Forearm oxygen uptake during maximal forearm dynamic exercise

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Summary. This study was undertaken in an attempt to determine the maximal oxygen uptake in a small muscle group by measuring directly the oxygen expenditure of the forearm. Five healthy medical students volunteered. The subjects' maximal forearm work capacity was determined on a spring-loaded hand ergometer. Exercise was continued until exhaustion by pain or fatigue. Two weeks later intra-arterial and intravenous catheters were placed in the dominant arm. Blood samples for measurement of oxygen concentration were collected via the catheters. Forearm blood flow was measured by means of the indicator dilution technique. Oxygen uptake was determined according to the Fick principle. The forearm oxygen uptake attained at maximal work loads was a mean of 201 (SD ± 56) μmol · min⁻¹ · 100 ml⁻¹. It was impossible at maximal exercise to discern a plateau of the oxygen uptake curve in relation to work output. It is suggested that a plateau in the oxygen uptake curve is not a useful criterion for maximal oxygen uptake in a small muscle group. Skeletal muscle may have an unused capacity for oxygen consumption even at maximal exercise intensity where muscle work cannot be continued due to muscle pain and fatigue.

Key words: Blood flow — Blood pressure — Heart rate — Lactate — Oxygen uptake

Introduction

The generally accepted criterion for pulmonary oxygen uptake (VO₂max) is that the oxygen uptake shows no further rise with increasing work intensity (Davies 1968; Shephard et al. 1968; Astrand and Rodahl 1970). During dynamic exercise with large muscle groups a plateau of the VO₂/work intensity curve is usually seen.

The criterion of a plateau in VO₂ has not been established for exercise with small muscle groups. Thus, pulmonary VO₂ in relation to work intensity during exercise with one leg or one arm showed no tendency for reaching an asymptote; rather the VO₂ curve showed an upward swing (Davies and Sargeant 1974, 1975). A possible explanation of these findings is that during heavy work additional muscle groups are recruited, and to an increasing extent, to cope with the demands for work output and to stabilize the body (Saltin 1985).

Therefore, to study whether the maximal oxygen uptake in a small limited muscle group can be defined by reaching a plateau in the oxygen uptake curve, the oxygen uptake should be determined for that specific muscle group. In the present study, we measured the forearm oxygen uptake during forearm exercise at different work loads up to near maximal.

Subjects and methods

Five healthy, non-obese, male medical students volunteered. Their mean weight was 71.3 kg (SD ± 9.8 kg) and mean age was 25.4 years (SD ± 4.4 years). The subjects consented to participate in the study after written information on the study protocol, its purpose and possible risks. The study complied with the Declaration of Helsinki and was approved by the Municipal Ethics Committee of Copenhagen and Frederiksberg.

Procedure. Each subject was studied twice at an interval of 2 weeks. On the 1st day the subject's maximal forearm working capacity was determined. The dominant arm was chosen, which in all cases was the right. In the supine position the sub-
ject performed rhythmic forearm exercise on an adjustable spring-loaded hand ergometer (Wahren 1966). The forearm was horizontal, at an angle of approximately 60° to the trunk. The elbow was extended and the volar side of the hand faced upwards. The hand grip on the ergometer handle in the relaxed position was adjusted so that the middle phalanges of the second, third and fourth fingers were approximately vertical. The exercise rate was 50 contractions \( \cdot \text{min}^{-1} \). The path of contraction was 30 mm. Work intensity ranged from 7 to 19 kpm \( \cdot \text{min}^{-1} \) and 3-min bouts of exercise were performed with 15-min intervals. With each exercise period the work intensity was increased until the work load could not be sustained for 3 min. Usually, it was not necessary to perform more than 3-4 exercise periods, since the starting work intensity at near maximal work load was estimated beforehand from arm size and impression of fitness.

On the 2nd day of investigation the subject arrived at the laboratory in the morning after an overnight fast and not having smoked for 12 h. The study was performed in an air-conditioned room maintained at 21°C. After we had placed the intravascular catheters, the subject rested in a recumbent position for 30 min. During a subsequent period of 30-min supine rest forearm blood flow was measured, and at the end of this period blood samples were collected. Then the subject, remaining in the supine position, performed bouts of right forearm dynamic exercise as described above at approximately 40%, 60%, 80%, and 90% of the maximal work load. The first exercise period was 10 min; the following periods were 5 min each. During the last minute of exercise a wrist cuff was inflated to a suprasystolic pressure to exclude the hand from the circulation, and blood samples were taken and forearm blood flow was measured. There were 30-min intervals of rest between exercise periods.

Techniques. By the Seldinger technique a polyethylene catheter (inner diameter 0.61 mm) was inserted percutaneously into the right brachial artery at the level of the humeral intercondylar line and advanced 5 cm upstream. A Teflon catheter was inserted into a deep cubital vein of the right arm and advanced 5 cm in the distal direction. The catheters were kept patent by injecting small amounts of sodium chloride solution (154 mmol \( \cdot \text{l}^{-1} \) saline).

Forearm blood flow at rest was measured by means of venous occlusion strain-gauge plethysmography with a collecting pressure of 50 mm Hg and during forearm exercise by the indicator dilution technique after an intra-arterial bolus injection of \( ^{131} \)I-labelled human albumin. The bolus volume was 0.8 ml containing about 70 kBq of the tracer. To protect the thyroid gland from possible free \( ^{131} \)I the subjects were given 100 mg of potassium iodine tablets three times daily on the day before and on the day of the study. The forearm volume was obtained by water displacement.

Intra-arterial blood pressure was recorded continuously, except when blood samples were being collected, with an Elema-Schönander EMT 35 pressure transducer (Elema Schönander, Stockholm, Sweden). Electrocardiograms were recorded continuously on a direct-writing recorder.

Blood samples for determination of oxygen saturation and substrate concentrations were taken simultaneously from the brachial artery and the deep vein. Blood oxygen saturation and haemoglobin concentration, glucose, and lactate were determined as referred to in a previous paper (Hartling et al. 1980).

Mechanical efficiency of work expressed as a percentage was calculated as the ratio of external work to the extra energy production, assuming a resting metabolic rate of 0.3 ml \( \text{O}_2 \cdot \text{min}^{-1} \cdot 100 \text{ ml}^{-1} \) of tissue.

Statistical analysis. Changes during exercise were evaluated by analysis of variance (ANOVA) (Armitage 1977; Wallenstein et al. 1980). If ANOVA showed that there were no statistically significant changes during exercise, exercise data were pooled and compared with the data obtained at rest using Student's \( t \)-test for paired observations: \( P<0.05 \) was considered statistically significant.

Results

Heart rate and arterial blood pressure increased moderately during forearm exercise at submaximal and maximal intensities (Table 1). These variables returned to resting levels after each exercise period. Forearm blood flow increased about tenfold during exercise (Table 1). Due to large interindividual variation, changes in forearm blood flow with further increments of the exercise level were not statistically significant (Table 1).

The forearm uptake of glucose increased with exercise (Table 1). Lactate releases from the forearm at the end of each exercise period were large. Likewise, concentrations of lactate in the vein draining the forearm muscles were increased during exercise, but again there was a broad scatter of values so that changes with increasing exercise intensities did not attain statistical significance.

Forearm oxygen uptake increased during exercise (Table 1, Fig.1). As could be expected, oxygen uptake values for the same relative exercise levels were quite different among the subjects. Oxygen uptake in relation to the work load seemed to form a plateau in one subject, whereas there was no tendency for the oxygen uptake curves to level off in the others, in whom the ox-

![Fig. 1. Forearm oxygen uptake in relation to work output in five healthy subjects. Work output is presented as a percentage of maximal forearm work capacity.](image-url)