this study were measured at rest with the subject in the supine position. Thereafter the same procedures were performed during upright arm exercise and leg exercise at two submaximal work loads which were chosen to give the same HR before training (ca. 130 and 170 beats/min) during both types of exercise. The subjects exercised for 15 min on each of these work loads and rested for 30 min between each exercise period. Leg exercise was performed on a electrically braked bicycle ergometer (Elena-Schonander). A specially constructed mechanically braked bicycle ergometer was used for the arm exercise. The data presented in this paper: oxygen uptake (V_{O_2}), cardiac output (Q), regional arteriovenous oxygen differences ((a-v)O_{2} diff), indocyanine green clearance (ICG: clearance), aortic blood pressures, and heart rate (HR), were collected according to a fixed schedule to give the best correspondence in time. During exercise, none of these measurements were taken sooner than 6 min after the start. In some cases a work load which led to exhaustion within 3-4 min was also performed. During these ‘supramaximal’ exercise periods, only HR and regional (a-v)O_{2} diff were determined. The schedule described above was used in the first 10 subjects, 5 from each group. The results obtained made some further leg-training data desirable and thus three additional subjects were studied. For them, a slightly modified scheme was used. The ICG clearance was omitted, the exercise periods were cut down to 10 min at each load, and during the same type of exercise no resting periods were interspaced between the two submaximal loads; however, the subjects rested 30 min between the two different types of exercise. The order of the two types of exercise was varied at random among all the 13 subjects, but for a given subject the same order and exactly the same scheme was used before and after training. Blood loss during the experiment was about 350 ml.

Techniques. V_{O_2} was determined using Douglas bags and the Scholander technique. Q was measured by the indicator-dilution technique (9). The (a-v)O_{2} diff values were calculated from spectrophotometrically measured oxygen saturations (9) and corresponding hemoglobin concentrations. ICG clearance was measured after a single injection of 12.5 mg ICG as described by Rowe et al. (25). The percent change in ICG clearance during exercise was calculated as \((t_{1/2} - t_{1/2} \text{ at rest}) / t_{1/2} \text{ during exercise}) \times 100; t_{1/2} is the half-life for ICG in arterial plasma. HR was counted from continuous ECG records. Aortic blood pressures were measured as previously described (9).

Training program. The subjects reported to the laboratory 5 days a week during 5 weeks for supervised training sessions lasting 50 min. The eight subjects who trained the leg muscles exercised on mechanically braked bicycle ergometers (Monark, Sweden). The five subjects who trained the arm muscles exercised on bicycle ergometers of the same type modified for arm work. Each training session started with a 15-min warm-up period on the same heavy submaximal work load as was used in the study with catheterization. Thereafter the subjects performed four exercise periods of 5 min, alternating with resting periods of equal duration. These work loads were chosen individually to give a heart rate exceeding 170 beats/min and to lead to complete exhaustion at the end of the last 5-min exercise period. The first five subjects in the leg-training group were allowed to exercise on the bicycle in the way they preferred. The last three, in whom maximal oxygen uptake (V_{O_2} max) was measured, were told to keep their arms on their backs during the pedaling in order to avoid any unintended training effects on the arm muscles. All subjects were instructed not to perform any kind of heavy exercise with the muscles which were not to be trained during the 5 weeks of training. No other interference with the subjects' daily lives was attempted (diet, smoking habits, etc.). All subjects cooperated satisfactorily and attendance at the training sessions was nearly 100%; only four subjects did not attend to all training sessions and none of them was absent more than once.

Statistics. Standard statistical methods have been used. Pre- and posttraining differences were analyzed by the Student t test for paired observations.

RESULTS

Effect of training on work performance. The effect of the training program on the subjects' ability to perform the type of work used for the training is illustrated by the difference between the work load the subjects could sustain for just 5 min at the beginning and at the end of the training program. The increase was on average 47 % in the arm-training group and 36 % in the leg-training group. The increase in V_{O_2} max for both types of work measured in three subjects from the leg-training group was, on the average, 17.3 % for leg exercise and 9.9 % for arm exercise. However, the highest individual value observed during arm exercise (15.9 %) was hardly due to a training effect alone. Despite repeated appeals to this subject, he made vigorous movements of pelvis and legs during the postraining determination.

Effect of training on circulatory parameters. Group averages for the most important circulatory data obtained before and after training at rest and at identical submaximal work loads (kpm/min) are presented in Tables 1 and 2. The differences between the circulatory response to arm and leg exercise found in the present study are in agreement with those reported by previous investigators (4, 16, 27) and will not be commented on in detail.

Heart rate (Fig. 1 and Tables 1 and 2). The HR values presented here are mean values from the 6th and 7th min of exercise corresponding in time to the determination of Q. After training, HR was reduced significantly at rest and during both types of exercise in all subjects. The fall in HR seen during exercise with trained muscles was most pronounced after arm training, whereas the reduction in HR seen at rest and during work with nontrained muscles was significantly greater after leg training. It should be noticed that during exercise with trained muscles, HR decreased more at the heavy than at the moderate submaximal work load. During exercise performed with nontrained muscle groups, in contrast, the reduction in HR was essentially the same at both submaximal work loads and equal to that seen at rest. This difference between exercise with trained and nontrained muscles was most clear-cut in the arm-training group.

Cardiac output (Tables 1 and 2). After training, Q was lower

CLAUSEN, KLAUSEN, RASMUSSEN, AND TRAP-JENSEN

676
CIRCULATORY EFFECTS OF TRAINING OF THE ARMS OR LEGS

TABLE 1. Mean circulatory data before and after training at rest supine and during upright submaximal arm and leg exercise: arm-training group

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During exercise with trained muscles at a given submaximal work load except during heavy leg exercise. If Q is related to Vo2, these changes were not significant. However, Q was unchanged during exercise with nontrained muscles with one notable exception, viz., after leg training during heavy arm exercise Q increased 11% with a proportional decrease in total (a-v)O2 diff.

Stroke volume (Tables 1 and 2). After training there was a trend to an increase in stroke volume (SV) as compared to the pretraining value during submaximal exercise performed with trained as well as with nontrained muscle groups. The greatest increase in SV seen in this study (22%) occurred during heavy submaximal work with nontrained arms.

Regional arteriovenous oxygen differences (Fig. 2 and Tables 1 and 2). Arm training caused an increase in (a-v)O2 diff in exercising arms at the two submaximal work loads and also during supramaximal arm exercise. (a-v)O2 diff in resting legs during heavy submaximal arm exercise was lower after arm training than after leg training, whereas no difference between the two groups was seen during supramaximal arm
exercise. No changes in $(a-v)O_2$ diff occurred during exercise with nontrained legs. After leg training $(a-v)O_2$ diff was changed in only two situations: during heavy submaximal work load, as was the case for the reduction in ICG clearance during exercise. The slope of the regression line was the same for arm exercise and did not change after training. During exercise with nontrained muscles, ICG clearance was unchanged. As seen in Fig. 4, there was a close and significant correlation between the percent reduction in ICG clearance and HR during exercise. The slope of the regression line was the same for arm exercise as for leg exercise and did not change after training.

Aortic blood pressures (Tables 1 and 2). After arm training systolic, diastolic, and mean blood pressures decreased during exercise performed with the trained arm muscles. No
CIRCULATORY EFFECTS OF TRAINING OF THE ARMS OR LEGS

FIG. 1. Heart rate in relation to oxygen uptake at rest supine and during upright submaximal arm exercise (upper panels) and leg exercise (lower panels). On left side of figure, mean values are given for arm-training group before O—O and after ●●● training. On right side, mean values are given from leg-training group before △—△ and after ▲—▲ training.

significant changes in blood pressures were observed during exercise with nontrained leg muscles. After leg training, no changes in blood pressure were observed during exercise performed with trained leg muscles, but there was a considerable increase in systolic—and a less pronounced increase in diastolic—and mean aortic blood pressure during heavy submaximal exercise with the nontrained arm muscles.

Peripheral vascular resistance (PVR). This parameter was unchanged after arm training both at rest and during exercise performed with trained as well as nontrained muscles. After leg training, PVR increased at rest and at the moderate work load performed with trained leg muscles.

Cross section area of upper arms. This area (mean value for right and left arm taken together) in the arm-training group was 57.6 ± 1.07 cm² at rest before training as compared to 64.4 ± 1.86 cm² after training (Δ = 6.6 ± 1.58 cm², t = 4.186). The acute increase in cross section after 15 min heavy arm exercise amounted to 7.7 ± 0.96 cm² before training, but was only 5.2 ± 0.45 cm² after training (Δ = 2.5 ± 0.70 cm², t = 3.530). In the leg-training group the cross-section area at rest was 60.5 ± 2.38 cm² before training and 61.3 ± 3.85 cm² after training (Δ = 0.8 ± 1.53 cm², t = 0.537). The acute increase after arm exercise was 7.6 ± 0.98 cm² before training and 7.6 ± 0.74 cm² after training.

Hemoglobin. The concentration of hemoglobin measured at rest was 14.8 g/100 ml in the arm-training group before training and was not changed significantly after. In the leg-training group Hb fell from 14.4 to 14.0 g/100 ml, t = 2.552.

DISCUSSION

The present study showed that both arm training and leg training reduce HR at rest and during exercise with trained as well as with nontrained muscles. However, it was also shown that the fall in HR seen during exercise with trained muscles was unlikely to be caused by the same physiological mechanism as the fall in HR at rest and during exercise with nontrained muscles: during exercise with trained muscles the reduction in HR became more pronounced the higher the work load and was closely related to a proportional increase in ICG clearance. At rest and during exercise with nontrained muscles, in contrast, the reduction in HR consisted simply in a parallel downward displacement of the HR-O₂ relation and was not related to any change in ICG clearance.

That the decrease in HR at rest and during exercise with nontrained muscles was most pronounced after leg training suggests that factors such as the total muscle mass engaged in the exercise and/or the absolute values for V̇O₂, SV₁ and Q attained during the training sessions are important determinants for the extent of this fall in HR. It would seem most likely that this component of the training bradycardia was...
caused by some central circulatory mechanism, cardiac or extracardiac, but the present data do not provide any obvious explanation as to the nature of the underlying mechanism. In two previous studies (10, 23) arm training did not produce a significant reduction in IIR at rest or during exercise with nontrained muscles. The probable reason for this is that fewer subjects were studied and a less strenuous training program was used than in the present investigation.

As already mentioned, the fall in HR seen during exercise with trained muscles was closely correlated to the changes in ICG clearance: a certain decrease in HR was accompanied by a proportional increase in ICG clearance. Thus the ICG clearance/HR regression line had the same slope before and after training. The ICG clearance/HR relation found in this study corresponds well to that which can be calculated from the data of Rowell et al. (25); similar high correlations with virtually identical slopes have been demonstrated for HR and splanchnic-hepatic blood flow measured using other methods (24) and unpublished data. Furthermore, the same relation has been observed for HR and renal blood flow (17).

These constant relationships are important because they suggest that a common neural activation mediates an increase in HR and reinforced vasoconstriction in abdominal viscera during exercise (24). According to results from the present study, training reduces this activation at a given submaximal \( V_{O_2} \) provided exercise is done with trained muscles. In animals and probably also in man, cardioacceleration and peripheral vasoconstriction can be elicited both via afferent nervous impulses arising in contracting muscles (1, 2, 11, 21) and from corticohypothalamic centers (14, 15). The results from this study cannot with certainty decide whether training changed the one or the other of these two modes of activation, but the finding that the proportional changes in HR and ICG clearance were confined to exercise with trained muscles strongly suggests that local alterations in these trained muscles are involved.

Training causes important oxidative enzymatic adaptations in muscle tissue (6, 18, 20, 22), which improve the muscle fiber's ability to perform rhythmic contractions for longer periods of time. Such enzymatic changes may provide a plausible explanation for a less pronounced activation of autonomic cardiovascular reflexes during dynamic exercise. We have no direct evidence that such enzymatic adaptations occurred in the subjects studied here. However, the 30% decrease in postexercise swelling of trained upper arms, which presumably reflects less pronounced local hyperosmolarity, together with our finding of a decreased lactate release from the arms (unpublished data) and increased axillary (a-v)O2 diff, suggested the occurrence of significant local metabolic alterations. The finding that the fall in HR and concomitant increase in ICG clearance was most pronounced after arm training may be explained by the fact that arm muscles are normally less accustomed to heavy rhythmic exercise than leg muscles and thus have a greater potentiality for local improvement.

On the other hand, it is also possible that part of the change of HR and of vasoconstriction in nonexercising tissues could be related to a change in an element of isometric exercise rather than to improved ability for rhythmic exer-
CIRCULATORY EFFECTS OF TRAINING OF THE ARMS OR LEGS

Exercise. The enlarged upperarm cross-section areas at rest suggested that arm training increased the strength of the arm muscles. In that case, a constant isometric work load related, e.g., to the handgrip would produce a smaller relative effort, and this can be expected to reduce the reflex increase in HR and vasoconstriction due to isometric contractions (12). Furthermore, with arm training the subjects may have learned to minimize the “wasteful” isometric component of exercise. Although we have no data that can decide whether possible changes in the isometric component of arm exercise contributed significantly to reduce HR and peripheral vasoconstriction, it was our impression that already during the preliminary exercise tests all subjects learned to use a rather loose handgrip in order to carry out the 15 min of strenuous arm exercise.

Both before and after training during arm and leg exercise, respectively, the (a-v)O₂ diff in resting legs and resting arms increased markedly as compared to the value at rest. Some of this increase of (a-v)O₂ diff in resting extremities can certainly be attributed to an increased local VO₂ max caused by unavoidable muscle contractions. This muscle activity was modest, however, and there can be no doubt that the main reason for the increase in (a-v)O₂ diff in resting extremities was a decrease in local blood flow. The circulatory response to arm exercise is very similar to that seen during bicycle exercise performed with only one leg. In the latter situation (a-v)O₂ diff in the resting leg increases as much as (a-v)O₂ diff in the exercising leg (7), and this phenomenon can be related to a virtually complete arrest of muscle blood flow in the resting leg (8). The more moderate increase in (a-v)O₂ diff in the resting arms as compared to resting legs is most likely explained by a greater relative and/or absolute cutaneous blood flow in the resting arms during exercise.

Assuming only negligible variations in local VO₂ max, the decrease in these regional (a-v)O₂ diff in response to training was compatible with the occurrence of less pronounced vasoconstriction in resting arms and legs during exercise after training. Like the increase in ICG clearance, this change was also confined to work performed with trained muscles. However, there was one exception to this statement: after leg training during heavy submaximal exercise with nontrained arms (a-v)O₂ diff in the resting legs decreased 11%. In fact, this was to be expected even if the degree of vasoconstriction was the same as before training, because mean aortic pressure increased 10%. As seen from Fig. 3, there was also a trend to a corresponding change in ICG clearance at this type and level of work.

Concerning exercise with trained muscles, the changes in ICG clearance and in (a-v)O₂ diff in resting extremities confirmed previous observations made in cardiac patients (9) that after training at a given submaximal VO₂ max total flow to nonexercising tissues is increased concomitantly to an unchanged or slightly decreased Q. This finding implies that blood flow to the exercising muscles is reduced, a deduction which is in agreement with evidence from investigations where muscle blood flow has been measured at the same submaximal work load before and after training (9, 13, 28–30). The increased (a-v)O₂ diff in the exercising trained arms seen in this study is consistent with a reduction in muscle blood flow. We failed, however, to demonstrate an increase in (a-v)O₂ diff in exercising trained legs, which would have suggested a decrease in muscle blood flow. Saltin et al. (26) have reported that femoral (a-v)O₂ diff is increased during submaximal leg exercise after training of the leg muscles. The explanation for this discrepancy can be that there was a greater admixture of blood from tissues other than exercising muscles in our study because we introduced the femoral venous catheters in the upstream direction. In the study of Saltin et al. (26) catheters were directed distally in the femoral vein.

Although (a-v)O₂ diff was increased in exercising trained arms at submaximal as well as supramaximal work loads, (a-v)O₂ diff was greater in exercising legs, trained as well as nontrained, at all comparable relative work levels. The reason for this difference in oxygen extraction efficiency between exercising arms and legs is probably that muscle tissue with high oxygen extraction makes up a smaller fraction of the total tissue volume in the arms as compared to the legs. On the other hand, it cannot be excluded that the oxygen extraction efficiency of arm muscles is relatively low. Even during maximal dynamic exercise with the forearm muscles, venous blood sampled from a deep muscular vein does not fall to the same low values as seen in femoral venous blood during maximal leg exercise (19).

In sharp contrast to the response observed in the arm training group, leg training caused a marked increase in Q and aortic pressures during heavy submaximal arm exercise. However, as judged from the regional (a-v)O₂ diff, this increase in Q was preferentially directed to tissues other than exercising muscles. Thus, the enhanced circulatory response to exercise with nontrained arms was not to any obvious benefit for the subject at this submaximal work load.

In contrast, during maximal exercise, an assumed corresponding increase in Q and aortic pressures probably enabled the increase in VO₂ max measured during exercise with nontrained arms. The unchanged (a-v)O₂ diff in the maximally exercising arms suggested that this increase in VO₂ max was mediated solely by an increased oxygen delivery to the muscles. This deduction implies that muscle blood flow and the mean blood pressure were limiting factors for VO₂ max during arm work before training.

Such a conclusion is in agreement with the traditional concept that the oxygen supply sets the upper limit for muscle oxygen consumption, but it is in variance with recently presented data which suggest that the oxidative metabolic capacity is the limiting factor (19). A conclusive statement on this controversial problem based on the experimental approach used in the present study naturally requires that VO₂ max be measured in more subjects and that data for Q and aortic pressures be obtained not only at submaximal levels, but also during maximal work.

The data obtained in this study for submaximal and maximal exercise with the arms or legs after either arm training or leg training warrant the general conclusion that training is not an absolute event that affects only the “central circulation” nonspecifically; it also causes important peripheral circulatory variations. The central and peripheral adaptations set together as far as the reduction in HR is concerned, but tend to counteract each other with respect to the effect on Q and arterial blood pressure. This antagonism certainly explains some of the conflicting information in the literature on the circulatory effects of training (3). The net effect of a
training program on blood pressure and Q seemingly depends on the relative contribution of peripheral and central factors. Therefore, it is also possible that peripheral and central circulatory adaptations show greater manifestation during arm exercise than during leg exercise. Thus a more precise evaluation of the relative contribution of central and peripheral factors should be done by training muscle groups which, with respect to size and degree of training, are strictly comparable in the pretrained state.

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