# PERIPHERAL BLOOD FLOW AT DIFFERENT LEVELS OF EXERCISE

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## ABSTRACT

It has often been said that the temperature in the core of the body (reflecting that in the hypothalamus) is an important factor in the regulation of the vasoconstrictor tone in skin blood vessels. Because of this regulation, the increase in flow of blood in the hand should be related to the rise in rectal temperature during exercise, both in respect to time and level of exercise. Studies were conducted to test this hypothesis and also to see whether any other factors might interfere with this association.

Observations of hand blood flow at various levels of exercise were made by means of the venous occlusion plethysmograph.

It is shown that the new levels reached by the rectal temperature and hand blood flow are directly proportional to the rate of metabolism. Furthermore, the rate of hand blood flow is directly proportional to the rectal temperature when both these parameters are in a steady state. A stage is reached when the rate of the hand blood flow decreases to supply more blood to the working muscles. This happens in spite of an increase in heat production.

# CHAPTER I

## THE PROBLEM

### 1. INTRODUCTION

Considerable research has been done on the physiology of exercise, but many problems still remain to be solved. One of these is the manner in which the blood flow to the skin and muscles changes during different phases of exercise and how the blood flow to these different areas is controlled during these changes.

A number of different techniques have been used for studying blood flow in the skin during exercise. Stewart (41), Bishop *et al*. (10), Muth *et al*. (31) and Kamon and Belding (27) used a hand calorimeter; Christensen *et al*. (13) used a finger plethysmograph; and Blair *et al*. (11) and Bevegård *et al*. (9) used a hand plethysmograph. All these investigations showed that there is a decrease in skin blood flow of the right hand at the commencement of exercise and a subsequent rise later during exercise.

### 2. STATEMENT OF THE PROBLEM

In nearly all of the abovementioned studies the duration of exercise was short. Little is known of the effect on skin blood flow of longer periods of work, say of up to 60 minutes, or the effect of different levels of work.

One of the reasons why it is important to study hand blood flow at different levels of work and for periods of up to 60 minutes is to establish the relationship between body temperature and skin blood flow. Nielsen (34) showed that rectal temperature increased during exercise and reached a steady level after 40 to 60 minutes of commencing work in cool conditions. Wyndham _et al_. (44) showed the same to be true for hot, humid conditions provided that the subjects are well-acclimatized to work in these environmental conditions and that the work rate is not too high.

Furthermore, the new level reached by the rectal temperature is directly proportional to the rate of metabolism. If the temperature in the core of the body (reflecting that in the hypothalamus) is an important factor in the relaxation of the vasoconstrictor tone in the skin blood vessels of the hand, then the increase in flow of blood in the skin should be related to the rise in rectal temperature during exercise, both in respect to time and level of exercise.

## 3. OBJECT OF THE STUDY

These studies were conducted to test the above-mentioned hypothesis and also to see whether any other factors might interfere with this association.

The object of this study was therefore:

(a) to measure the blood flow of the hand during prolonged leg exercise at progressively increasing work loads and,

(b) to determine the effects of body temperature, time and work rate on the blood flow of the hand.

## 4. RATIONALE OF THE PLETHYSMOGRAPHIC METHOD FOR DETERMINING HAND BLOOD FLOW

For measuring total blood flow the most useful and almost certainly the most reliable method is venous occlusion plethysmography.

The principle on which the plethysmograph works is very simple. Any swelling of an organ enclosed within the plethysmograph, displaces for example fluid from the rigid chamber to a system for measuring these changes in volume. To be able to do this the following conditions should be adhered to:-

(1) The compartment must be bound by a rigid, absolute barrier that cannot be distorted or expanded.

(2) An increase in volume of one component in a closed system at constant pressure must be compensated for by the displacement of an exactly equal volume of some other component.

(3) The increase in volume which causes this displacement should not be hampered in any way by the instrument.

(4) The recording instrument should be primarily a volume detector, insensitive to other types

of physical changes such as atmospheric pressure or temperature.

In this study a water-filled plethysmograph was used. The disadvantages of this apparatus are:-

(1) the limb is in an abnormal environment which

(a) prevents evaporation and

(b) may physically alter the response of the skin vessels;

(2) it imposes hydrostatic pressure upon the limb;

(3) the subject is not free to move around at will.

The advantages of this apparatus are that:-

(1) observations can be made several times a minute; (2) it is innocuous; (3) and it causes negligible discomfort. The advantages of using water instead of air in the plethysmograph are: water is virtually incompressible and thus gives rapid transmission of volume changes, it has a small coefficient of thermal expansion and heat conduction and it is easier to detect any leakage.

For the plethysmographically recorded flow to be equal to the arterial flow before occlusion, several assumptions must be made:-

(1) There should be complete occlusion of the veins.

(2) The arterial inflow should not be altered initially by the occlusion pressure or the rising venous pressure.

(3) The occlusion artifact should be insignificant or easily evaluated.

(4) These factors should hold true for a length of time which is sufficient for measurements to be made.

The following evidence has been presented to justify these assumptions:-

(1) Landowne and Katz (28) measured tissue pressures under an occlusion cuff around the human calf and concluded that 50 mm Hg of cuff pressure is sufficient to occlude all collapsible veins. Barnett (7) noted that the same apparent flow was recorded within a wide range of occlusion pressures, indicating that all collapsible veins were occluded. After injecting a radioisotope in a dorsal vein of the hand and then quickly inflating an occlusion cuff on the arm, Formel and Doyle (18) could detect venous leakage only after venous pressure approached occlusion pressure.

(2) Landowne and Katz (28) measured the artifact produced by the occlusion cuff and found that after an abrupt rise the curve continued in a slower secondary rise. The initial artifact is rapid and obvious and can easily be avoided. The second rise, however, is significant and cannot be avoided.

(3) Conrad and Green (14) showed that the arterial inflow decreased after application of the occlusion pressure. This decrease in arterial inflow and the secondary artifact described by Landowne and Katz (28) are in opposite directions and therefore tend to cancel out each other. Conrad and Green (14) also found a good agreement between the plethysmographically measured flow and the true arterial inflow as measured by means of a cannulating-type electromagnetic flow-meter.

(4) Conrad and Green (14) showed that venous occlusion was rapid and complete, and the duration of occlusion was adequate for the measurement of inflow within a wide range of occlusion pressures.

# CHAPTER II

## LITERATURE REVIEW

### 1. HISTORICAL BACKGROUND (5,26)

For centuries physicians held Galen's view concerning the cardiovascular system. According to him the heart stirred and heated the blood while the lungs acted as fans for cooling. The liver was regarded as the centre of the blood system. This concept remained although a gradual change of view took place which culminated in the work of Harvey published in his book "De Motu Cordis" in 1628. Harvey clearly showed that blood flowed from the heart through the arteries and back to the heart through the veins.

In 1661 Malpighi was able to discover with the aid of a primitive microscope, minute blood vessels connecting arteries and veins. The circulation of the blood thus became an accepted fact.

It was only until after the discovery of the plethysmograph and it's uses that it became possible to determine the role of blood flow through an organ.

The modern plethysmograph can be traced back to the 17th Century when Francis Glisson published his "De Ventriculo" in 1677. In this book Glisson reported that a muscle was not inflated during contraction, i.e., its volume remained constant. This he proved by placing the organ in a rigid, nondistensible, watertight compartment. Any volume changes in the organ displaced fluid from the rigid case to a system for measuring volume.

In the 19th Century Poisenelle (1828) showed that the changes in the diameter of an artery was caused by the heart beat. He used a similar method as Glisson. The same principle was employed by Piegu in 1864 and by Chelius in 1850 to study circulatory and respiratory changes in the human limbs.

The first instrument to record volume changes graphically and which could therefore truly be said to have been a plethysmograph, was described by Buisson in 1862.

In 1875 the Mosso plethysmograph was used to record slow variations in the volume of the vessels of the forearm.

Brodie and Russel (1905) discovered that the plethysmograph could be used to determine the rate of blood flow through an organ by venous occlusion. They studied renal blood flow in animals by placing the kidney in an oncometer and then temporarily clamping the part of the renal vein in the chamber. The resultant rate of swelling of the organ was recorded on a drum and the rate of renal blood flow determined from the curve. They also suggested that blood flow through a limb could be measured by this technique.

Hewlett and Van Zwaluwenburg followed this up in 1909. The hand, forearm and elbow were enclosed in their instrument and they successfully recorded the blood flow. Due to the fact that air was used in the plethysmograph, temperature fluctuations influenced the results.

We thus have two types of plethysmographs, namely, a hydro- and a pneumoplethysmograph. These authors also suggested a smaller plethysmograph, it's ends sealed to the skin of a segment of the extremity. Measurements of forearm and calf blood flow were thus possible, and information about highly muscular segments was obtained.

In 1935 Freeman described the first plethysmograph to be used for the determination of the rate of the blood flow in the hand.

In 1938 Grant and Pearson showed that what was measured by the hand-plethysmograph was for the most part the circulation through the skin, and what was measured by the forearm-plethysmograph was mainly the blood flow through the skeletal muscles.

Although the hand-plethysmograph technique was used for recording blood flows with the subjects at rest, it could not be used while the subject was active, e.g. while pedalling a bicycle ergometer. Some observations were made by earlier workers, e.g. Hewlett and Van Zwaluwenburg in 1909, but this was after exercise and they showed an increased blood flow.

It was only in 1961 that Blair _et al_. (11) successfully used the hand-plethysmograph during exercise by suitably damping the recording system.

2. TEMPERATURE

Heat affects the skin circulation in two ways. It either affects the blood vessels directly or via the sympathetic nervous system.

(a) The hand:

Hewlett et al. (24) were the first to demonstrate the tremendous acceleration of the skin blood flow following overheating of the body in a hot tub. They obtained resting values at normal body temperature of ± 3 ml/100 cc tissue/minute and values of 15,6 ml/100 cc/min at an oral temperature of 103,8$^{o}$F.

Abramson et al. (1) varied the temperature of the water in the hand-plethysmograph and found that the blood flow changed accordingly while body temperature showed no change. They recorded the lowest blood flow at a plethysmograph temperature of 20 - 25$^{o}$C, higher values at 32$^{o}$C and the highest values at 45$^{o}$C which is about the highest temperature a man can withstand without discomfort. They found that the normal range of variation in blood flow was very small at 45$^{o}$C, i.e., there was a more steady blood flow than at lower temperatures. Brown and Page (12) came to the same conclusion. However, in contrast to Abramson et al. (1), they found that not only was the flow the highest at 45$^{o}$C, but the magnitude of variation increased with an increase in local temperature.

It is obvious from the literature that there is an increase in skin blood flow with an increase in body temperature and an increase in skin blood flow associated with an increase in local temperature without a concomitant increase in body temperature. The effect increased local temperature has on skin blood flow is a direct effect of heat on the blood vessels as pointed out by Freeman (21). He showed that the increase in flow associated with an increase in plethysmograph temperature, was a purely local reaction because the increase in hand blood flow was the same in a normal and a sympathectomized hand.

Abramson _et al_. (1) found a vasodilatation in the hand when heat was applied to other body areas. They kept the plethysmograph temperature constant at 32°C and changed the air temperature. They found a blood flow of 4,6 ml/100 cc/min at an air temperature of 21° - 24°C and 12,0 ml/100 cc/min at an air temperature of 25° - 27°C.

Roddie _et al_. (35) found that a combination of local heat and indirect heating (with the consequent release of sympathetic vasomotor-tone) caused a much greater hand blood flow than could be produced by either procedures separately.

Spealman (40) used two different plethysmograph temperatures. With a plethysmograph temperature of 35°C and the rest of the subject in a cold, normal and warm environment alternatively, blood flow values of 1,9, 5,9 and 20,6 ml/100 cc/min, were recorded, respectively. At a plethysmograph temperature of 15°C and the rest of the subject at similar temperatures, he found blood flow values of 0,3, 0,9 and 5,5 ml, respectively.

Not only is there a change in skin blood flow with varying local temperatures, but changes in other skin areas also have an effect.

Gaskell (22) showed that anaesthetization of the nerves which supply the hand, had no significant effect on the blood flow of the hand in indirectly heated subjects. Intra-arterially injected atropine also had no effect. These results suggest that there are no sympathetic vasodilator nerves to the hand (22).

Fox and Hilton (19) found a bradykinin-forming enzyme in sweat collected in the hand. The bradykinin plays no role in regulating the blood flow of the hand (Roddie _et al_. (38)).

Beaconsfield and Ginsburg (8) passively raised subjects from the horizontal to the vertical position. The immediate response was a vasoconstriction which was absent in a recently sympathectomized hand. The constriction was of nervous origin.

It is obvious from the literature that a release of vasoconstrictor tone is brought about reflexly by an increase in the environmental temperature (local effect) and/or an increase in body temperature (central effect). The skin blood flow at any given moment is the result of an inter-action of central, local and reflex effects of heat. These effects may either oppose or reinforce each other.

(b) Forearm skin

Wilkens and Eichna (42), showed a vasodilatation in the forearm when body temperature was raised. Brown et al. (12) showed the same increase in forearm flow with increase in local temperature and constant body temperature. They used plethysmograph temperatures ranging from $5^{o}C$ to $45^{o}C$. At a constant body temperature the minimum forearm blood flow was at a plethysmograph temperature of between $10^{o}$ - $20^{o}C$ and the maximum flow at a plethysmograph temperature of $45^{o}C$.

The problem now was to determine whether this increase in flow was in the whole forearm, the skin of the forearm or the muscles of the forearm.

Barcroft et al. (4) came to the conclusion that the increase in forearm blood flow during body heating, was restricted to the skin.

Edholm et al. (17) recorded blood flows on both forearms using plethysmographs. They made recordings before and after adrenaline iontophoresis of the right arm and found that initially the flows were similar in both forearms. After "skinning" the right forearm with adrenaline iontophoresis, the flow decreased. They also found that the left forearm (normal) responded to body heating by an increase in flow, while the right forearm (treated) showed little or no change. They concluded that the increase in flow due to body heating was restricted to the skin.

Roddie et al. (36) determined the oxygen saturation of superficial and deep venous blood of the forearm. They found that during body heating the oxygen saturation of the superficial samples gradually increased, while that of the deep samples showed no change. It was concluded that the increase in blood flow of the forearm was entirely due to an increase in the blood flow through the skin.

It can be concluded from the literature that the forearm blood flow increases with an increase in local temperature and during an increase in body temperature.

Roddie *et al*. (37) showed that the oxygen saturation of superficial venous blood increased after cutaneous nerve block. This increase was attributed to a release of constrictor tone to the skin vessels.

Roddie *et al*. (38) used the venous occlusion plethysmograph to determine forearm blood flow during body heating. Their results showed that before the onset of sweating the increase in the forearm blood flow was slow, but with the onset of sweating there was a rapid increase in forearm blood flow. This secondary increase of forearm blood flow was prevented by atropine. They concluded that the initial increase in forearm blood flow was due to a release of vasoconstrictor tone and the secondary increase was due to the release of a vasodilator substance as a result of the increased metabolic activity of the sweat glands.

Hilton and Lewis (25) detected a stable vasodilatory material in the perfusate collected during chorda stimulation from the submandibular salivary gland of the cat perfused with Locke's solution. They concluded that this substance (later known as bradykinin) was produced or released from the gland as a result of its activity.

Fox et al. (19) used polythene bags to collect the sweat from the forearm of a heated subject. Bradykinin-forming activity was found in all the samples tested. In a later study Fox et al. (20) infused saline through the skin before and after body heating. They found that: "When the subject was kept cool, the protein content and bradykinin-like activity of successive samples remained relatively steady.

However, on indirect heating the bradykinin-like activity increased three to five-fold, without any rise in the protein and peptide content. The increase in bradykinin began with the onset of vasodilatation, even when the subject had not yet begun to sweat".

The increase in forearm blood flow during body heating is thus facilitated by two mechanisms. Firstly, a release of vasoconstrictor tone to the skin vessels and secondly, a vasodilatation as the result of the direct action of bradykinin released by the sweat glands on the blood vessels.

(c) Forearm muscle

Indirect heating of a subject has no affect on the muscle blood flow of the forearm (Cooper et al. (15), Edholm et al. (17), Roddie et al.(36).

Roddie _et al_. (37) showed that the oxygen saturation of the venous blood from forearm muscle increased after peripheral nerve block, indicating that these vessels are supplied by vasoconstrictor nerves.

3. EXERCISE

(a) The hand

Stewart (41) used a calorimeter for determining peripheral flow. He found that the hand blood flow decreases at the beginning of leg exercise. Christensen _et al_. (13) measured the skin temperature of the finger, arch of the foot and toe at rest, work and work with "no load". They found that " .... a general reduction of the skin's blood flow is usually to be observed at the transition from rest to work." During light work, "The responsible vasoconstriction must be considered as purely psychic and without any regulatory importance."

During heavy work, " .... we conclude that the vasoconstriction in the beginning of heavy work is of regulatory significance for the adjustment of the circulation at the transition from rest to work." Bishop _et al_. (10), using the hand calorimeter, showed an initial drop and an increase in blood flow later in exercise. At the 6th minute of exercise the blood flow reached the resting values. During the last minute of exercise the mean hand flow was twice that at rest before exercise. Muth et al. (31) also used the hand calorimeter and found a reduction in blood flow at the beginning of exercise followed by a subsequent vasodilatation. Cardiac patients showed lower values during rest and work, and the dilatation during work was delayed. Blair et al. (11) used a suitably damped hand-plethysmograph to record hand blood flow during leg exercise and found the same as the previous authors. Bevegård et al. (9) using the hand-plethysmograph came to the same conclusion. Kamon and Belding (27) used a water-filled calorimeter at constant temperatures to determine hand blood flow during leg exercise of 60 minute duration. They found an initial decrease lasting approximately 10 minutes. Thereafter the hand blood flow increased and reached a steady level after between 30 - 40 minutes of exercise.

It is apparent from the literature that the hand blood flow decreases immediately with the onset of leg exercise and increases as exercise continues, and levels off at a value higher than the resting value. This decrease in the blood flow occurs practically instantaneously at the start of work and it is assumed that it is of nervous origin, caused either by cortical impulses or by reflex influences from the working muscles.

Christensen et al. (13) found no change in hand blood flow during their "no load" experiments, showing that the expectation of work had no affect. Blair et al. (11) showed that the initial vasoconstriction and the later vaso-dilatation were reduced when the hand had been treated with Bretylium tosylate to block the adrenergic vasoconstrictor nerves. They came to the conclusion that "it is likely that they (i.e. constriction and dilatation) were both due to alterations in vasoconstrictor tone" and further " .... it is likely that the increase in heat production during exercise was responsible for the reflex release of vasoconstrictor tone." Bevegård et al. (9) came to the conclusion, that the response of the hand blood flow to leg exercise is a balance between reflex increase in constrictor tone due to exercise, opposed by a reflex decrease in constrictor tone caused by a rise in body temperature. A compromise is reached between the need of the body for temperature regulation and that of utilising most of the increase in cardiac output for the active muscles.

(b) The forearm

Bishop et al. (10) sampled blood from the axillary vein of their subjects at rest, during and after leg exercise. They found an initial decrease in oxygen saturation and after a variable length of time, an increase in oxygen saturation. The initial decrease in oxygen saturation was unrelated to the severity of the work. The changes in oxygen saturation were taken to indicate that blood flow to the arm decreased at the beginning of leg exercise but increased again as exercise continued. Using an isotope clearance technique they found little alteration in forearm muscle blood flow during leg exercise. These investigators also found that total blood flow to the arm was reduced during leg exercise. The reduction in blood flow therefore occurred in the skin, since no evidence for reduction in muscle blood flow was found. Mitchell <u>et al</u>. (30) also showed a decrease in forearm blood flow during short periods of exercise on a treadmill.

Blair <u>et al</u>. (11) measured forearm blood flow during leg exercise (supine) using a water-filled plethysmograph. They showed a fall in forearm blood flow over the first minute of exercise, followed by a gradual return toward the resting level of blood flow. The initial gradual fall in blood flow was more marked during heavy exercise. When infusing

Bretylium tosylate intra-arterially in one forearm and thereby blocking the adrenergic vasoconstrictor fibres, Blair et al. (11) found that the blood flow in the control side decreased, whereas the blood flow in the experimental side rose at the beginning of leg exercise. This indicates that adrenergic vasoconstrictor fibres are responsible for the fall in forearm blood flow at the beginning of leg exercise. The increase in constrictor tone occurred in muscle rather than skin and was sufficient to cause an actual reduction in flow in the whole arm.

Bevegård and Shepherd (9) used a temperature compensated strain-gauge plethysmograph, to measure forearm blood flow on exercising supine subjects. They found an increase in forearm blood flow during the first minute of exercise. This increase was followed by a decrease close to pre-exercise levels. The blood flow remained at this level for the remainder of the exercise period. At a higher exercise level (1 200 kg.m/min. compared to the previous maximum of 810 kg.m/min.), the forearm blood flow, after the initial increase, decreased to less than half the pre-exercise value. By catheterization of the superficial and deep veins of the forearm Bevegård and Shepherd (9) were able to show that the transient increase in forearm blood flow was confined to the muscle vessels. After this transient increase the muscle vessels constricted and blood flow decreased. The skin vessels on the control forearm showed little change during the first 30 - 60 seconds of exercise. Thereafter the skin blood flow increased. These two investigators therefore concluded that "with exercise up to about 2 litres/min of oxygen consumption, blood flow is redistributed from muscle to skin in the forearm; but the total blood flow to the forearm is little changed. This facilitates the regulation of body temperature during exercise without any part of the increase in cardiac output being diverted to the inactive parts. With severe exercise, the muscle vasoconstriction is so intense that the total forearm flow decreases to such an extent that more of the cardiac output is available for the active muscles."

Kamon and Belding (27) using a water-filled calorimeter determined forearm blood flow over a prolonged period of leg exercise on a bicycle ergometer. They found no change in forearm skin blood flow during the first 10 minutes of exercise. Thereafter, there was a marked and continuous increase to a peak which was reached in between 30 - 40 minutes. During the last part of the hour of leg exercise there was again a fall in forearm blood flow.

In summarising forearm blood flow during leg exercise we find that the total blood flow decreases at the beginning of exercise (10,11). This is in contrast with other authors (9) and the "unpracticed subjects" of Blair et al. (11). As exercise continues, total forearm blood flow may increase (10,11) or decrease (9,11). The forearm skin blood flow shows no change at the beginning of exercise but later increases (9,11,27), although some authors show a decrease (10). The findings on muscle blood flow show even more discrepancies between authors. Some show no change (10), some a decrease (11), and others an increase (9) in forearm muscle blood flow at the beginning of leg exercise. However, as leg exercise progresses blood flow in the resting muscles of the arm decreases (9,11).

Most of the differences seem to be due to the different methods, exercise levels and duration of exercise used.

## 4. BODY TEMPERATURE AND SKIN BLOOD FLOW DURING WORK

For a given oxygen consumption Nielsen (34) has shown that the rectal temperature will always increase to a certain level, irrespective of the level of the rectal temperature before the start of work or the environmental conditions during work (excluding extremes). B. Nielsen (33) has shown that deep body temperature as reflected by oesophageal temperature, is the same for different types of work requiring different muscle groups (e.g., arms and/or legs) provided that the metabolic rate is the same. The same author (32) also showed that the increase in body temperature during work is independent of the total heat production. The increase in body temperature during work is therefore independent of the ambient temperature (within wide limits) and total heat production of the body, but depends on the work intensity (metabolic rate). It is therefore quite clear that the increase in body temperature is not a passive rise, caused by the increased heat production, but is due to a "setting of the body thermostat" at a higher level. According to Asmussen and Boje (2), the body temperature increase would benefit the enzymatic reactions in the working muscles and increase the efficiency of the work.

At the beginning of exercise there is a strong dermal vasoconstriction (9,10,11,13, 27, 31) and at the same time there is also a fall in body temperature (27,45). The transient fall in body temperature seems to be the result of the displacement of cool blood from the skin to the blood circulating in the core of the body (9,46). According to Kamon and Belding (27) this displacement of cool blood results in the perfusion of the hypothalamus with cooler blood, thereby reinforcing the skin vasoconstriction. It was shown that the initial dermal vasoconstriction during exercise is followed by a release of dermal vasoconstriction later during exercise. The release of dermal vasoconstriction is concomitant with the beginning of the rise in hypothalmic temperature (Kamon and Belding (27), and is therefore viewed as a manifestation of readjustment of dermal blood flow to accomplish heat balance (17,27,36).

In a study in which the metabolic rate and total heat production were made to change out of step, B. Nielsen (32) found that the increase in skin blood flow was the best correlated with the total heat production. This was achieved by having the subject walking (running) downhill (negative work), on the horizontal and uphill (positive work) on a treadmill. When plotting the skin blood flow against body temperature three distinct groups of points are evident. All three show a linear relationship between skin blood flow and body temperature (metabolic rate). When comparing negative and positive work, it is quite clear that for a given metabolic rate the skin blood flow is always higher during negative work than during positive work. When the skin blood flow is plotted against total heat production for the three different types of work the distinct grouping of points disappear. It is therefore quite evident that skin blood flow shows a higher correlation with total heat production than with metabolic rate.

This study of Nielsen (32) also shows that deep body temperature correlates better with metabolic rate than with total heat production.

From the literature it is apparent that most of the work done on the blood flow of the hand during exercise was concentrated on the transition from rest to work and the first few minutes of exercise. The only publications that are directly relevant to this thesis is the work of Kamon and Belding (27), and Nielsen (32). Kamon and Belding (27) studied blood flow during prolonged exercise but at one work rate only. However, they did show a readjustment of dermal blood flow to accomplish heat balance. On the other hand Nielsen (32) showed that total skin blood flow correlated well with metabolic rate during positive work. Nielsen (32) also showed the good correlation between deep body temperature and metabolic rate.

# CHAPTER III

## APPARATUS AND METHODOLOGY

### 1. SUBJECTS

Three healthy, young, male Bantu mine recruits were used. Their physical characteristics are given below.

| Subject | Weight (kg) | Height (cm) | Age (years) |
|---|---|---|---|
| A | 65,70 | 173,40 | 23 |
| B | 57,40 | 155,90 | 21 |
| C | 65,40 | 170,90 | 21 |

These men were highly-trained at pedalling a bicycle ergometer at both aerobic and anaerobic work rates and were kept in a highly-trained state during the whole of the experiment.

### 2. EXPERIMENTAL PROCEDURE

After a light breakfast, the subjects came to the laboratory at about 7.00 a.m., changed into shorts and rested on the bicycle-ergometers in a room controlled at an environmental temperature of 21°C. At about 8.30 a.m. two subjects were prepared for the respective experiments in which they would participate that day, i.e. the determination of either cardiac output or hand blood flow. The preparation of the subjects comprised: insertion of the rectal thermocouple, placing of the E.C.G. electrodes on the chest and where applicable, placing the subject's hand in the plethysmograph. After taking resting observations (at about 9.00 a.m.) the subjects commenced pedalling. Observations were now made as described below.

## 3. METHODS AND APPARATUS

The environmental temperature was controlled at about 21°C.

The hand blood flow was measured by using a hand venous occlusion plethysmograph (Greenfield (23)). The plethysmograph was constructed of "Perspex" and covered with cotton wool for insulation against any heat loss or gain from the environment. The recording of hand blood flow during leg exercise was made possible by damping the recording system as proposed by Blair *et al*. (11) and by placing the plethysmograph on a critically balanced table with the forearm and elbow resting on a suitably made foam rubber cushion. The use of a critically balanced table resulted in less movement between the forearm and plethysmograph as these two tended to move in conjunction with each other. The waterbath, was kept at a temperature of 35°C. Resting values were recorded on different days. During leg exercise each hand blood flow value was an average of seven observations taken at one-minute intervals. Thus the 15-minute value is an average of observations after 12, 13, 14, 15, 16, 17 and 18 minutes of work. The same was done for the 30, 45 and 60-minute values.

Rectal temperature was measured by means of a copperconstantan thermocouple inserted in the rectum to a depth of 8 centimetres. Readings were taken on a potentiometer and converted to degrees Fahrenheit by means of a calibration chart. Rectal temperatures were recorded at rest and at 5-minute intervals during work.

<u>Ventilation and oxygen consumption</u>. The Douglas bag technique was used to collect expired air. An Edwards rubber face mask fitted with low resistance valves was connected to the Douglas bag via corrugated rubber tubing. Volumes were measured in a bell-type gasometer. Two aliquot samples were taken from the Douglas bag and analysed for oxygen on the Beckman oxygen analyser. Samples were collected over two 3-minute periods during work, that is, at 26-29 minutes and 56-59 minutes.

<u>Cardiac output</u> was determined with the oxy-acetylene re-breathing technique and samples were analysed on a Haldane apparatus. Samples were taken during the 30th and 60th minutes of work.

<u>Heart rate</u> was recorded with an E.C.G. (using a chest lead), during rest and at the 15th, 30th, 45th and 60th minutes of work.

<u>Blood pressure</u> was determined by auscultation after 20 minutes of work.

<u>Work rates</u> of 4 000-10 000 ft.lb/min were used. Each subject worked at only one work rate per day. The subjects were required to pedal the bicycle ergometer continuously for 60 minutes at each work rate unless the work rate was so high that it limited the exercise period to 30 minutes. It is important to note that only positive work was used in the course of this study (Snellen (39)).

The statistical formulae used for calculating regression lines, correlation coefficients and standard deviations are given in an Appendix.

Duration of the study. The study required approximately fifty-five working days.

# CHAPTER IV

## RESULTS

All the physiological values reported on are averages of three experiments.

### Hand blood flow

Figure 1 shows the hand blood flow in relation to time at different work rates. It is clear that hand blood flow increases with an increase in work rate. The individual blood flow values of Subjects A and B for the first three levels of work differ markedly, with Subject C showing hardly any change. It is also clear that after an initial decrease, seen in figures 2 - 4, the hand blood flow increases rapidly during the first 15 minutes of work, then slows down and tends to level off after 30 minutes of work. It will also be noted that the rate of increase of blood flow increased with each successive increase in work rate. In Figures 5, 6 and 7 confidence limits were added to the mean blood flow values of individuals (Table 2). Where these limits do not overlap the two means are significantly different at approximately the 10% level, i.e. it is about 90% sure that they are truly different. It can therefore be said that for subject A the blood flow values at 9 000 ft.lb/min are significantly higher than the 4 000 ft.lb/min values. For subject B the 7 000 ft.lb/min values are significantly higher than the 4 000 ft.lb/min values. For subject C the 8 000 ft.lb/min values are significantly higher than the 4 000 ft.lb/min values. Figure 1 also indicates that the hand blood flow of subjects A and C show distinct changes at the highest work rates. These changes are summarised in Figures 5 and 7, respectively.

Subject A showed a steady increase in blood flow rate with each successive work rate up to 9 000 ft.lb/min (2,88 litres of oxygen/min). With any further increase in work rate (to 3,35 litres of oxygen/min) the blood flow rate decreased. This decrease is significant at the 10% level (Fig. 5) and occurred despite the fact that the body temperature and blood pressure were increased.

Subject C showed the same effect at 8 000 ft.lb/min, but to a lesser extent. His blood flow differed somewhat from that of subject A in that the blood flow did not increase after 30 minutes (Fig. 7). This subject's body temperature, systolic pressure and cardiac output increased. This difference between 7 000 and 8 000 ft.lb/min is not significant at the 10% level (Fig. 7). Figures 13 - 15 show that the hand blood flow was proportional to the rectal temperature over the range 4 000 ft.lb/min to 7 000 ft.lb/min for subjects B and C and over the range 4 000 ft.lb/min to 9 000 ft.lb/min for subject A. Figure 20 shows that the blood flow was in fact proportional to the rate of metabolism but not over the whole range of work rates. Figures 21 - 23 show the regression lines fitted to the data (blood flow vs. oxygen consumption).

Rectal temperature

Figure 8 shows the response of rectal temperature to time at different work rates. A tendency to level off after about 45 minutes of work can be seen. It is also clear that the rate of increase of the rectal temperature increased with each progressive work rate. During work the rectal temperature of subject A showed hardly any change over the first three work rates. His rectal temperature also remained below that of the other two subjects. Figures 3 and 4 show the close resemblance between the graphs for blood flow and rectal temperature.

Oxygen consumption

It will be noted in Figure 9 that there were no marked differences in oxygen consumption between the different subjects at any of the work rates. The linear relationship between work rate and oxygen consumption is quite clear.

Cardiac output

Figure 10 summarizes the cardiac output results of two subjects. It can be seen that there was an increase in cardiac output with each progressive increase in work rate. There was no marked difference between determinations made at 30 minutes and 60 minutes.

Heart rate

Figure 11 shows the normal pattern of increased heart rate with increase in work rate. After 15 minutes of work the heart rate tended to level off as there was no marked difference when compared with those recorded after 60 minutes of work. Subject A differed from the other two subjects in that his heart rate showed little increase over the first three work rates, but thereafter the normal increase in the heart rate was seen. His heart rate remained lower than those of the other two subjects over the range 6 000 ft.lb/min to 8 000 ft.lb/min.

## Blood Pressure

From Figure 12 it is clear that the systolic blood pressures increased with each progressive increase in work rate. For subject A, values of 204 mm Hg were reached at 10 000 ft.lb/min. The diastolic pressures showed a drop over the first two work rates, but no further drop at the other work rates.

# CHAPTER V

## DISCUSSION

In this study only three subjects were used. The author is aware that the use of only three subjects could be a limitation in this study, but on account of the clear-cut results obtained and the time involved in doing this study he feels justified in using the results obtained on three subjects only.

When this experiment was started it was doubtful whether it would be possible to measure hand blood flow at high work rates, that is, work demanding an oxygen consumption exceeding 2,0 litres/minute. However, Table 4 shows that it was possible even at an oxygen consumption rate of 3,35 litres/minute in the case of subject A. Only subject A worked at such a high rate of oxygen consumption. Due to circumstances beyond the Laboratory's control the other two subjects resigned before they could do work at these high work rates. This resulted in subject B completing only one run at 8 000 ft.lb/min and subject C completing three runs at 8 000 ft.lb/min. The highest work rates for these two subjects were at an oxygen consumption of approximately 2,5 litres/min. For the same reason the cardiac output determinations on subjects B and C had to be stopped prematurely.

Most of the work done on the blood flow of the hand during exercise was concentrated on the transition from rest to work and the first few minutes of exercise. Barger (6), whose subjects worked until exhaustion, changed the work rate during exercise. In a recent study on hand blood flow by Kamon and Belding (27) work was done for 60 minutes but at one work rate only. In the study reported on here, more attention was paid to the later phase of exercise, and to the effect of different levels of exercise on the hand blood flow.

The different work rates employed in this study were all submaximal. Figure 11 shows that all the heart rates were below 180 beats/min, which is the average maximum heart rate of the Bantu at the medium altitude of Johannesburg (Maritz _et al_. (29)). Furthermore, the period of exercise ranged from 30 to 60 minutes, which is more than the stated 3 - 5 minutes exercise possible at maximum effort.

In Figures 2 - 3 it will be seen that rectal temperature and hand blood flow increased during exercise and a fairly steady state was reached. The increase in rectal temperature was a result of the "setting of the body thermostat" at a higher level, and was in proportion to the energy production (B. Nielsen (32) and Wyndham (44). These experiments confirm that the new level reached by the rectal temperature was proportional to the rate of metabolism, as can be seen in Figure 17. According to Blair _et al_. (11) the readjustment of the hand blood flow during exercise is brought about by a release of vasoconstrictor tone associated with the increased heat production as a result of the exercise. The hand blood flow does tend to reach a steady level before the rectal temperature. This is most probably due to the rectal temperature lagging behind the arterial temperature. It is therefore clear that the hand blood flow and rectal temperature are proportional to the rate of metabolism both in respect of time and level of exercise, for any specific combination of exercise and environmental conditions.

The blood flow/rectal temperature curves presented here will be shifted to the left for negative work (32,39). The relationship will, however, still be maintained.

From the above it is quite clear that the temperature in the core of the body (reflecting that in the hypothalamus) is a major regulating factor in the relaxation of the vasoconstrictor tone in the skin blood vessels of the hand. As pointed out previously the temperature in the core of the body has to be maintained at a predetermined level for a given oxygen consumption. The only way the body can do this is by losing any extra heat through an increase in the skin blood flow. For any specific environment and type of exercise the skin blood flow increases in association with the rise in rectal temperature both in respect of time and level of exercise. This point is well illustrated in these experiments. This relationship between hand blood flow and body temperature does not hold true at higher levels of exercise.

Both subjects A and C showed a distinct change in hand blood flow in relation to body temperature at the highest level of exercise. Subject A showed a lower hand blood flow at 10 000 ft.lb/min than at 9 000 ft.lb/min, whereas subject C showed no change in hand blood flow at

8 000 ft.lb/min when compared to 7 000 ft.lb/min (Figures 5 and 7). However, both these subjects showed the expected increase in deep body temperature (Figure 8).

In their study on circulatory and metabolic reactions to work in heat, Williams et al. (43) showed that at maximal and near maximal rates of work in heat, blood flow to the skin and viscera was shunted to working muscles. This was attributed to the fact that cardiac output remained unchanged at these levels while the arteriovenous oxygen difference showed a sharp increase. The excess lactate was not significantly different from those in comfortable conditions.

Åstrand et al. (3) in their study on cardiac output during submaximal work also showed a smaller increase in cardiac output when oxygen consumption approached maximum.

Furthermore, Donald et al. (16) in their study on patients with rheumatic heart disease found that these patients had a lower skin blood flow during exercise as compared with patients with a normal cardiac output. They state "In contrast (to normal subjects), the patients with a lower cardiac output and a high axilliary arterio-venous oxygen difference at rest showed a marked delay before a fall in axillary venous oxygen saturation occurred. This delayed fall may have been due to a more marked and sustained stimulus being necessary to initiate further vaso-constriction in skin in which the blood flow is already greatly restricted". And again: "In the more disabled subjects with severely restricted skin flow the prior need of the exercising muscles for increased blood flow appears to preclude skin vaso-dilatation in later exercise".

As the level of maximal work is approached, the rate of increase in cardiac output is reduced. At these very high work rates the reserves of the exercising human body are taxed to the utmost. Cardiac output cannot keep pace with the increasing demand for oxygen by the working muscles and blood must therefore be diverted away from some other source. We can compare this situation with that of a patient with an impaired cardiac output exercising at a much lower work rate. Such a subject will be working under an enormous strain and subsequently there will be a reduced skin blood flow so that a greater percentage of the cardiac output will be available for the working muscles. This was clearly shown by Donald et al. (16).

We must therefore attribute the lower hand blood flow at the higher work rates to the fact that the vasoconstrictor tone in the hand was not released to the same extent in spite of the increase in body core temperature. A greater percentage of the cardiac output was then available to supply oxygen to the working muscles.

It is thus possible to postulate a fuller picture of hand blood flow during leg exercise (Figures 2 - 4). The response of hand blood flow can be divided into four phases:-

(i) A vasoconstriction in the skin of the hand immediately at the beginning of exercise. This is part of the response to exercise as pointed out by Christensen et al. (13) in their "no load" experiment. This phase corresponds to the period between the beginning of exercise and the increase in body temperature.

(ii) After the initial vasoconstriction in the skin of the hand we find a rapid increase in hand blood flow due to a release of vasoconstrictor tone, corresponding to the rapid increase in body temperature. This phase gradually develops into the next.

(iii) The skin blood flow of the hand tends to level off as a state of equilibrium in heat transfer is reached.

(iv) In the final phase there is no further increase in skin blood flow of the hand but in fact a decrease, despite the further increase in body temperature. This phase actually represents the stage at which body temperature no longer plays the dominant role, as there is now a decrease in hand blood flow in response to the higher demands of the working muscles for more oxygen.

## CONCLUSIONS

These studies clearly show that during exercise hand blood flow increases in association with the rise in rectal temperature not only in respect of time as shown by Kamon and Belding (27), but also in respect of the level of exercise. The author is not aware of any publication illustrating the relationship between hand blood flow and level of exercise. It is therefore clear that the temperature in the core of the body (reflecting that in the hypothalamus) is an important factor in the relaxation of the vasoconstrictor tone in the skin vessels of the hand both in respect of time and level of exercise. These studies therefore confirm the hypothesis mentioned.

However, a most important point is illustrated in these studies. The relationship between hand blood flow and body temperature does not hold true at higher levels of exercise. This change in relationship between hand blood flow and body temperature is well illustrated by the increase in rectal temperature with an increase in work rate without any further increase in hand blood flow. The author is not aware of any publication illustrating a change in this relationship during prolonged exercise.

These studies raise a few interesting questions. Does the skin as a whole react to exercise in a manner similar to that of the hand blood flow both in respect of time and level of exercise? Is the final phase of hand blood flow (mentioned in the discussion) related to the individual's maximum aerobic capacity? These questions and many others, can be answered only by further research and the use of more sophisticated techniques and instrumentation.

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# APPENDIX

## STATISTICAL FORMULAE USED

1. Regression Line

$$M'y.x = c + dx \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

where $$d = \frac{n\,\varepsilon\,x\,y - \varepsilon\,x\,\varepsilon\,y}{n\,\varepsilon\,x^2 - (\varepsilon x)^2} \quad \ldots\ldots\ldots\ldots \quad (2)$$

and $$c = \frac{\varepsilon\,y - d\,\varepsilon\,x}{n} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (3)$$

Where n = total number of pairs

x = rectal temperature

y = hand blood flow

2. Correlation coefficient

$$\frac{\frac{\varepsilon xy}{n} - \bar{x}\,.\,\bar{y}}{Sx\,.\,Sy} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (4)$$

3. Standard deviation

$$S = \sqrt{\frac{\varepsilon(x)^2 - \frac{(\varepsilon x)^2}{n}}{n - 1}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (5)$$

To add limits $\bar{x} \pm 1{,}72 \frac{S}{\sqrt{n}}$ ................ (6)

If the limits do not overlap then the two means are significantly different at approximately the 10% level, i.e., we are about 90% sure that they are truly different.

TABLE 1

BLOOD FLOW (ml/100cc/min)

SUBJECT A:

| FT.LB/ MIN | REST | EXERCISE | | | |
|---|---|---|---|---|---|
| | | 15 | 30 | 45 | 60 |
| 4 000 | 4,0 | 10,9 | 16,6 | 17,5 | 19,6 |
| 5 000 | | 13,5 | 16,6 | 18,3 | 19,2 |
| 6 000 | | 11,4 | 19,0 | 19,8 | 20,2 |
| 7 000 | | 16,0 | 23,3 | 21,8 | 23,1 |
| 8 000 | | 20,0 | 26,4 | 25,1 | 27,7 |
| 9 000 | | 24,1 | 27,4 | 27,9 | 30,6 |
| 10 000 | | 15,5 | 18,0 | | |

SUBJECT B:

| FT.LB/ MIN | REST | EXERCISE | | | |
|---|---|---|---|---|---|
| | | 15 | 30 | 45 | 60 |
| 4 000 | 2,6 | 4,1 | 4,1 | 4,5 | 4,8 |
| 5 000 | | 7,1 | 8,0 | 9,0 | 10,4 |
| 6 000 | | 6,7 | 10,0 | 10,8 | 10,7 |
| 7 000 | | 17,1 | 22,2 | 22,5 | 25,2 |
| 8 000 | | 17,8 | 24,8 | 25,8 | 25,7 |

SUBJECT C:

| FT.LB/ MIN | REST | EXERCISE | | | |
|---|---|---|---|---|---|
| | | 15 | 30 | 45 | 60 |
| 4 000 | 2,3 | 5,9 | 10,0 | 9,5 | 10,4 |
| 5 000 | | 4,9 | 8,5 | 10,1 | 11,0 |
| 6 000 | | 9,8 | 15,9 | 16,8 | 19,4 |
| 7 000 | | 13,9 | 20,1 | 20,4 | 23,4 |
| 8 000 | | 14,6 | 18,4 | 18,5 | 19,7 |

TABLE 2

BLOOD FLOW (ml/100cc/min)

STANDARD DEVIATION:

| SUBJECT | WORK RATE FT.LB/MIN | | 15 MIN | 30 MIN | 45 MIN | 60 MIN |
|---|---|---|---|---|---|---|
| A | 4 000 | M | 10,9 | 16,6 | 17,5 | 19,6 |
| | | SD | 4,24 | 3,05 | 2,51 | 2,09 |
| B | | M | 4,1 | 4,1 | 4,5 | 4,8 |
| | | SD | 1,25 | 1,03 | 1,06 | 1,57 |
| C | | M | 5,9 | 10,0 | 9,5 | 10,4 |
| | | SD | 3,11 | 3,52 | 2,45 | 2,35 |
| A | 5 000 | M | 13,5 | 16,6 | 18,3 | 19,2 |
| | | SD | 4,23 | 3,20 | 2,69 | 3,59 |
| B | | M | 7,1 | 8,0 | 9,0 | 10,4 |
| | | SD | 2,09 | 1,91 | 2,22 | 2,77 |
| C | | M | 4,9 | 8,5 | 10,1 | 11,0 |
| | | SD | 2,03 | 2,78 | 2,46 | 2,21 |
| A | 6 000 | M | 11,4 | 19,0 | 19,8 | 20,2 |
| | | SD | 2,83 | 3,04 | 4,00 | 2,23 |
| B | | M | 6,7 | 10,0 | 10,8 | 10,7 |
| | | SD | 1,39 | 3,01 | 3,42 | 2,43 |
| C | | M | 9,8 | 15,9 | 16,8 | 19,4 |
| | | SD | 5,12 | 4,03 | 3,79 | 4,57 |
| A | 7 000 | M | 16,0 | 23,3 | 21,8 | 23,1 |
| | | SD | 2,97 | 4,44 | 3,93 | 3,26 |
| B | | M | 17,1 | 22,2 | 22,5 | 25,2 |
| | | SD | 1,79 | 2,65 | 4,14 | 3,63 |
| C | | M | 13,9 | 20,1 | 20,4 | 23,4 |
| | | SD | 4,11 | 2,65 | 1,82 | 2,26 |
| A | 8 000 | M | 20,0 | 26,4 | 25,1 | 27,7 |
| | | SD | 3,94 | 3,46 | 5,69 | 3,98 |
| C | | M | 14,6 | 18,4 | 18,5 | 19,7 |
| | | SD | 3,12 | 2,35 | 2,04 | 2,82 |
| A | 9 000 | M | 24,1 | 27,4 | 27,9 | 30,6 |
| | | SD | 4,89 | 3,30 | 4,26 | 2,98 |
| A | 10 000 | M | 15,5 | 18,0 | | |
| | | SD | 1,97 | 2,05 | | |

TABLE 3

RECTAL TEMPERATURE ($^{o}F$)

SUBJECT A:

| FT.LB/MIN | REST | EXERCISE | | | |
|---|---|---|---|---|---|
| | | 15 | 30 | 45 | 60 |
| 4 000 | 97,9 | 98,2 | 98,7 | 99,1 | 99,2 |
| 5 000 | | 98,0 | 98,7 | 99,1 | 99,3 |
| 6 000 | | 98,0 | 98,7 | 99,1 | 99,3 |
| 7 000 | | 98,7 | 99,2 | 99,5 | 99,6 |
| 8 000 | | 98,8 | 99,5 | 99,7 | 99,8 |
| 9 000 | | 99,2 | 100,0 | 100,3 | 100,5 |
| 10 000 | | 99,2 | 100,5 | | |

SUBJECT B:

| FT.LB/MIN | REST | EXERCISE | | | |
|---|---|---|---|---|---|
| | | 15 | 30 | 45 | 60 |
| 4 000 | 98,7 | 98,6 | 99,0 | 99,2 | 99,3 |
| 5 000 | | 99,1 | 99,5 | 99,7 | 99,7 |
| 6 000 | | 99,1 | 99,7 | 99,9 | 100,0 |
| 7 000 | | 99,8 | 100,2 | 100,4 | 100,5 |
| 8 000 | | 100,0 | 100,8 | 101,3 | 101,5 |

SUBJECT C:

| FT.LB/MIN | REST | EXERCISE | | | |
|---|---|---|---|---|---|
| | | 15 | 30 | 45 | 60 |
| 4 000 | 98,3 | 98,5 | 99,1 | 99,3 | 99,5 |
| 5,000 | | 98,1 | 98,9 | 99,4 | 99,6 |
| 6 000 | | 98,9 | 99,8 | 100,1 | 100,3 |
| 7 000 | | 99,4 | 100,3 | 100,6 | 100,8 |
| 8 000 | | 99,5 | 100,5 | 100,9 | 101,0 |

TABLE 4

OXYGEN CONSUMPTION (Litres/min)

SUBJECT A:

| FT.LB/ MIN | REST | EXERCISE 26-29 | EXERCISE 56-59 |
|---|---|---|---|
| 4 000 | 0,2982 | 1,2757 | 1,2768 |
| 5 000 | | 1,4933 | 1,5294 |
| 6 000 | | 1,7541 | 1,7791 |
| 7 000 | | 2,0674 | 2,1153 |
| 8 000 | | 2,4987 | 2,5522 |
| 9 000 | | 2,8849 | 3,0277 |
| 10 000 | | 3,3532 | |

SUBJECT B:

| FT.LB/ MIN | REST | EXERCISE 26-29 | EXERCISE 56-59 |
|---|---|---|---|
| 4 000 | 0,3284 | 1,1689 | 1,1836 |
| 5 000 | | 1,4790 | 1,4532 |
| 6 000 | | 1,7840 | 1,7516 |
| 7 000 | | 2,1601 | 2,1485 |
| 8 000 | | 2,5211 | 2,6288 |

SUBJECT C:

| FT.LB/ MIN | REST | EXERCISE 26-29 | EXERCISE 56-59 |
|---|---|---|---|
| 4 000 | 0,2776 | 1,2595 | 1,1916 |
| 5 000 | | 1,6860 | 1,5870 |
| 6 000 | | 1,8827 | 1,9156 |
| 7 000 | | 2,1615 | 2,2283 |
| 8 000 | | 2,5382 | 2,5516 |

## TABLE 5
## CARDIAC OUTPUT (Litres/min)

SUBJECT B:

| FT.LB/ MIN | EXERCISE 30 | 60 |
|---|---|---|
| 4 000 | 12,96 | 13,09 |
| 5 000 | 14,44 | 14,32 |
| 6 000 | 16,65 | 17,20 |
| 7 000 | 18,18 | 18,06 |
| 8 000 | 19,15 | 20,76 |

SUBJECT C:

| FT.LB/ MIN | EXERCISE 30 | 60 |
|---|---|---|
| 4 000 | 12,27 | 12,64 |
| 5 000 | 14,77 | 14,40 |
| 6 000 | 15,21 | 14,63 |
| 7 000 | 16,47 | 16,77 |
| 8 000 | 17,47 | 18,81 |

TABLE 6

HEART RATE (Beats/min)

SUBJECT A:

| FT.LB/ MIN | REST | EXERCISE 15 | 30 | 45 | 60 |
|---|---|---|---|---|---|
| 4 000 | 60 | 101 | 101 | 100 | 98 |
| 5 000 | | 96 | 99 | 99 | 101 |
| 6 000 | | 103 | 104 | 105 | 107 |
| 7 000 | | 118 | 118 | 117 | 120 |
| 8 000 | | 128 | 133 | 135 | 141 |
| 9 000 | | 148 | 156 | 158 | 161 |
| 10 000 | | 169 | 177 | | |

SUBJECT B:

| FT.LB/ MIN | REST | EXERCISE 15 | 30 | 45 | 60 |
|---|---|---|---|---|---|
| 4 000 | 58 | 96 | 94 | 95 | 93 |
| 5 000 | | 105 | 104 | 103 | 104 |
| 6 000 | | 114 | 119 | 115 | 115 |
| 7 000 | | 128 | 132 | 132 | 131 |
| 8 000 | | 146 | 149 | 150 | 154 |

SUBJECT C:

| FT.LB/ MIN | REST | EXERCISE 15 | 30 | 45 | 60 |
|---|---|---|---|---|---|
| 4 000 | 51 | 87 | 88 | 90 | 95 |
| 5 000 | | 96 | 101 | 100 | 105 |
| 6 000 | | 115 | 115 | 117 | 116 |
| 7 000 | | 127 | 133 | 130 | 135 |
| 8 000 | | 145 | 150 | 150 | 152 |

TABLE 7

BLOOD PRESSURE (mm Hg)

| FT.LB/ MIN | SUBJECT A | | SUBJECT B | |
|---|---|---|---|---|
| | SIST. | DIAST. | SIST. | DIAST. |
| REST | 126 | 80 | 124 | 75 |
| 4 000 | 150 | 75 | 158 | 55 |
| 5 000 | 165 | 60 | 155 | 60 |
| 6 000 | 164 | 60 | 164 | 55 |
| 7 000 | 160 | 60 | 174 | 50 |
| 8 000 | 182 | 65 | 184 | 50 |
| 9 000 | 184 | 70 | | |
| 10 000 | 204 | 60 | | |

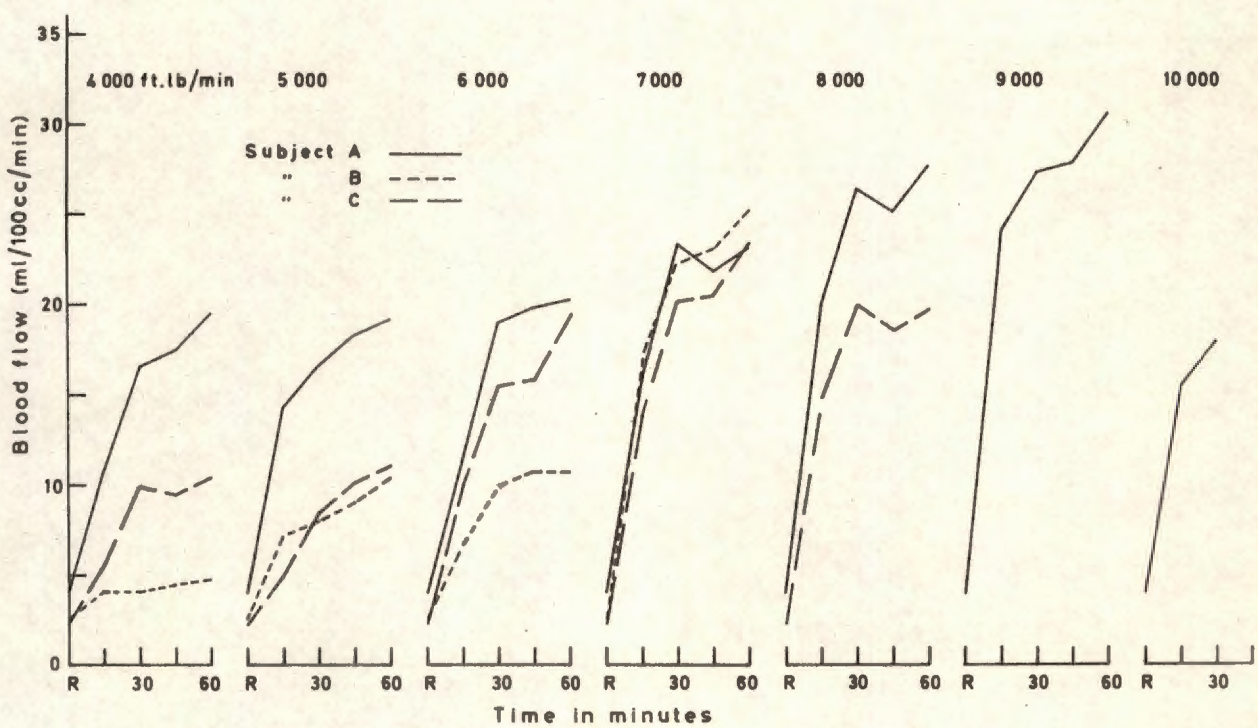


Fig. 1 Blood flow vs. time at different levels of exercise.

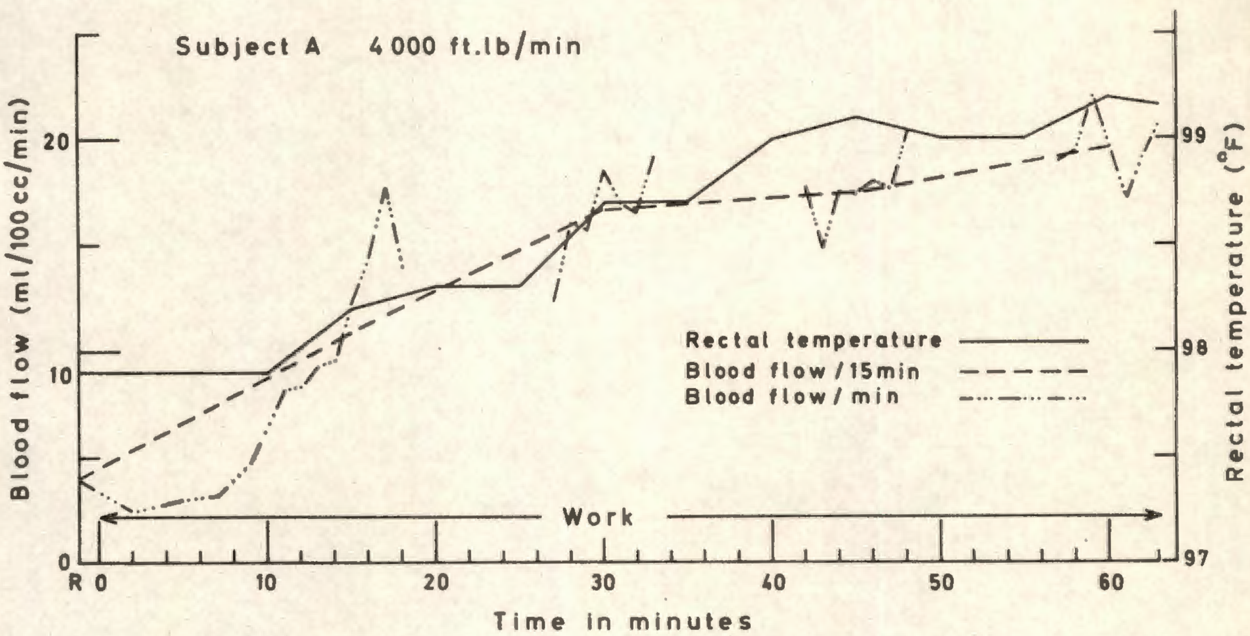


Fig. 2 Subject A. 4 000 ft.lb/min

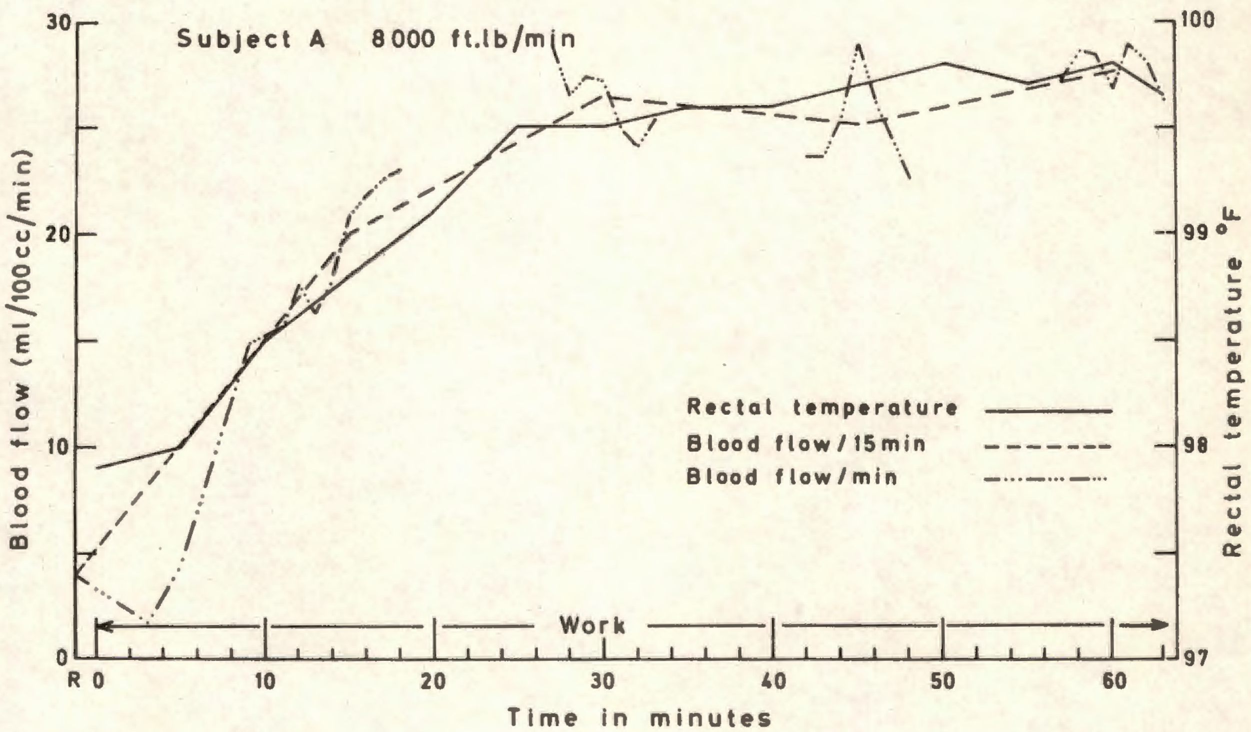


Fig. 3 Subject A. 8 000 ft.lb/min

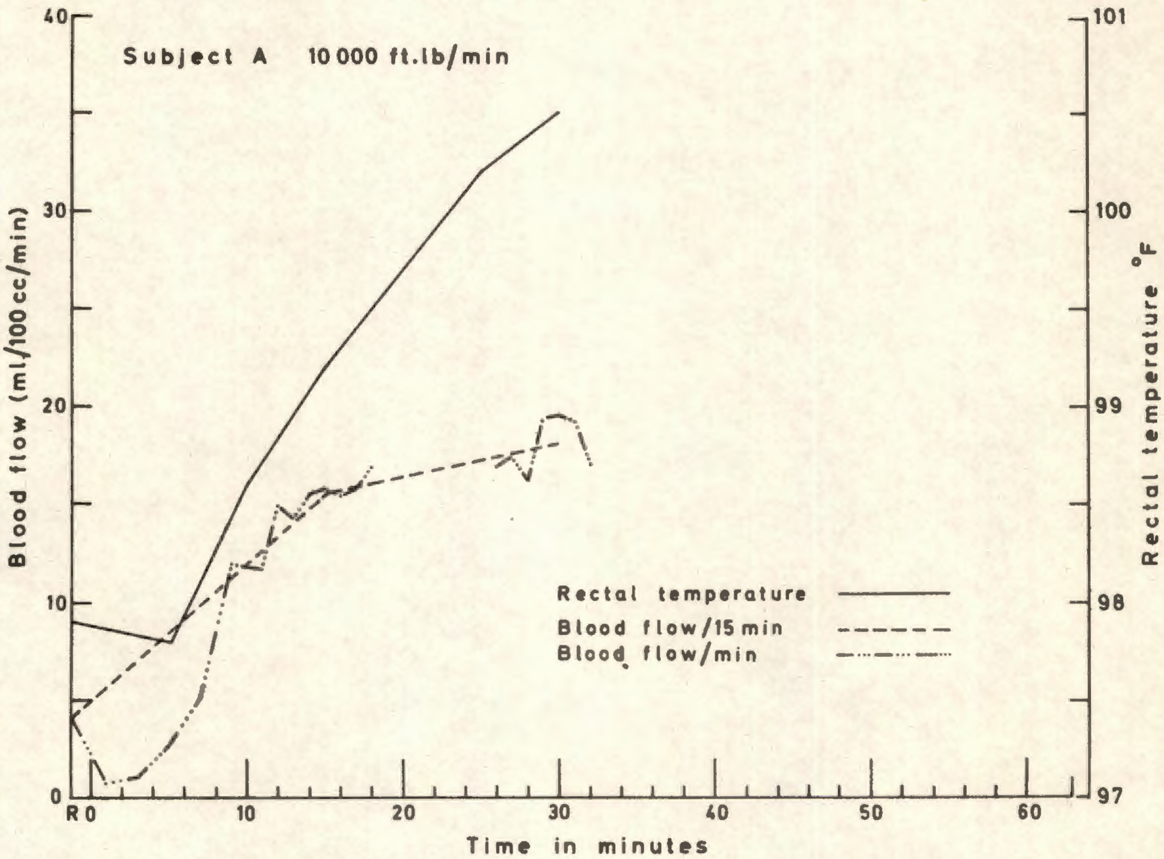


Fig. 4 Subject A. 10 000 ft.lb/min.

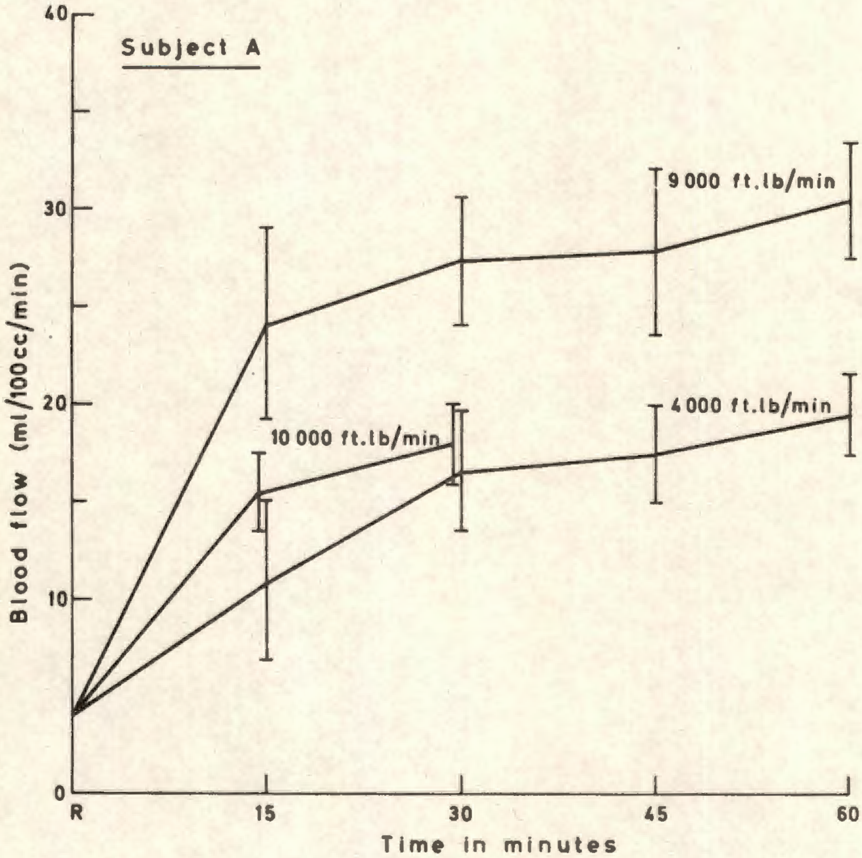


Fig. 5 Subject A. Blood flow vs. time at different work rates.

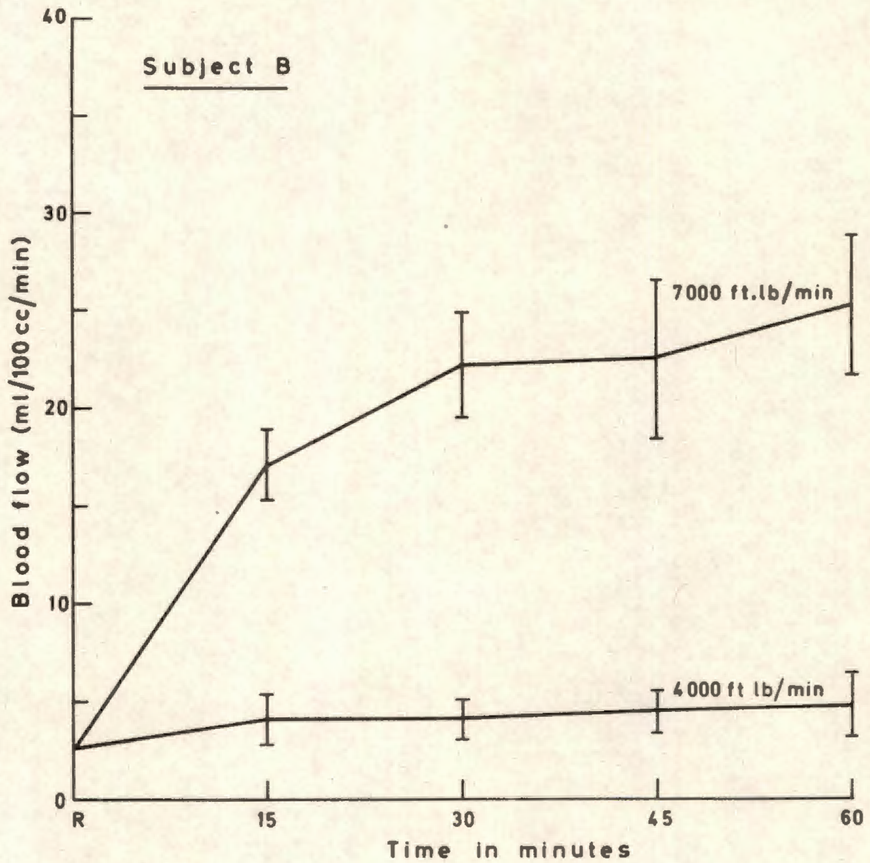


Fig. 6 Subject B. Blood flow vs. time at different work rates.

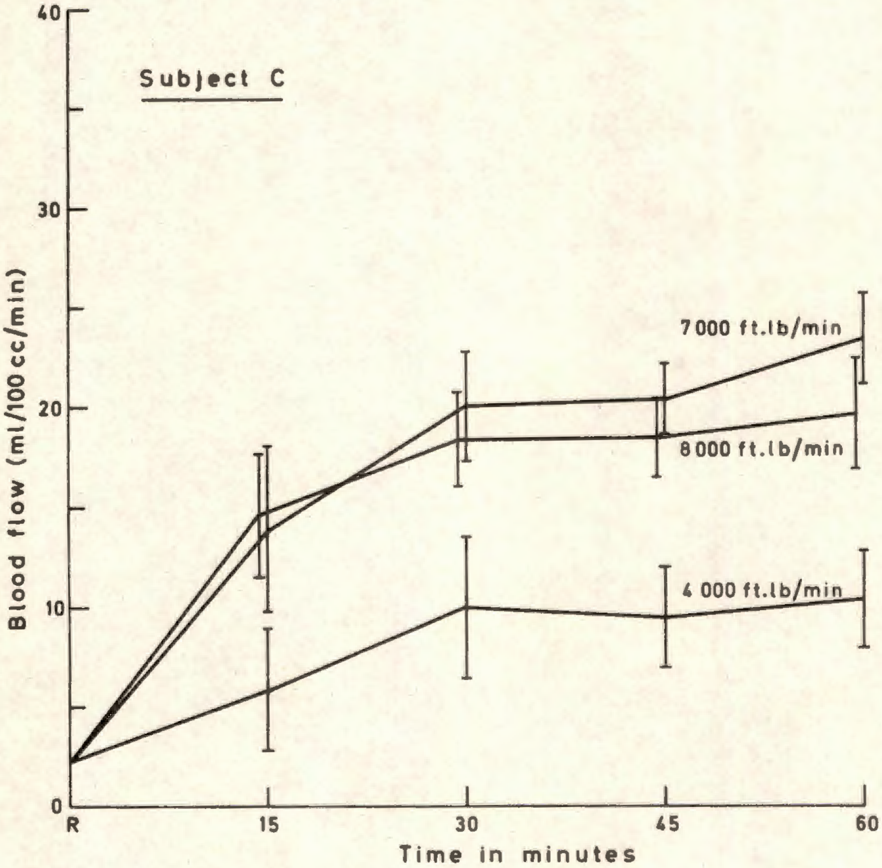


Fig. 7 Subject C. Blood flow vs. time at different work rates.

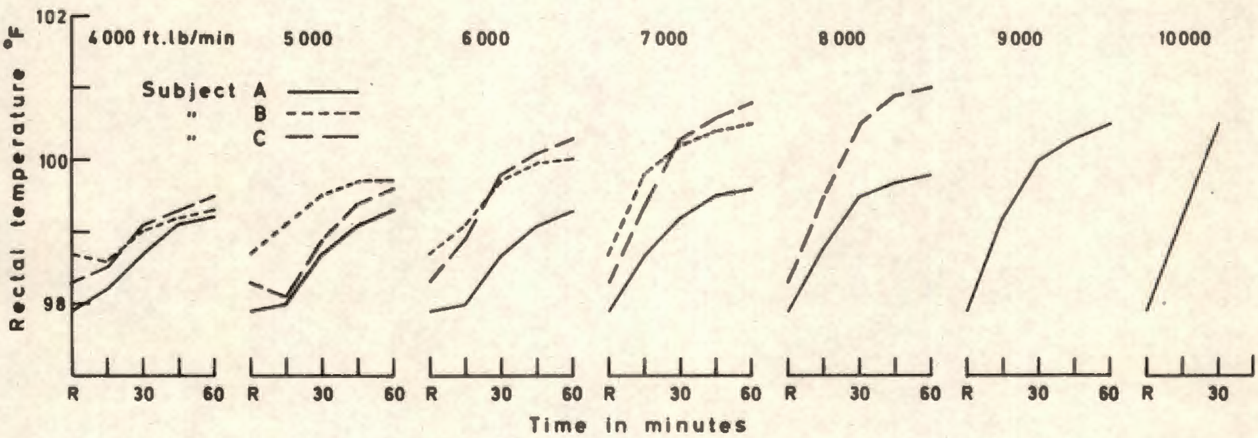


Fig. 8 Rectal temperature vs. time at different work rates.

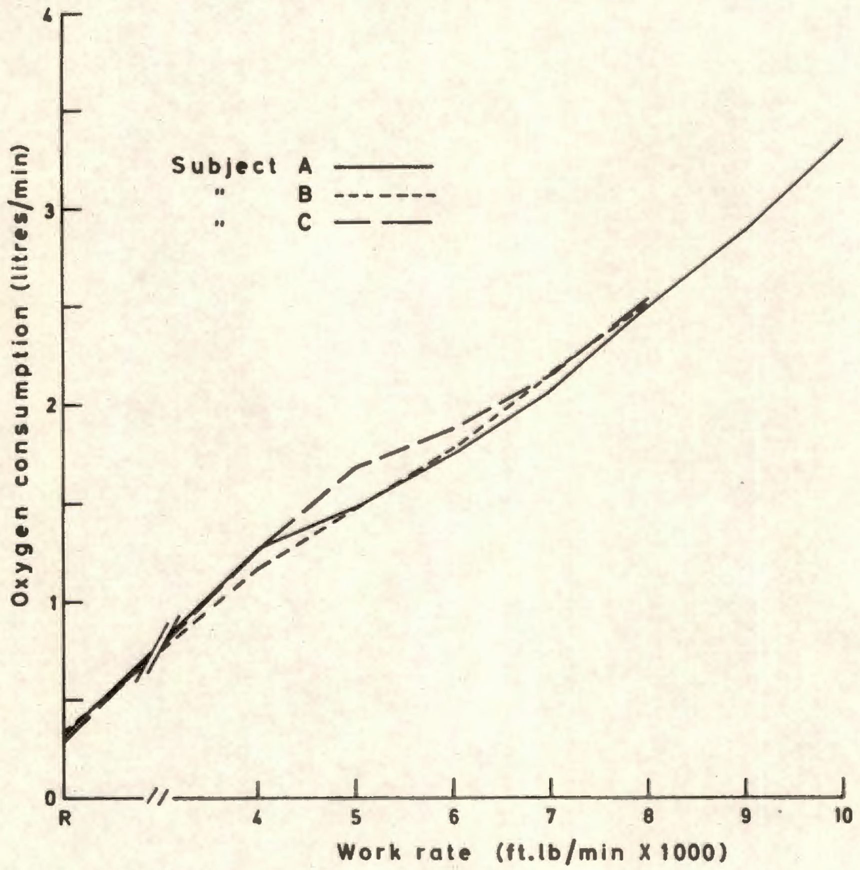


Fig. 9 Oxygen consumption vs. work rate.

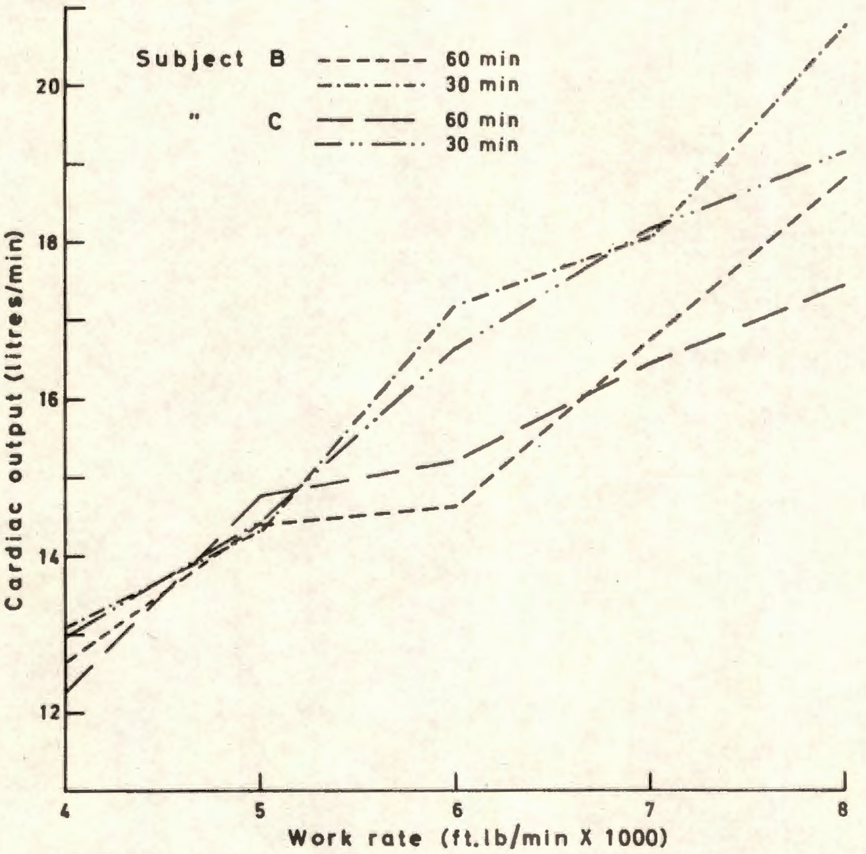


Fig. 10 Cardiac output vs. work rate.

Subjects B and C.

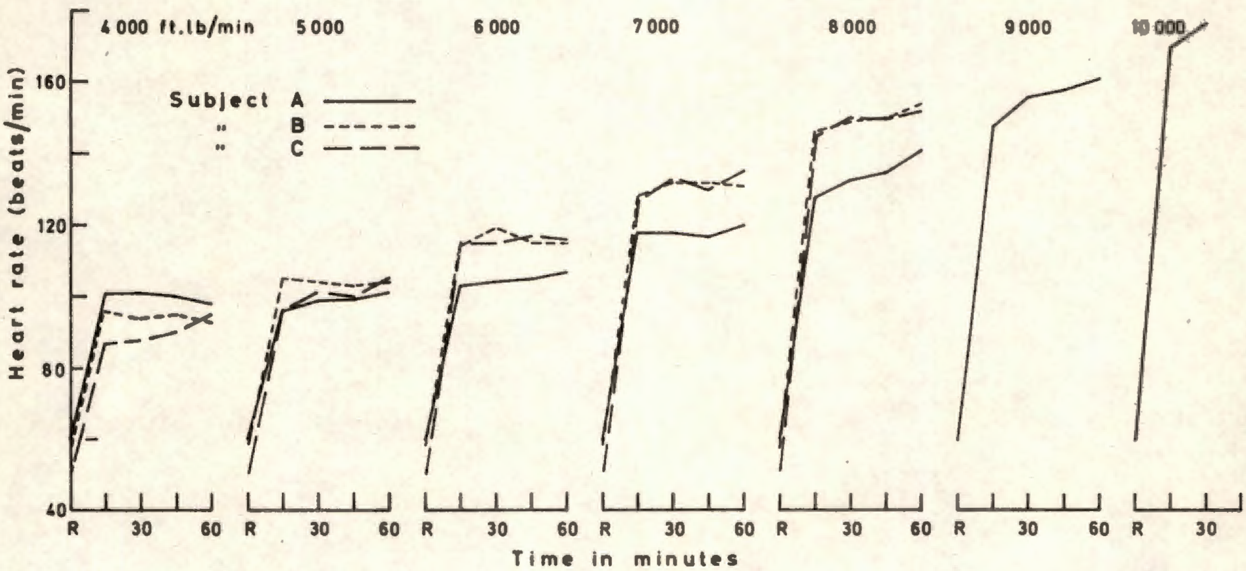


Fig. 11 Heart rate vs. time at different levels of exercise.

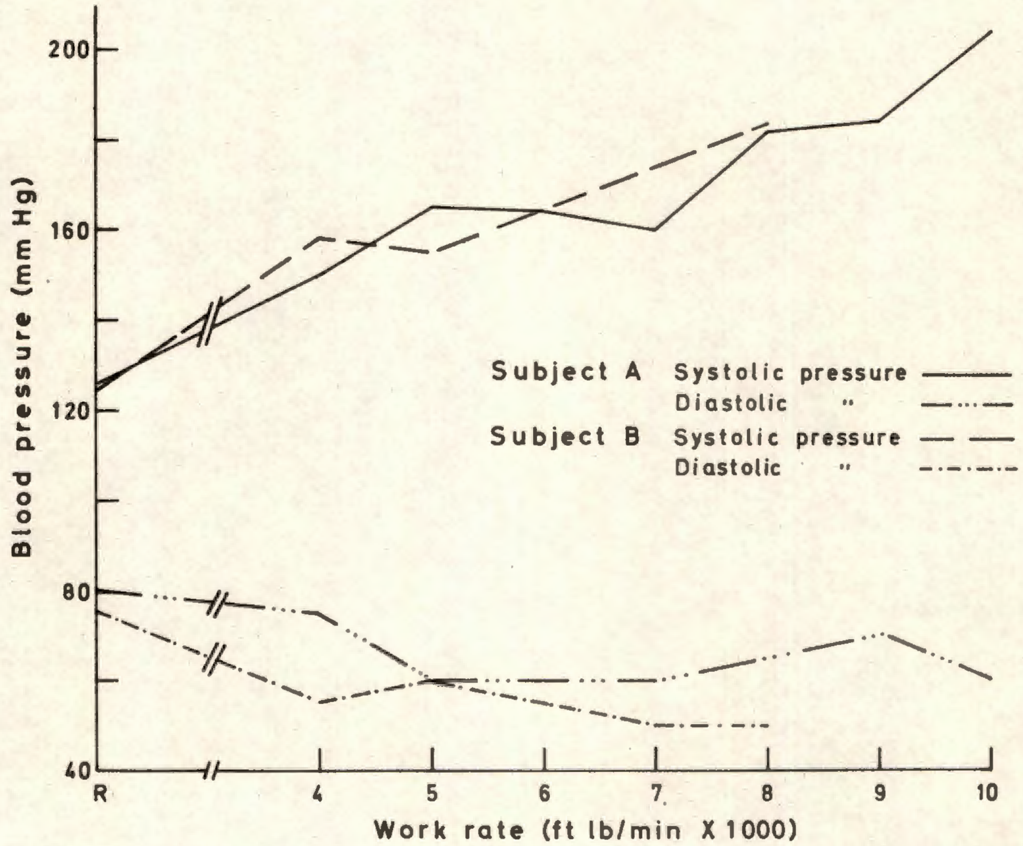


Fig. 12 Blood pressure vs. work rate.

Subjects A and C.

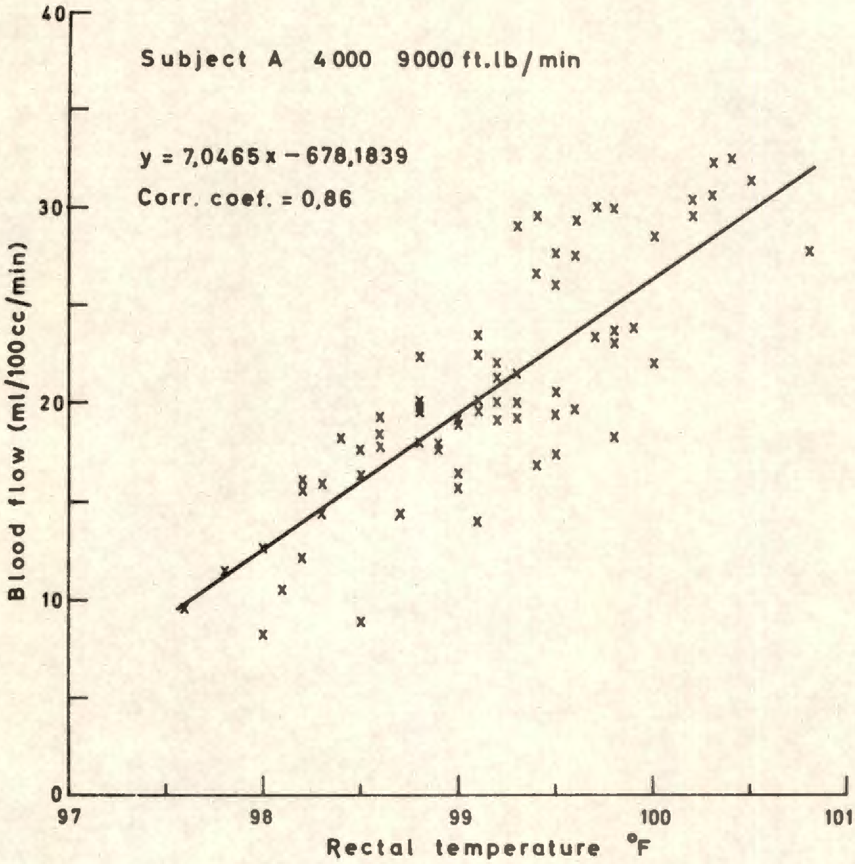


Fig. 13 Subject A. Blood flow vs. rectal temperature.

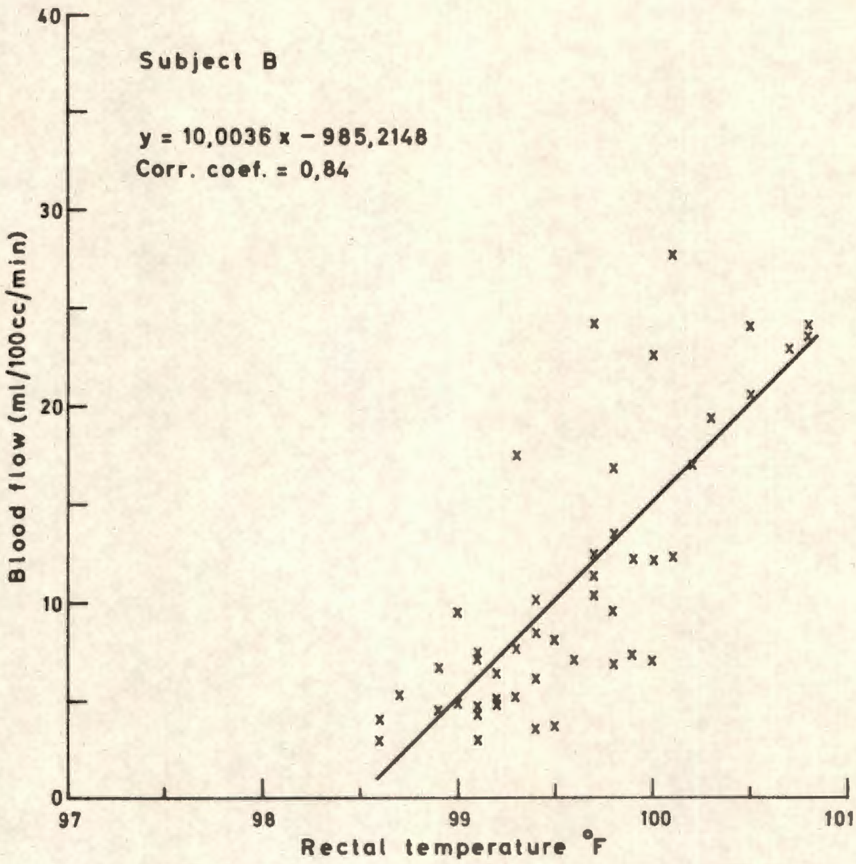


Fig. 14 Subject B. Blood flow vs. rectal temperature.

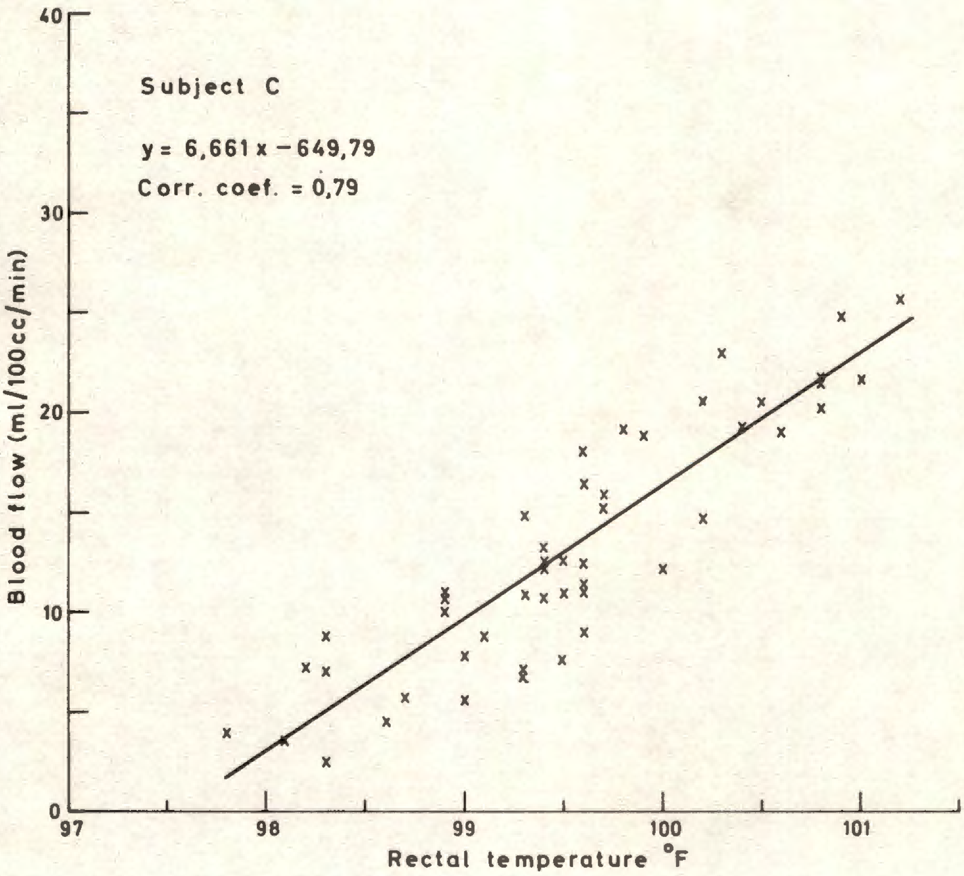


Fig. 15 Subject C. Blood flow vs. rectal temperature.

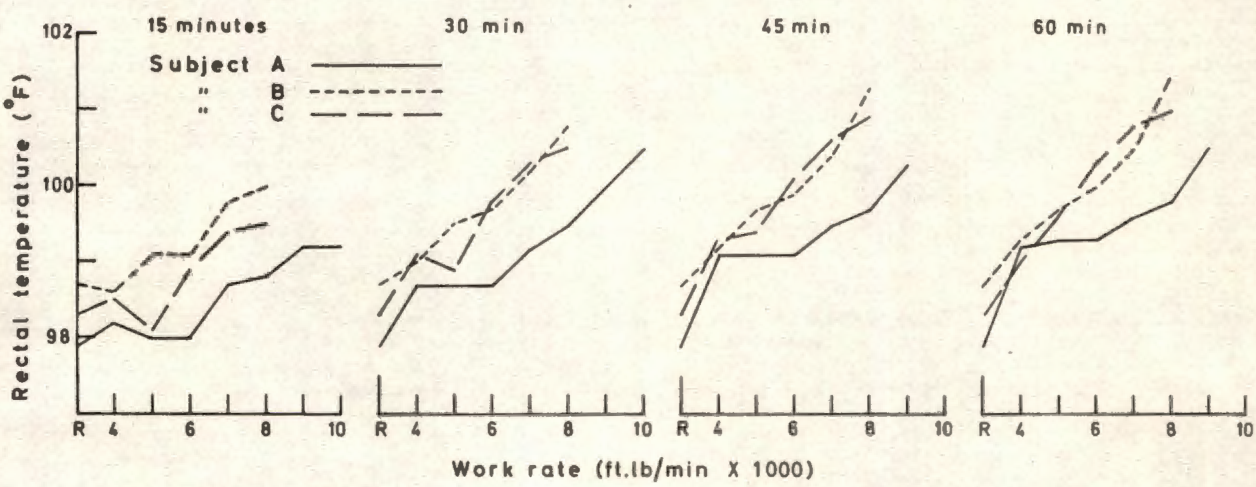


Fig. 16 Rectal temperature vs. work rate at different time intervals.

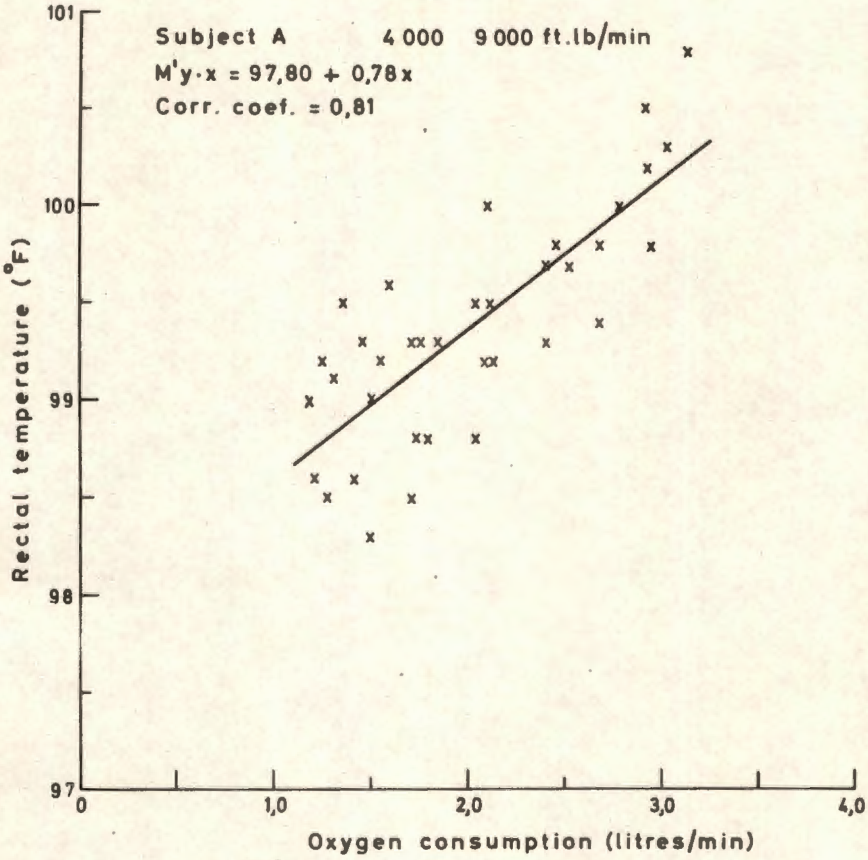


Fig. 17 Subject A. Rectal temperature vs. oxygen consumption.

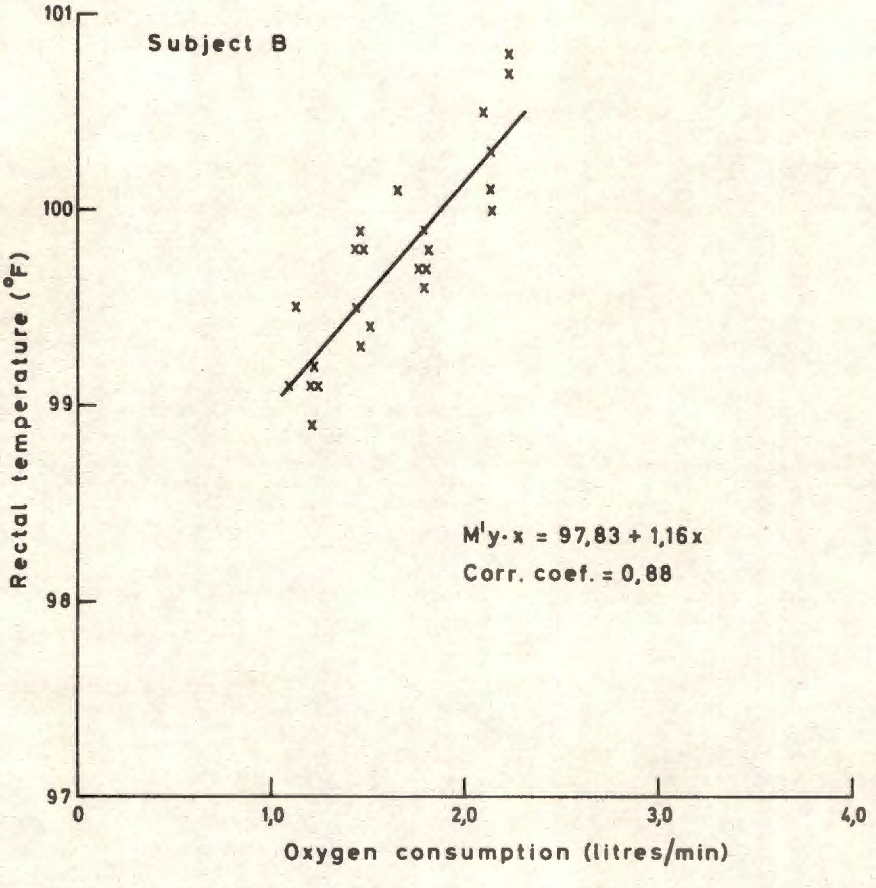


Fig. 18 Subject B. Rectal temperature vs. oxygen consumption.

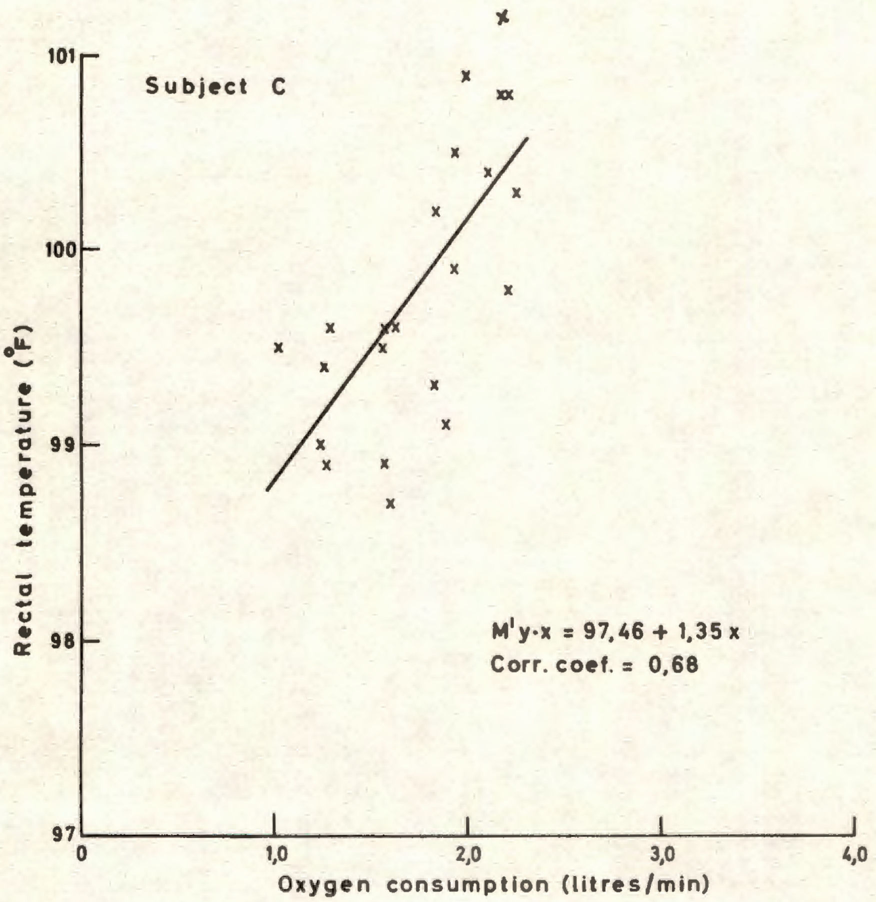


Fig. 19 Subject C. Rectal temperature vs. oxygen consumption.

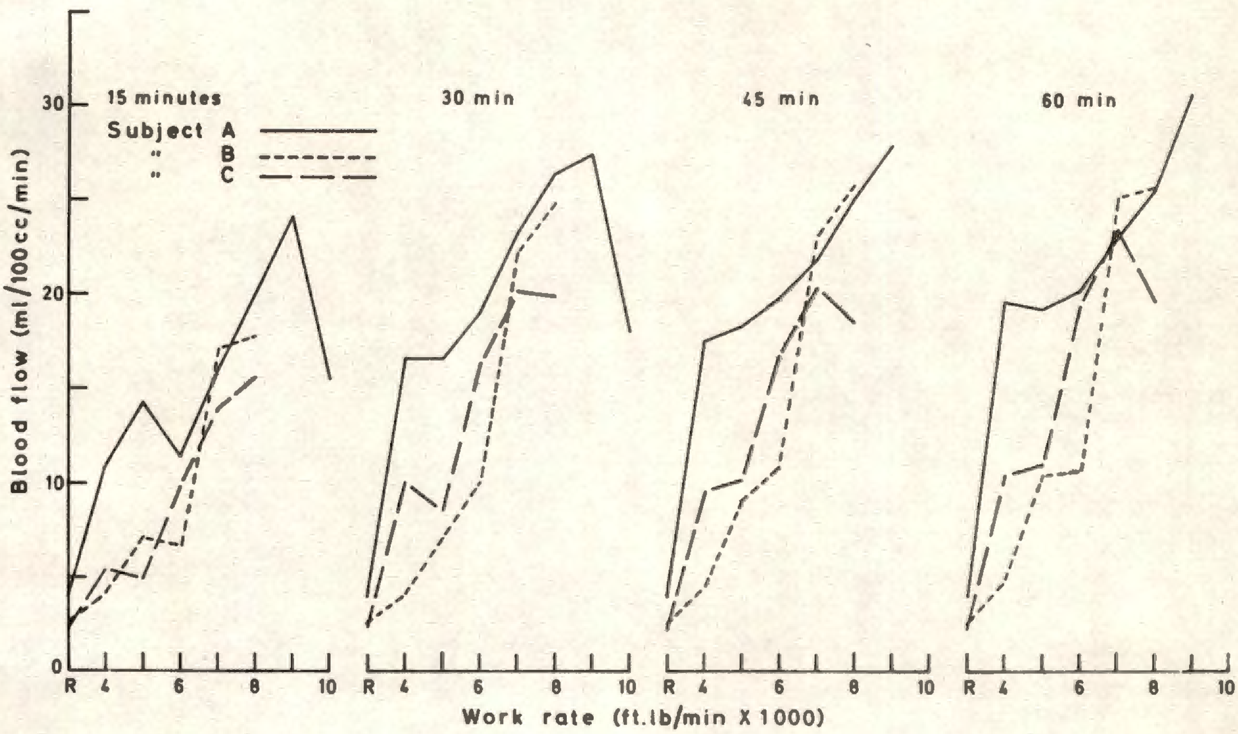


Fig. 20 Blood flow vs. work rate.

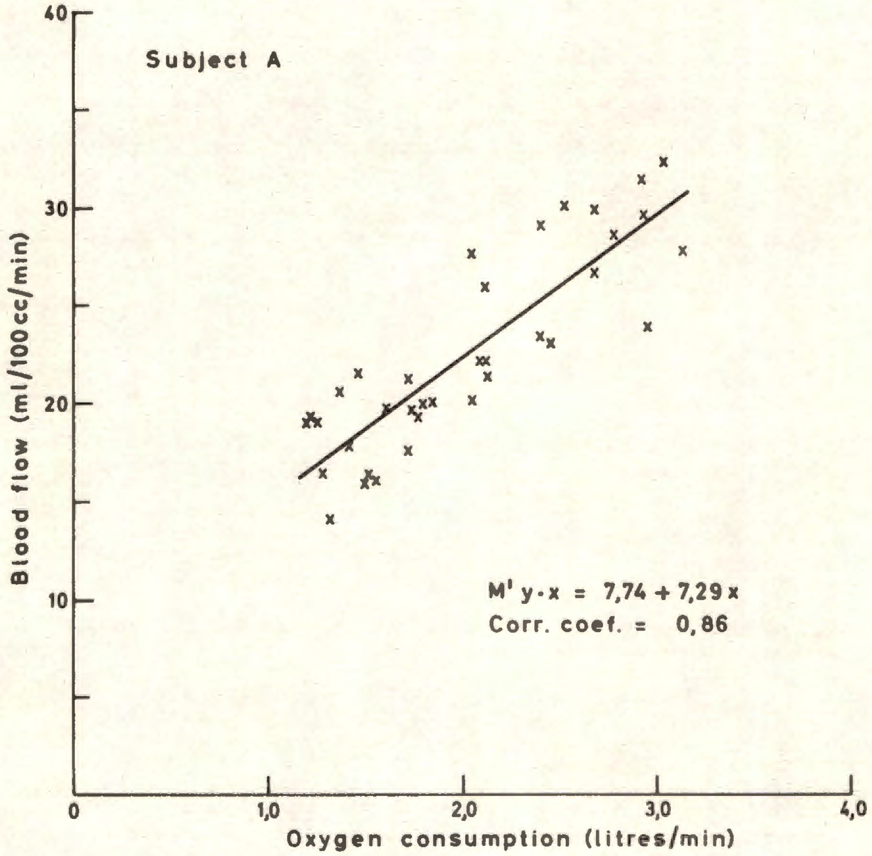


Fig. 21 Subject A. Blood flow vs. oxygen consumption.

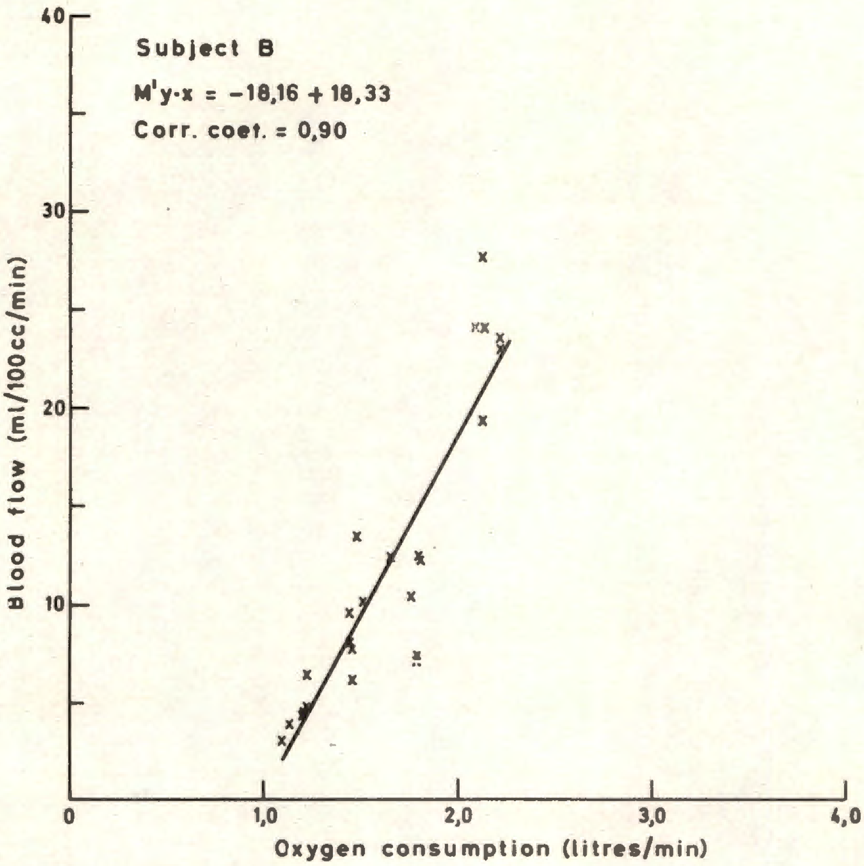


Fig. 22 Subject B. Blood flow vs. oxygen consumption.

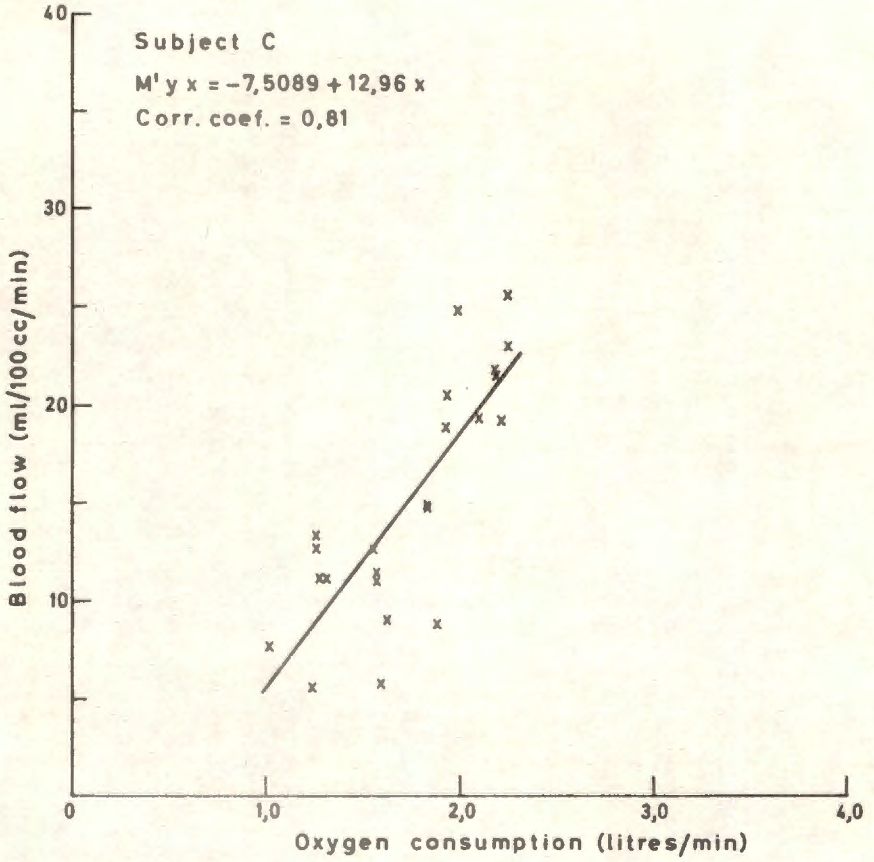


Fig. 23 Subject C. Blood flow vs. oxygen consumption.