

THE PHYSIOLOGICAL EFFECTS
OF A MID-SHIFT FEED OF
SUCROSE

by

A.J.S. BENADÉ B.Sc., Hons.

A DISSERTATION SUBMITTED
IN PARTIAL FULFILMENT OF THE
REQUIREMENTS FOR THE DEGREE
MASTER OF SCIENCE

TO THE
DEPARTMENT OF PHYSIOLOGY
FACULTY OF SCIENCE
POTCHEFSTROOM UNIVERSITY
FOR
CHRISTIAN HIGHER EDUCATION

DECEMBER 1971

DECLARATION

I hereby declare that this thesis, entitled

"THE PHYSIOLOGICAL EFFECTS OF A
MID-SHIFT FEED OF SUCROSE"

presented to the Faculty of Science, Potchefstroom University for Christian Higher Education, for the degree Magister Scientium is my own work except to the extent indicated in the Acknowledgements and References. This work has not been submitted for any other degree at any other University.

The work for this thesis was carried out at the Human Sciences Laboratory of the Chamber of Mines of South Africa as a contract project for the South African Sugar Association. The necessary permission was obtained to use the results of the project as a basis for this thesis.

DATE

A.J.S. BENADE

ABSTRACT

Four well-trained subjects worked for fifty minutes of every hour for six hours on a bicycle ergometer at loads requiring about 30 per cent and 50 per cent of the subjects' maximal aerobic capacity. Subjects were studied when they received only water and again when they were fed 100 g and 200 g sucrose at the beginning of the fourth hour of work. The physiological responses of the men given the mid-shift feed of sucrose were compared with those obtained when no sucrose was fed.

The respiratory quotients of men who received no sucrose during six hours at the two work loads, showed a continuous decrease in carbohydrate metabolism from 70 per cent in the first hour to 30 per cent at the end of the sixth hour. This decrease in carbohydrate metabolism and corresponding increase in fat metabolism was accompanied by a continuous rise in oxygen uptake and heart rate. Physiologically, these subjects exhibited relatively more strain and were mechanically less efficient at the end of the work period than they were at the start.

When the same subjects received a mid-shift feed of 100 g or 200 g sucrose at the end of the third hour of the work period, they displayed a significant increase in carbohydrate metabolism as shown by the higher respiratory quotient. This was associated with a lower rate of oxygen consumption and heart rate than in the fasting state. Subjects were mechanically more efficient

at the higher work load and also showed less circulatory strain as evidenced by the lower heart rate and higher stroke volume.

The best results were obtained when 100 g sucrose was administered as a mid-shift feed, the extra benefit obtained with a feed of 200 g being small. Subjects working at the higher rate benefited more than men working at the lower rate.

TABLE OF CONTENTS

CHAPTER 1	PAGE
1.1 INTRODUCTION	1
1.2 Statement of the problem	3
1.3 Limitations of the study	4
1.4 Significance of the study	5
 CHAPTER 2	
SURVEY OF THE LITERATURE	6
2.1 RQ and diet	7
2.2 RQ and intensity of work	10
2.3 RQ and duration of exercise.....	11
2.4 Other factors influencing RQ	14
i) Training	14
ii) Insulin	15
iii) Adrenaline	15
iv) Nicotinic acid	16
v) Ingestion of carbohydrate	17
a) Resting experiments	17
b) Work experiments	18
vi) Lactic acid and hyperventilation.	19
2.5 The significance of RQ during work ..	19
 CHAPTER 3	
METHODOLOGY	23
3.1 General outline	23
3.2 No-sucrose weeks	24
3.3 Sucrose weeks	25

CHAPTER 3	PAGE
3.4 Additional observations	25
i) Blood-lactic acid content	25
ii) Blood-glucose content	26
iii) Urinary ketone excretion	26
iv) Cardiac output.....	26
3.5 Analytical procedures	26
i) Expired-air samples	26
ii) Blood-lactic acid	27
iii) Blood-glucose content	27
iv) Urinary-ketones	27
v) Cardiac output	27
3.6 Statistical analysis	28

CHAPTER 4	
RESULTS	29
4.1 Respiratory exchange	29
i) Respiratory quotient	29
a) Work rate 1,5 litres O ₂ /min .	29
b) Work rate 1,0 litre O ₂ /min ..	30
ii) Oxygen uptake	31
a) Work rate 1,5 litres O ₂ /min .	31
b) Work rate 1,0 litre O ₂ /min ..	31
iii) Carbon dioxide output	32
iv) Pulmonary ventilation.....	32
a) Work rate 1,5 litres O ₂ /min .	32
b) Work rate 1,0 litre O ₂ /min ..	32
4.2 Circulatory responses	33
i) Heart rates	33
a) Work rate 1,5 litres O ₂ /min .	33

CHAPTER 4

PAGE

b) Work rate 1,0 litre O_2 /min ..	34
ii) Cardiac output	34
4.3 Blood constituents	35
(i) Lactic acid	35
(ii) Glucose	35
4.4 Urinary ketones	35
(i) Total ketones	35
(ii) B-OH butyric acid	35
(iii) Acetoacetic acid	36
4.5 Utilization of carbohydrates	36
(i) Work rate 1,5 litres O_2 /min	36
(ii) Work rate 1,0 litre O_2 /min	36
4.6 Calories from carbohydrate and fat ..	37
4.7 Body weight loss	37
4.8 Rectal temperature	38

CHAPTER 5

DISCUSSION	39
5.1 Measurement of RQ	39
i) Accuracy of the RQ measurement ..	39
ii) The non-protein RQ	40
iii) Interpretation of the RQ	42
5.2 Fat and carbohydrate metabolism during exercise in the fasting state	43
5.3 Effects of mid-shift feed of sucrose on fat and carbohydrate metabolism ..	45
5.4 Utilization of carbohydrate.....	52
5.5 Circulatory changes	52

CHAPTER 5	PAGE
5.6 Comparison of the results of the two work intensities	54
5.7 Validity of results obtained on four subjects	55 ✓
CHAPTER 6	
Summary and conclusions.....	56
Recommendation	58
ACKNOWLEDGEMENTS	59
REFERENCES	61
TABLES	73
FIGURES	78

LIST OF TABLES

TABLE	PAGE
1. Physical characteristics of subjects	23
2. Average body weight loss	73
3. Average rectal temperature	73
4. Analysis of variance for pulmonary ventilation	74
5. Analysis of variance for oxygen consumption	74
6. Analysis of variance for respiratory quotient	75
7. Analysis of variance for heart rate	75
8. Figures for sucrose loads of 100 g and 200 g expressed as percentages of those for no sucrose load at 1,5 litres O ₂ /min	76
9. Figures for sucrose loads of 100 g and 200 g expressed as percentages of those for no sucrose load at 1,0 litre O ₂ /min ..	77

LIST OF FIGURES

FIGURE	PAGE
1. Respiratory quotient at $\dot{V}O_2$ 1,5 litres/min relative to time	78
2. Respiratory quotient at $\dot{V}O_2$ 1,0 litres/min relative to time	79
3. Oxygen uptake relative to time	80
4. Carbon dioxide output relative to time	81
5. Ventilation relative to time	82
6. Heart rate relative to time	83
7. Stroke volume and cardiac output relative to time	84
8. Carbon dioxide partial pressure in mixed venous and arterial blood relative to time ..	85
9. Lactate relative to time	86
10. Blood glucose relative to time	87
11. Total ketones in urine relative to time	88
12. 3-OH Butyric acid in urine relative to time .	89
13. Aceto acetic acid in urine relative to time .	90
14. G carbohydrate utilized at the two work intensities	91
15. Percent calories derived from carbohydrate relative to time at the two work intensities.	92

CHAPTER 1

1.1 INTRODUCTION

According to Huxley's sliding filament theory for muscular contraction, actin and myosin filaments overlap and slide with the help of cross-bridges (61). The immediate available energy source is adenosine triphosphate (ATP) which is hydrolyzed by myosin ATP-ase, yielding free energy for mechanical work. The concentration of ATP in muscle is limited, being, about 2,43 mmol/100 g of dry tissue (59). With these low ATP levels it becomes necessary for the energy-producing metabolic processes in the muscle cell and other energy reserves to provide a continual replenishment of the ATP if contraction is to continue for any length of time.

Immediate re-synthesis of ATP takes place by transphosphorylation of phosphocreatine (PC) catalyzed by creatine phosphokinase, or from adenosine diphosphate (ADP). These two processes represent a significant source of energy for the contractile process. However, the concentration of PC in muscle is limited, being only about three times that of ATP in human muscle (59). During prolonged work of heavy intensity, this energy store is expended almost completely.

It is well established that under conditions of adequate nutrition, the energy required for the re-synthesis of ATP in the muscle during exercise, all comes from the oxidation of the fat and carbohydrate reserves of the muscle itself or from those supplied to

it by the circulatory system. However, the bulk of the ATP produced from both of these substrates comes from a single oxidative pathway, the Krebs cycle and the related electron transport system. The only differences between the oxidation of carbohydrates and fats are the methods by which the original substrate, namely, glucose, glycogen, triglyceride or free fatty acid (FFA) is fed into this pathway and the amount of ATP produced per unit weight of the substrate. Both fat and carbohydrate participate in energy metabolism during exercise, but the proportions of energy derived from these two sources at different phases of exercise and at different levels of effort are not well established.

Christensen and Hansen (28), and Courtice and Douglas (33) provided indirect evidence that the proportion of energy for muscular work from the oxidation of fat increases during prolonged exercise while the subject is fasting. This conclusion was based upon an observed fall in the respiratory quotient (RQ) over the work period. The results of these earlier investigations have recently been confirmed by the application of radioisotope techniques (51,52,64,65,66,67,84,85,92,107).

Measurement, by means of muscle biopsy, of the amount of glycogen in working muscle has shown that the glycogen stores are depleted by prolonged heavy exercise (17,18,19,55,58). Moreover, the capacity to continue strenuous exercise is affected when the glycogen stores are depleted.

Studies have been made to determine whether the proportions of energy for muscular work from carbohydrate and fat sources can be altered by different dietary regimes and whether the subjects will benefit from these dietary regimes. Havel et al. (52) have reported a decreased mobilization and oxidation of FFA after ingestion of sucrose during exercise. Data obtained by Bergström et al. (17) indicated that the glycogen content of muscle after exhaustive work was restored to higher values by a carbohydrate-rich diet than by a high-fat or high-protein diet. The length of time that men can endure exhaustive work after three days on these different dietary regimes, is very significantly greater after the carbohydrate-rich diet. Whether the proportions of energy for muscular work from carbohydrate and fat sources could be altered by a mid-shift feed of sucrose and whether the subjects will benefit from such a practice, is not known. This question forms the basis of this study.

1.2 Statement of the problem

The Bantu worker does most of the heavy muscular work in industry in South Africa. Following tradition and personal choice he has one large meal in the late afternoon after work. From this it can be assumed that his carbohydrate reserves would be depleted after three to four hours of physical work and that the energy for muscular work in the latter part of the shift would be obtained predominantly from the fat stores laid down

during the previous 12 hours. The question has been raised as to whether a pre-shift or mid-shift feed of carbohydrate would improve their ability to do prolonged muscular work. This would be so only if the ingested carbohydrate is absorbed and metabolised during the shift. In order to examine this question, respiratory quotients, which give some indication of whether carbohydrates or fats are predominantly metabolised, were measured during a six-hour period of work in fasting men and men fed a mid-shift feed of 100 and 200 g of sucrose. Two work rates which gave oxygen consumptions of 1,0 and 1,5 litres/min were chosen. These were equivalent to moderate and hard rates of work, respectively.

1.3 Limitations of study

Four well-trained Bantu subjects were used in the study reported on here. It is possible that their reactions might be different from those of less-trained or unfit individuals performing similar exercise under the same conditions.

The results were obtained under comfortable temperature conditions, which does not necessarily mean that they would be the same in extreme temperature situations.

Insulin concentration in blood after sucrose administration was not measured and it is therefore not possible to determine the role played by insulin during the early rise in the RQ. It is also not known whether the increased RQ was caused by the administered sucrose directly, or indirectly by enhanced utilization of

endogenous carbohydrate stimulated by a possible "insulin response".

1.4 Significance of the study

Some metabolic adaptations that occur in well-trained subjects performing prolonged moderate exercise under comfortable temperature conditions are illustrated. The metabolic responses of these subjects were determined while they worked for six hours receiving only water, and again when a sucrose solution was administered by mouth at the end of the third hour of work. The significance of the differences between the results of the sucrose and no-sucrose experiments is discussed.

CHAPTER 2

SURVEY OF THE LITERATURE

To determine the effect of sucrose administration on carbohydrate and fat metabolism during prolonged exercise at moderate and hard rates of work, it was necessary to evaluate the metabolism of carbohydrate and fats during the exercise period. For this purpose, heavy reliance was placed on the respiratory quotient and it was therefore decided to carry out an extensive review of the literature of the respiratory quotient during work, and of all possible factors affecting it.

Until about 15 years ago, carbohydrate was thought to be the only source of energy available for the working muscle. The utilization of fat as a source of energy was thought by many to involve, first, a conversion to carbohydrate (44). However, recent evidence suggests that the plasma free fatty acids are an important source of fuel for muscular work.

The relative amounts of carbohydrate and fats oxidized during muscular exercise can be determined from the nonprotein RQ during the steady state of exercise. This ratio is determined from the carbon dioxide (CO_2) output and oxygen (O_2) uptake after subtraction of the small amounts of CO_2 and O_2 that are connected with protein metabolism. As carbohydrate is oxidized with an RQ of 1,0 and fat with an RQ of 0,7 the RQ value of mixtures of carbohydrate and fat can be calculated. This principle was formulated by

Zuntz (108) and tables for this determination were modified by Lusk (74,75).

Careful determination of RQ during muscular exercise have shown that the value of this ratio in exercise depends mainly on three factors:

- a) The diet of the subject
- b) The intensity of the work and
- c) The duration of the work

These will be considered separately.

2.1 RQ and diet

Early in this century, Zuntz (108) published results of experiments showing that the diet could influence the metabolism of the muscles. During mild exercise performed after a diet extremely rich in fat he found RQ values which suggested an almost exclusive fat oxidation. In 1920 Krogh and Lindhard (73) studied changes in the RQ under various conditions of diet and exercise. They suggested that both at rest and during work, the proportion of fat and carbohydrate metabolised might be a function of the available supplies of these substrates.

Benedict and Cathcart (16) reported a considerably higher RQ during a preliminary rest-period in one subject on a carbohydrate-rich diet compared to a control on a carbohydrate-low diet, namely 0,85 as compared to 0,79. They stated:

"During the periods with muscular work, there was a marked increase in the respiratory quotient with

both diets which was somewhat greater with the carbohydrate-rich diet."

Christensen and Hansen (26-30) in an extensive and exacting series of investigations studied subjects engaged in exercise of such intensity that the metabolic processes were essentially aerobic. In subjects living for almost a week on an extremely high fat diet, where less than 5 per cent of the caloric intake was derived from carbohydrate, RQ was low throughout the work period of about 1,5 hours. They calculated that about 70-99 per cent of the energy was obtained from fat metabolism. In subjects living on a carbohydrate diet, where 90 per cent of the food calories were derived from carbohydrate, RQ was high and it was estimated that 70-75 per cent of the energy was derived from carbohydrate.

Issekutz et al. (63) in an investigation using subjects living on four different diets and exercising at light work loads for 20 minutes, measured RQ during rest and work over a period of 68 to 70 days. Subjects receiving diets containing about 65 per cent carbohydrate had higher basal and working RQ's compared to those receiving diets containing 30 to 45 per cent carbohydrate. A reduction of the protein intake which caused a 50 per cent decrease in the oxidation of protein, did not cause any consistent change in the basal metabolic RQ or in the work RQ compared with the diet rich in carbohydrate.

Pruett (87,88) studying the effects of three different diets, namely, diets containing $\pm$ 25 per cent, $\pm$ 60 per

cent and 87 per cent carbohydrate, showed that subjects on the high carbohydrate diet had higher working RQ's at both 50 per cent and 70 per cent of the maximal aerobic capacity compared with those on high fat diets. Exercise was performed until exhaustion and lasted from 270 to 330 minutes.

Bergström et al. (17) studied the effects of three different diets on the re-synthesis of muscle glycogen stores. Muscle glycogen stores were first depleted by exhaustive exercise at about 75 per cent of the subjects maximal oxygen uptake. Different subjects were then put on one of three diets, i.e. mixed, protein- and carbohydrate-rich diets for three days and were then re-tested. The muscle glycogen averaged 1,75, 0,63 and 3,31 g/100 g wet muscle after the mixed, protein and carbohydrate diet, respectively. Subjects who received the mixed and high carbohydrate diets, had significantly higher RQ's both at rest and during exercise compared with subjects who received the protein diet.

Fasting had been shown to be associated with a decline in RQ's in working men (54). Henschel et al. studied four men walking on a motor-driven treadmill at about 53 per cent of their maximal aerobic capacity for one hour each day during a three-day fasting period. A significant decline in RQ was observed during the three-day fasting period.

It is thus clear from the literature that diet is a very important factor influencing RQ. Issekutz et al.

(63) found that it is the amount of carbohydrate rather than the amount of fat in the diet which determines whether fat or carbohydrate is the preferred fuel.

2.2 RQ and intensity of work

Benedict and Cathcart (16), summarizing their results of studies to investigate RQ during varying work intensities on a bicycle ergometer, stated:

"Our final conclusion must be, therefore, that the more severe the muscular activity, the heavier is the draft upon the carbohydrate material in the body."

Christensen and Hansen (30) demonstrated that the RQ was, among other things, also dependent on the intensity of work. With increasing intensity of exercise, RQ increased and approached unity. This means that, as work became heavier, carbohydrate delivered an increasing percentage of the energy. At near maximal work loads, RQ is usually above 1,0 (26,94,102) and values of 2,1 have been reported (78). The results of Christensen and Hansen have recently been confirmed by Issekutz and Rodahl (69) as well as by Hermansen et al. (55).

Several explanations have been proposed for the high RQ during heavy exercise. One explanation is that as work becomes more difficult, more energy is produced by anaerobic breakdown of glycogen in the muscles (8,56,71,96,104,106). The lactic acid produced is oxidized with an RQ value of 1,0, either in the working muscles themselves or elsewhere in the organism. Another explanation is that during heavy

exercise, with the production of lactic acid, pH shifts to the acid side and hyperventilation results. It therefore seems likely that the increase in RQ during heavy or near maximal exercise is partly or entirely due to an imbalance between the formation and elimination of acids (particularly lactic acid) and to their reaction with the bicarbonate pool of the body. Issekutz and Rodahl (69) found that the RQ after $3\frac{1}{2}$ to 4 minutes of work, correlated with the changes of lactic acid level in blood. Robinson (94), after investigating the physical work capacity of different age groups, pointed out the parallelism between RQ and blood lactic acid level found during maximal work in adult men.

The rise of blood lactate level and the decrease of blood CO_2 concentration observed during the first five minutes of exercise led Christensen and Hansen to the conclusion that the work RQ could be used in metabolic studies only if the blood CO_2 and lactic acid concentrations reached a steady state after 10 to 30 minutes of exercise, depending on the rate of work performed.

2.3 RQ and duration of exercise:

An inverse relationship exists between work intensity and duration of exercise and from the previous section, this suggests a direct relationship between work intensity and RQ.

In Christensen and Hansen's experiment (27) the relative work load was around 60 to 70 per cent of the maximum aerobic capacity, and the RQ dropped from 0,88 to 0,80 during 180 minutes of work. The same tendency,

with a decreasing carbohydrate combustion as work proceeded, was reported by Saltin and Stenberg (97), when they found the RQ dropped from 0,91 to 0,86 during 3 hours exercise at a relative work level of 72 per cent.

Courtice and Douglas (33) studied the effects of a 10 mile walk at a rate of 4,5 miles per hour on themselves. They concluded:

"In the post-absorptive subject who had previously been living on his normal diet it is shown that the respiratory quotient during the work rises somewhat above the preliminary resting value in the early stages and falls gradually as the work continues, and that these changes cannot be ascribed to the accumulation of excess lactic acid in the blood, to rise of body temperature, to a material degree of change in the CO_2 combining power of the blood, or to a developing ketosis. It is therefore concluded that the respiratory quotient under the conditions of the experiments can be taken as an index of the materials oxidized in the body, implying that during the course of the work about 100 gm of carbohydrate were used and that as the work continues there is a substantial alteration in the ratio of carbohydrate to fat metabolized."

Irma Astrand (7) studied four subjects while working for six hours of effective work at 50 per cent of their maximal aerobic capacity. Respiratory quotient decreased about one unit (0,1) during the work period.

Pruett (87,88), studying the effects of three different diets reported a lower RQ at the end of work as compared to RQ values at the beginning of work. Subjects received standard, high fat and high carbohydrate diets for 14 days and they worked for six hours or until exhaustion at 50 per cent and 70 per cent of their maximal aerobic capacities.

Olsson (82) studied three subjects during 11,5 hours of effective work time, pedalling a bicycle ergometer at 54 per cent of the individual aerobic power. RQ declined about 1 unit (0,1) during the first 5 hours, after which it remained constant.

Havell et al. (52) also showed a decline in RQ in subjects walking at 3 to 4 miles per hour on a treadmill. The work required an oxygen uptake of 1,0 liter per minute and was performed for 2 hours. Ahlborg in a study requiring about 50 per cent of the maximal oxygen uptake of the subjects, also observed a decline in RQ during the hour of exercise (1).

Bergström et al. (17), and Hultman (58) confirmed the observations of other workers who reported a decline in RQ during prolonged exercise at 70-75 per cent of the maximum aerobic power. The decline in RQ had also been observed in dogs running for periods of four hours on a treadmill (64, 66, 67, 85).

Little information is available regarding the RQ during prolonged exercise at intensities above 75-80 per cent of the maximal aerobic capacity. Hedman (53)

found that during cross-country skiing for 150 minutes at constant speed with a relative load of 82 per cent, RQ was essentially constant from start to finish. Hermansen et al. (55) presented results of a study with relative work loads of 76 and 79 per cent that supported the findings of Hedman. Hermansen concluded:

"It is highly probable that at high relative work loads with RQ's around 0,9, the glycogen stores in the exercising muscles is decisive for maximal work time."

Prolonged exercise at work intensities of up to 75 per cent of the maximal aerobic capacity, is associated with a decline in RQ with time. Exercise at levels above 75 per cent maximal aerobic capacity is characterized by an unchanged RQ with time. This observation is interpreted as an inability of the muscles to substitute carbohydrate with fat (55) when working above a certain level.

2.4 Other factors influencing RQ

- (1) Training: Well-trained subjects, having high aerobic power expressed as $\text{ml} \times \text{kg} \times \text{min}$, have a lower RQ not only at the same absolute, but also at the same relative work loads as compared to subjects with low maximal oxygen uptakes (27). Hermansen (55), also in a cross-sectional study, reported a lower RQ in trained as compared to untrained subjects performing exhaustive exercise at 77 per cent of their

maximal aerobic capacity. The same general type of response is obtained in subjects studied before and after several months of physical conditioning (96).

(ii) Insulin: Insulin administration to the fasting normal organism results in variable changes of small magnitude in the respiratory quotient (47, 76, 90). Insulin plus sugar causes a more abrupt and more pronounced rise in the RQ than does sugar alone. Courtice and Douglas (34,35) showed that an intravenous injection of 1 to 2 units of soluble insulin caused the RQ to rise $\pm 0,1$ during rest and exercise.

(iii) Adrenaline: Dill, Edwards and de Meio (40) found that a subcutaneous injection of 0,5 to 1,0 mg adrenaline during muscular work increases the RQ and the concentration of glucose and lactic acid in the blood, and concluded that the rise of the RQ is mainly due to an increase in the proportion of carbohydrate oxidised. Courtice, Douglas and Priestley (34) studied the effect of a single subcutaneous injection of 0,5-1,0 mg adrenaline in two subjects during light and moderate muscular exercise.

They stated:

"The changes of respiratory quotient, when followed in detail, appear to depend on the

accumulation and subsequent disappearance of excess lactic acid, and afford no evidence that there is an enhanced oxidation of carbohydrate in spite of the long maintained rise of blood-sugar concentration."

Adrenaline is known to be a very potent stimulator of glycogenolysis, which in turn will result in accumulation of glucose-6-phosphate. The latter inhibits hexokinase powerfully (36). This inhibition of the hexokinase system has been held responsible for the reduced uptake of glucose from the blood and explains the hyperglycemia observed after adrenaline injection.

- (iv) Nicotinic Acid: Nicotinic acid (NA) has been shown to decrease the rate of mobilization of FFA at rest and to inhibit the increased mobilization which normally occurs when fasting subjects exercise (21). Subjects who received NA during exercise or rest, had higher RQ's compared with subjects who did not receive nicotinic acid (21). The rise in RQ and fall in plasma concentration of glucose suggest that increased oxidation of carbohydrate occurred in association with decreased availability of energy from FFA. Paul et al. (85) working on dogs confirmed these results. They found that Na-nicotinate decreased the turnover rate and oxidation of plasma free fatty acids, and

increased the RQ and rates of turnover and oxidation of plasma glucose in normal dogs running on a treadmill. Bergström et al. (19) studied the effect of intravenous administration of NA on metabolism of muscle glycogen in man. The decrease in glycogen content of the quadriceps femoris muscle, induced by exercise, as determined in muscle biopsy specimens, was significantly larger after administration of nicotinic acid than in the control studies. The RQ was significantly higher during prolonged exercise after administration of NA compared to the studies without NA.

v) Ingestion of carbohydrate:

a) Resting experiments:

Bachmann and Haldi (12) reported increased RQ's in resting subjects who ingested 50 g of glucose or fructose or 25 g of each sugar. Edwards et al. (42) studied the effects of the ingestion of 50, 75 or 100 g of glucose, fructose or galactose on the respiratory quotient over a period of four hours in two resting normal men. All three sugars caused a significant increase in RQ.

Saltzman and Salzano (98) studied the effect of carbohydrate ingestion (930 kcal) on respiratory gas exchange in five resting normal men. They confirmed the observations of Carpenter and Lee (22) on one subject, namely, that RQ is increased

by ingestion of carbohydrate.

b) Work experiments:

Courtice and Douglas (33) reported a significant increase in the RQ in Courtice after ingestion of 100 g sucrose 4 hours after a 10 mile walk at 4,5 miles per hour. The same authors also reported a higher RQ for themselves during a 10 mile walk as compared to a similar walk without carbohydrate ingestion. The walk was started 80-110 minutes after the ingestion of either 50 g glucose or fructose mixed with 20-40 g of bread.

Wrightington (105) showed that a sugar load before the work may influence the work RQ. Issekutz (63) reported that ingestion of 100 g glucose two hours before exercise requiring an oxygen uptake of about 1,0 liter per minute, caused an increase in the exercise RQ.

Havel et al. (52), among other physiological parameters, measured RQ in two subjects receiving 25 g of sucrose every half hour and in four other subjects receiving only water during a two-hour walk on a treadmill requiring about 1 liter O_2 per minute. Subjects who received sucrose had higher RQ's during and after the work period as compared to subjects receiving only water.

Issekutz et al. (67), studying the oxidation of

glucose during continuous glucose infusion in dogs running on the treadmill for four hours, reported an enhanced glucose utilization and higher RQ's as compared to dogs not receiving glucose infusions.

vi) Lactic acid and hyperventilation:

Robinson (94) pointed out the parallelism between the RQ and blood lactic acid level during maximal work. Issekutz found that the RQ after $3\frac{1}{2}$ to 4 minutes of work correlated with the changes of lactic acid level in blood (69). This increase in blood lactic acid will displace carbon dioxide from blood bicarbonate with the result that there will be a loss of non-metabolic carbon-dioxide in the blood resulting in a non-metabolic RQ. Hyperventilation either voluntarily or secondarily will also result in a loss of CO_2 from the blood, resulting in a high non-metabolic RQ.

The effect of carbohydrate ingestion on the interrelationship between blood lactic acid and RQ in men during rest have been studied and reported on by several workers (12,42).

2.5 The significance of RQ during work

RQ has been shown to be variable both in rest and exercise. Many factors affect the RQ, some of which are non-metabolic. Great caution should therefore be used in the interpretation of RQ and situations where the validity

of the RQ could be questioned, should be avoided. If carefully applied and interpreted as shown by Christensen and Hansen (26-30) RQ provides a valid indication of the relative proportions of fat and carbohydrate used by the muscles during exercise. They concluded, on the basis of measurement of CO_2 and lactate content of the blood that after 10 to 15 minutes of exercise the RQ values at high, but not maximum, work levels gave a true representation of the fuels utilized. The same investigators found, in agreement with the results of Courtice and Douglas (33), that the RQ during prolonged work in the fasting state showed a clear tendency to decrease during the course of work and assumed this to be due to the progressive decrease in glycogen stores.

Results obtained on the glycogen content of working muscles, by the muscle-biopsy technique, and the evidence from studies with C^{14} -labelled glucose and palmitic acid support the conclusion of Christensen and Hansen that a low RQ during prolonged muscular exercise is indicative of a decrease in the proportion of muscular energy derived from carbohydrate metabolism. There is good evidence that during prolonged muscular exercise of moderate intensity there is an increase in the concentration of FFA in plasma (21,51,52, 64-68,77,84,85,87,88) and an increase in the turnover rate of FFA as measured by palmitate-1- C^{14} (21,51,52,64-68,84, 85). It has been shown that FFA turnover rate, uptake and oxidation increase as plasma FFA concentration increases (4,64,65,66,68,84). Under these circumstances, an increase in plasma FFA during exercise can be taken as an

index of increased fat utilization. Paul et al. (85) showed a significant negative correlation between RQ and plasma free fatty acids in dogs. They also showed a good negative correlation between the percentage CO_2 from plasma FFA and RQ as well as a good positive correlation between the percentage CO_2 from plasma glucose and RQ.

When the release of FFA from fat depots is blocked by NA (19) muscle glycogen was depleted at a faster rate during muscular exercise and RQ values were significantly higher. Paul et al. (85) working on dogs, showed that infusions of Na-nicotinate decreased the turnover rate and oxidation of plasma FFA in both normal and pancreatectomized dogs. RQ's were higher and rates of turnover and oxidation of plasma glucose in normal dogs were increased.

Oral administration of carbohydrate is known to block the mobilization of FFA from fat depots and the higher RQ's, and lower plasma FFA reported by Havel (52) in exercising subjects who received carbohydrate, compared with subjects receiving water only, are clear indications of a shift towards carbohydrate metabolism. They also measured the turnover rate of palmitate-1-C-14 and concluded that oxidation of FFA entering tissues accounted for 41 to 49 per cent of energy metabolism during exercise in fasting subjects and 7 to 10 per cent in fed subjects. Thus a shift towards carbohydrate metabolism had occurred as demonstrated by both RQ and isotope-dilution studies. Young et al. (107) in very prolonged exercise at a moderate rate (1,2 litres/min oxygen uptake) state that

the quantity of carbohydrate utilized, as determined by C^{14} studies of glucose rate of turnover and metabolism, is less than they would have predicted from RQ values during exercise. They were, however, not confident about the accuracy of their RQ values during work.

Ahlborg et al. (2), Bergström et al. (17,18), Hermansen et al. (55), and Hultman (58) using muscle-biopsy techniques to measure the glycogen concentration of working muscle, found a good correlation between the amount of glucose utilized during work, as calculated from the RQ and oxygen consumptions, and the decrease in muscle glycogen in the thigh muscles. This applied over a wide range of RQ values and glycogen concentrations. More recent work seems to indicate that the period of the greatest reduction in muscle glycogen during prolonged work, coincide with the period of the greatest decline in RQ (82).

These later studies have confirmed the observations of the earlier workers on RQ during prolonged aerobic exercise. The validity of the RQ at high or near maximal work intensities has still to be confirmed.

CHAPTER 3

METHODOLOGY

3.1 General outline

Four well-trained Bantu males in the age group 18-22 years were used as subjects for the experiment. Before the main experiment was started, the subjects went through a four-week training regime as described by Williams et al. (104). To maintain their state of training, the training programme was followed on Mondays and Saturdays although no observations were made on these days. No attempt was made to alter their standard compound diet consisting of ± 13 per cent fat, ± 14 per cent protein and ± 73 per cent carbohydrate (45). Their physical characteristics are given in Table I.

TABLE 1

Subject	Weight (kg)	Height (cm)	Max O ₂ ml/kg ²
J	71,5	173,3	47,8
Fa	59,0	165,0	45,0
A	60,0	163,0	45,0
Fe	65,0	167,4	46,6

Studies were made of each subject at two work loads, one requiring an oxygen uptake of 1,0 litre per minute and the other an oxygen uptake of 1,5 litres per minute. These loads corresponded, respectively, to ± 30 per cent and ± 50 per cent of the groups' average maximum oxygen uptake. Studies were conducted on pairs of subjects on four days per week and each pair of subjects

were studied according to the following schedule:-

<u>Week</u>	<u>Work rate</u>	<u>Sucrose administration</u>	<u>Total number of observations per pair</u>
1	1,5 litres O ₂ /min	None	8
2	"	100 g	8
3	"	200 g	8
4	1,0 litre O ₂ /min	None	8
5	"	100 g	8
6	"	200 g	8

This experimental approach was used in preference to isolated studies on the effect of sucrose administration during exercise, because, firstly, any day-to-day variation in diet would have been compensated for during the six weeks duration of the investigation, and, secondly, all results were comparable on a weekly basis. By conducting the studies on four days of the week, except Mondays, any possible "Monday effect" was eliminated.

3.2 No-sucrose weeks

Each morning of the test days observations were made on the subject after he had been resting in a lying position on a couch for at least one hour at room temperature. Expired air was collected in Douglas bags for five minutes. A Collins mask, fitted with a low-resistance breathing valve and having a dead space of 100 ml, was used. The subject was then weighed, and his rectal temperature measured with a clinical thermometer inserted to a depth of about 8 cm.

Work consisted of pedalling a bicycle ergometer (11) at a continuous fixed work load for fifty minutes of every

hour for six hours. Recordings of heart rate were made with a standard electrocardiograph (ECG) during the 45th minute of every hour of exercise. Expired air was collected from the 46th to 49th minutes of exercise. The subject stopped at the 50th minute of exercise to be weighed and for his rectal temperature to be measured. Work was resumed at the 60th minute. An attempt was made to prevent subjects from becoming dehydrated by administering drinking water to replace weight loss other than that due to voided urine.

3.3 Sucrose weeks

During the second, third, fifth and sixth weeks, 100 g and 200 g of sucrose were administered orally immediately after work was resumed for the fourth hour. The sucrose was dissolved in the amount of water required to compensate for the hourly weight loss. The solution was flavoured with lime juice, which was also used during the first and fourth control weeks. Observations were conducted in the same way as during the no-sucrose weeks. Additional samples of expired air were collected after 15, 25 and 35 minutes of the administration of sucrose.

3.4 Additional observations

- (1) Blood-lactic acid content: Blood samples were collected from the subject's pre-heated fingertip at the end of the first and sixth hours of work during the first, second and third weeks.

- (ii) Blood-glucose content: Fingertip blood samples were collected from two subjects on two days during the first week and again on two days during the third week of the experiment. Samples were taken during resting, and during the second, fourth and sixth hours of work.
- (iii) Urinary ketone excretion: On two days during both the first and third weeks urine samples were collected on two subjects for the determination of ketone-body content. Samples were taken at the end of the second, fourth and final hours. The subjects emptied their bladders every hour.
- (iv) Cardiac output: Cardiac output was measured on two subjects, twice weekly during the first, second and third weeks. Observations were made at the end of the second, fourth and sixth hours of work.

3.5 Analytical procedures

- (1) Expired-air samples: Douglas bag volumes were measured with a chain-compensated spirometer. Samples of expired air were collected in two butyl rubber bags of 2 to 2½ litres capacity and analysed on a Beckman LB 1 infrared medical gas analyser for carbon dioxide content. The apparatus was calibrated with high purity nitrogen and about 4 per cent

carbon dioxide in air. The remainder of the air was then analysed for oxygen content on two Beckman Model E₂ paramagnetic oxygen analysers according to the method described by Strydom et al. (101). From the carbon dioxide and oxygen contents of the samples and the corrected volume of expired air at STPD, oxygen uptake and RQ's were calculated. RQ's determined in this way agreed well with those obtained by accepted chemical methods (14).

- (ii) Blood-lactic acid was analysed by the method of Barker and Summerson (13) with some modifications by Hullin and Noble (57).
- (iii) Blood-glucose content was determined by the o-toluidine method as reported by Hyvarinen and Nikkila (62).
- (iv) Urinary ketones were determined according to the method described by Michaels et al. (80).
- (v) Cardiac output was measured by means of a carbon dioxide re-breathing procedure described by Defares (38). A rapid infrared carbon dioxide meter was used for following the changes in PCO_2 during re-breathing. Arterial PCO_2 was determined by using the Bohr formula, and dead space was estimated by the method of Asmussen and Nielsen (6).

3.6 Statistical analysis

To test for differences between the no sucrose and sucrose experiments, two-way analysis of variance were done separately on the results of each work rate and hour. A 5 per cent level of significance had been used.

CHAPTER 4

RESULTS

Average results are given in Figures 1-15, and Tables 2 and 3.

In order to establish differences between the reactions for no-sucrose and 100 g, no-sucrose and 200 g, and 100 and 200 g sucrose, an analysis of variance was performed on the results. These analyses with respect to RQ, oxygen uptake, pulmonary ventilation and heart rate are given in Tables 4-7.

4.1 Respiratory exchange

(i) Respiratory quotient

(a) Work rate 1.5 litres O_2 /min. (Fig. 1)

The decrease in RQ when no sucrose and sucrose was given was similar during the first three hours of work. During this period, RQ decreased from about 0,90 to about 0,83. During the no-sucrose experiment, RQ continued to decrease to the fourth-hour value of 0,80, after which little change occurred.

When 100 g of sucrose was given, RQ increased significantly during the fourth hour and although it declined thereafter it remained significantly higher during the fifth and sixth hours as compared to the value in the no-sucrose experiment. Administration of 200 g of

sucrose caused a rapid increase in RQ to reach a peak, during the fourth hour, of about the same value as that obtained with 100 g.

This increase was maintained until the fifth hour, after which the RQ decreased during the final hour. The response obtained during the fifth and sixth hours with 200 g was significantly different from that obtained after administration of 100 g of sucrose. The peak RQ value after administration of sucrose usually equalled the value observed during the first hour of work.

(b) Work rate 1.0 litre O_2 /min (Fig. 2).

When no sucrose was given, RQ decreased continuously until the fifth hour, after which there was no change. A dose of 100 g of sucrose after the third hour caused a rapid and significant increase in RQ during the first fifteen minutes, and a peak value was reached at the fourth hour. Thereafter RQ decreased towards the sixth hour but still remained significantly higher than the corresponding value for no sucrose. A similar effect was achieved after the administration of 200 g of sucrose. The peak RQ value after administration of 100 g sucrose equalled, and that of 200 g usually exceeded, the value observed during rest:

The difference between the reactions to 100 g and 200 g of sucrose was statistically significant for all hours after sucrose ingestion.

(ii) Oxygen uptake (Fig. 3).

(a) Work rate 1.5 litres O_2 /min. When no sucrose was given, a steady increase in oxygen uptake during the six-hour work period was observed. When sucrose was given, oxygen uptake remained practically unchanged after the third hour. Oxygen uptakes for the fourth, fifth and sixth hours were significantly lower compared with those obtained in the experiments during which no sucrose was administered. A significant difference was observed between the results obtained after administration of 100 g and 200 g of sucrose during the fifth hour.

(b) Work rate 1.0 litre O_2 /min. Oxygen uptake increased with time when no sucrose was given. Administration of sucrose after the fourth hour prevented a further increase in oxygen uptake. The significantly higher oxygen uptake observed during administration of 200 g was already present before sucrose administration. The difference between work rates when 100 and 200 g of sucrose was administered was significant during the fourth, fifth and sixth

hours of work.

(iii) Carbon dioxide output (Fig. 4)

Carbon dioxide output remained fairly unchanged during both work loads for the whole period during which no sucrose was given.

Sucrose caused a marked increase in carbon dioxide production at both work loads. effect was more pronounced when 200 g was administered.

(iv) Pulmonary ventilation (Fig. 5)

(a) Work rate 1.5 litres O_2 /min. Pulmonary ventilation remained relatively constant for the whole six hours of work when no sucrose was given. One hundred grams of sucrose caused a slight but significant increase in ventilation during the fourth hour. There was no significant difference between the values for the fifth and sixth hour observed for no-sucrose and 100 g of sucrose.

(b) Work rate 1.0 litre O_2 /min. Pulmonary ventilation during the no-sucrose experiment remained relatively unchanged during the entire six hours. Administration of 100 g or 200 g of sucrose resulted in a significant increase in ventilation during the fourth and fifth hours. Last-hour values were close to those observed when no sucrose was given. There was a significant difference between the

ventilation responses following administration of 100 g and 200 g of sucrose in that the latter produced higher values.

4.2 Circulatory responses

(1) Heart rates (Fig. 6).

(a) Work rate 1.5 litres O₂/min. Average heart rate changed little during the first three hours of all experiments. When no sucrose was given, average heart rates showed a continuous increase during the second three-hour period from 118 to 128 beats per minute. When 100 g of sucrose was given, heart rate continued to increase towards the fourth hour and then remained constant until the sixth hour. Values for the fifth and sixth hours were statistically significantly different from those of the corresponding hour of the non-sucrose study.

The responses obtained by the 200 g dose was very similar to that for the 100 g dose.

Although heart rate remained unchanged after the fourth hour, results for no-sucrose and 200 g of sucrose were significantly different only for the final hour. The results obtained with 100 g and 200 g were significantly different only for the fifth hour. The net results with the two doses seem to be the same.

(b) Work rate 1.0 litre O_2 /min. Average heart rates remained practically unchanged throughout the whole six-hour period during which no sucrose was given. The overall result of administration of 100 g of sucrose was one of no change. On the other hand, a dose of 200 g caused a significant cardio-acceleration in the fourth and fifth hours. Sixth-hour values, although still elevated, did not, however, differ significantly from those of the no-sucrose experiment. There was a significant difference between the results for 100 g and 200 g of sucrose in the fourth, fifth and sixth hours.

(ii) Cardiac output (Figs. 7 and 8).

Cardiac output measured in two subjects at the higher work load showed the following:

- (a) Cardiac output had no time trend and was not influenced by either 100 g or 200 g of sucrose.
- (b) Stroke volume decreased with time. This trend was eliminated by administration of sucrose.
- (c) The calculated arterial PCO_2 was not influenced by time or administration of sucrose.
- (d) Mixed venous PCO_2 was increased after administration of sucrose with 200 g causing a bigger rise than 100 g.

4.3 Blood constituents

(i) Lactic acid (Fig. 9).

Lactic acid had no time trend and was not influenced by a dose of 200 g of sucrose. When 100 g of sucrose was given, lactic acid values for the sixth hour were lower than those for the first hour.

(ii) Glucose (Fig. 10).

Average values for blood glucose on two subjects showed a decrease from 85 mg% during resting to about 73 mg% after six hours of work. 200 g of sucrose increased blood glucose levels to 88 mg% during the fourth hour of work and these levels eventually dropped to about 78 mg% during the sixth hour.

4.4 Urinary ketones

(i) Total ketones (Fig. 11).

Total urinary ketones expressed as milligram of acetone per hour showed a decrease during six hours of work. Administration of 200 g sucrose resulted in a higher excretion for the sixth hour.

(ii) B-OH butyric acid (Fig. 12).

This fraction of the ketone bodies decreased with time when no sucrose was given. Administration of sucrose caused a marked reduction in the excretion of this metabolite.

(iii) Acetoacetic acid (Fig. 13).

Acetoacetic acid showed little change during six hours of work when no sucrose was given. When 200 g of sucrose was given it was increased almost three-fold during the fourth and sixth hours.

4.5 Utilization of carbohydrates (Fig. 14).

Calculations based on RQ and assuming a calorific value of 4.0 cal/g of carbohydrate, gave the following information.

- (i) Work rate 1.5 litres O_2 /min. When no sucrose was given, a total of 260 g of carbohydrates was utilized during the six hours of work. During this period 170 g was utilized during the first three hours and 90 g during the second three-hour period. When 100 g of sucrose was administered, utilization of carbohydrate during the second three-hour period increased to 155 g, causing a rise of 65 g compared with the results of the no-sucrose study. Calculations for the 200 g sucrose dose showed that the carbohydrate utilization was increased to 185 g during the second three-hour period thus resulting in an increase of 95 g.
- (ii) Work rate 1.0 litre O_2 /min. A total of 185 g of carbohydrate was utilized during the six

hours, of which 120 g was used during the first three hours and 65 g during the second three-hour period. A dose of 100 g of sucrose caused a utilization of 120 g in the second three-hour period, while 200 g caused a utilization of 150 g for this period. Thus utilization was increased by 55 g and 80 g when 100 g and 200 g of sucrose were given respectively.

4.6 Calories from carbohydrate and fat. (Fig. 15)

Fig. 15 shows that the percentage calories derived from carbohydrate declined from about 70 per cent in the first hour to 30 per cent in the fifth and final hours of work. The decrease was steepest during the first three hours of work, namely, from about 70 per cent to about 40 per cent. A dose of 100 g of sucrose caused a return to first-hour values with a subsequent decline to reach the third hour or higher values at the end of the sixth hour.

4.7 Body weight loss

The average body weight losses during the sucrose and no-sucrose experiments are given in Table 2. Total weight losses for the higher work load varied from 1,38 kg to 1,65 kg over the six-hour period and was apparently only slightly influenced by sucrose ingestion. A similar tendency was observed at the lower work load where the total weight loss varied from 0,79 to 1,26 kg.

4.8 Rectal temperature

Table 3 shows the average rectal temperature during the six hours of work of all experiments. The biggest change in rectal temperature was observed during the first hour of exercise in all experiments after which little change occurred. Rectal temperatures during the sucrose experiments did not differ from those observed during the no-sucrose experiments.

CHAPTER 5

DISCUSSION

The ability of muscle in vivo to perform prolonged moderate exercise is among others dependent on a continuous resynthesis of ATP. Substrates like carbohydrates and fat, from the intramuscular stores or supplied to the muscle by the circulation, are necessary for this purpose. The circulation is also responsible for a continuous supply of molecular oxygen for the aerobic oxidative processes as well and for the removal of the products of catabolism.

Substrate utilization during prolonged exercise is the main emphasis of the study reported on here. The RQ during the work period was used as a relative index of carbohydrate and fat metabolism. The validity of the RQ as a relative measure of the carbohydrate and fat metabolism during moderate exercise was discussed and reviewed in Chapter 2. The accuracy of the RQ measurements used in this investigation had to be considered and examined critically before any evaluation of the carbohydrate and fat metabolism during the exercise period could be made.

5.1 Measurement of RQ

1) Accuracy of the RQ measurement:

The RQ is the ratio of the volume of CO_2 produced to the volume of O_2 consumed per unit of time. From this it is clear that the concentration of oxygen and carbon dioxide have equal weightings in the RQ equation.

The accuracy of any RQ is therefore dependent on the accuracy of the determination of the oxygen and carbon dioxide concentrations in expired air.

The Haldane method, based on the "chemical trapping" principle of CO_2 and O_2 , has generally been accepted as the standard method for the determination of the RQ. Physical methods were used to determine RQ in the present study, applying the same precautionary measures as described earlier (14).

Physical methods have been shown to be as accurate for the determination of RQ as the accepted standard chemical method, the only prerequisite being the proper use and frequent calibration of the apparatus. Under these conditions, RQ calculated by chemical and physical methods were almost identical (14).

It can, therefore, be stated with confidence that the RQ values reported on in this work, possess the required degree of accuracy necessary for the overall evaluation of carbohydrate and fat metabolism during prolonged exercise.

11) The non-protein RQ

The average person derives about 7 to 15 per cent of his total energy from the metabolism of protein. This variation in the metabolism

of protein is mainly determined by the protein content of the diet.

Under conditions of adequate nutrition, protein has been shown to play only a minor role in the metabolic oxidation of substrates during exercise. Protein metabolism as measured by the nitrogen excretion technique is not higher during exercise compared with resting conditions (86, 107). Similar findings have been reported by Hedman (53) in skiers during $2\frac{1}{2}$ hours of skiing at a rate requiring about 82 per cent of the maximal aerobic capacity, amounting to a total expenditure of about 3 000 kcal. Even after exhaustion of the glycogen depots, continued exercise did not raise the nitrogen excretion significantly (25,79).

It therefore seems as if a relatively constant amount of protein is metabolized per 24 hours, irrespective of whether exercise is performed or not. In the calculation of RQ, the oxygen required and the carbon dioxide formed for the oxidation of protein are all included, unless corrected for. Correction for protein metabolism is usually made by measuring the protein metabolism by means of the nitrogen excretion technique. The oxygen required for and the carbon dioxide formed in the oxidation

process for the observed amount of protein, are then subtracted from the total oxygen consumption and carbon dioxide output measured during the observation period. The respiratory quotient so obtained is known as the non-protein RQ.

The respiratory quotients measured in this study were not corrected for protein metabolism and are therefore not non-protein RQ's. For the following reasons, it was thought defensible to use the measured RQ's without correction for protein metabolism:-

- a) Nitrogen excretion in urine has been shown to be unchanged by exercise.
- b) The amount of protein metabolized during the six-hour experiments could be assumed to be constant and the error introduced by not correcting for protein metabolism, is relatively constant and would apply to both sucrose and non sucrose experiments.
- c) Even if a correction is made for protein oxidation, such a correction makes only an insignificant difference in the RQ and would result in a change amounted to only a fraction of one per cent.

iii) Interpretation of the RQ

The physiological observations, indicate that none of the factors which influence the RQ,

e.g. hyperventilation, hypoventilation and lactic acid in blood, could have been responsible for the observed RQ during exercise in the fasting state.

5.2 Fat and carbohydrate metabolism during exercise in the fasting state

The results on RQ of fasting men obtained in this study during prolonged exercise agree with those reported by a number of workers (2,30,51,97). It was found that the RQ decreased from 0,94 at the beginning of exercise to 0,80 after six hours of work at both work intensities. From these RQ values it was calculated that 68 per cent of the caloric requirements for the first hour was supplied by the metabolism of carbohydrate and that only 30 per cent came from this source in the sixth hour. It is interesting to note that RQ fell to the same level at the end of the sixth hour at both work levels. This low level of RQ was reached at the end of the fourth hour at the high rate of work and one hour later at the lower rate of work. It can be concluded that the working muscle has to rely more and more upon fat metabolism for its oxidative processes towards the end of prolonged exercise. There is indirect support for this contention in the five-fold increase in blood FFA's after seven hours of exercise at 5,6 k/hr on the treadmill in the fasting state (77) and in the high turnover and oxidation rates of palmitate- l -C¹⁴, given by intravenous infusion, during muscular exercise (21,51,52).

The continuous increase in fat metabolism with time, as indicated by the decrease in RQ, was associated with a continuous increase in oxygen uptake as well as heart rate at the higher work load. This finding is in accord with that of Krogh and Lindhard (73), who showed that the relative change from carbohydrate to fat metabolism reduces the mechanical efficiency by five to ten per cent. A decreased mechanical efficiency was also reported by Henschel et al. (54) in fasting subjects walking on a treadmill. They showed a negative correlation between efficiency and the percentage of calories derived from fat. In the present experiments first-hour oxygen uptake values were used as baseline to calculate the percentage change in oxygen uptake with time. By the end of the second hour, oxygen uptake increased by two per cent, whilst by the end of the sixth hour, oxygen uptake increased by nine per cent. The bicycle ergometer used in the experiments was a constant work load ergometer of the type described by Atkins and Nicholson (11). The work load performed was thus constant and could therefore be excluded as a cause of the increase in oxygen uptake with time.

Kok (71) also reported a continuous increase in oxygen uptake with time in subjects exercising for prolonged period on a bicycle ergometer. However, subjects showed this increased oxygen uptake with time only when they worked at levels requiring more than 40 per cent of their maximal aerobic capacity. The increased oxygen uptake with time was absent in work loads requiring less than 40 per cent of the maximal aerobic capacity, which again is

confirmed by the findings of the present study. I. Astrand (7), however, interpreted an increase in oxygen consumption during work as being due to deterioration of muscular co-ordination. Our subjects did not show any sign of loss of co-ordination during the work period of six hours.

The increase in utilisation of fat during prolonged exercise was accompanied by a decrease in the excretion of ketone bodies in urine. Skeletal muscles as well as heart muscles have been shown to have a high affinity for these substrates (50,95). Normally B-hydroxybuturate and acetoacetate are not major sources of energy because of their low concentration in blood plasma, but the situation may be quite different during prolonged exercise in the fasting state and effective utilization of these substances in working muscle may account for the decreased excretion of ketone bodies in the urine.

It will be noted that the RQ before exercising averaged 0,94 in these experiments. This is higher than is usually found in the post-absorptive state. It is, however, consistent with the findings of other workers (16,17,26-30,63,73,88) who reported higher RQ after carbohydrate rich diets as compared to high-fat diets, or diets low in carbohydrate content. The subjects of the present experiments were fed a diet containing a very high proportion of mealie meal in the diet (46).

5.3 Effects of mid-shift feed of sucrose on fat and carbohydrate metabolism

Within 15 minutes of ingestion of sucrose at the

end of the third hour of the six-hour period of work there was a significant rise in RQ. The peak value of the RQ occurred an hour after ingestion and the RQ remained significantly higher than that for the control and fasting values for the remainder of the work period. The rise in RQ was significantly higher after administration of the 200 g dose than after administration of the 100 g dose and it was maintained at the higher level for a longer period.

The question that must be answered is whether the early rise in RQ after the ingestion of sucrose really means that a change occurred in the proportions of carbohydrate and fat metabolised. Courtice et al. (34,35) showed that an intravenous injection of 1 to 2 units of soluble insulin caused the RQ to rise during rest and exercise, but that the increase was not as rapid nor as consistent as after a subcutaneous injection of 0,5 mg of adrenalin. The ingestion of glucose leads to an increase in insulin level in blood in association with a rise in blood sugar level (72,93,100). The results of these experiments showed that blood sugar concentration rose during exercise after the ingestion of sucrose for a period of one hour and it can be assumed that blood insulin levels also rose during that period.

Whether a significant increase in blood insulin occurs during exercise after the ingestion of sucrose and whether this could account for the rise in RQ observed, is open to conjecture. Intravenous infusion of glucose did not result in as significant, or as consistent, an increase

in blood insulin after exercise as it did in men at rest (87). Furthermore, it is generally agreed that insulin is not the only factor which facilitates the uptake of glucose and its oxidation in cells during muscular exercise (31,49,60,87,92,93,99,103,107). For example, there is evidence that the lowering of blood sugar by exercise still occurs in pancreatectomised animals and in diabetic humans (41,99). At present, and until measurements of blood insulin are made in experiments similar to those reported in the present study, it must be accepted that the part insulin plays in the rise in RQ after the ingestion of sucrose during muscular exercise, is still an open question.

Apart from a possible effect of endogenous insulin on the early rise in RQ after sucrose administration, there are two other factors to be considered. Firstly, it is well known that ingestion of sucrose during rest is associated with an increase in lactic acid concentration in blood (12,42). It is this increased lactic acid concentration in blood that was held to be responsible for the non-metabolic increase in RQ following sucrose administration (12,42). It is doubtful whether lactate concentration in blood could have been responsible for the changes in RQ after ingestion of sucrose. Lactic acid concentration in blood was not measured when the peak values in RQ were observed. Figure 9 shows that lactic acid concentrations in blood at the end of the experiment were slightly lower when the subjects received sucrose as compared to the no-sucrose experiments. RQ was, however, still significantly higher during the last hour of exercise in the sucrose

experiments as compared to the no-sucrose experiments.

The second factor that could possibly have influenced the RQ in the sucrose experiments was the increased respiratory ventilation observed in the sucrose experiments. It is tempting to regard the increase in ventilation observed as hyperventilation. It is however not supported by the finding on arterial PCO_2 . Estimations of arterial PCO_2 did not differ significantly from those observed for men in the fasting state. Saltzman et al. (98) recently reported unchanged arterial PCO_2 in resting subjects who received about 230 g of carbohydrate in which sucrose was included. The same authors also observed an increased pulmonary ventilation brought about by an increased tidal volume. The increase in minute ventilation in the present study could not, per se, have been responsible for the rise in RQ because the RQ remained significantly higher compared with the no sucrose experiment, even after the minute ventilation had returned to control levels.

There may be some doubt whether the rise in RQ during the first hour after the ingestion of sucrose indicates an increase in the rate of carbohydrate metabolism and a decrease in the rate of fat metabolism. This doubt is not present in the last two hours after the ingestion of sucrose because the oxygen consumption in that period does not increase with time as it does when the men are fasting. This indicates, as mentioned in the previous section, that the mechanical efficiency of the work decreases with prolonged exercise in the fasting state with a change to

fat metabolism. When sucrose is administered the decrease in mechanical efficiency is prevented. The improvement in mechanical efficiency following administration of sucrose is good evidence that the working muscles are metabolising a higher proportion of carbohydrates and that this is reflected in the rise in RQ. It should be stated that the oxygen-sparing effect of sucrose ingestion is not due to anaerobic metabolism because there was no difference between the concentration of lactic acid in blood in the first and sixth hours.

There is little in the literature which has a direct bearing on the subject of feeding during prolonged exercise. Christensen and Hansen (26) exercised subjects on a fat diet to complete exhaustion. At the point of exhaustion, the subject was given a solution containing 200 g of glucose to drink. His blood sugar level, which had dropped to 60 mg%, immediately increased to values above 100 mg%, and the subject was able to continue work for an hour or more. His RQ did not increase, indicating that his muscles were still burning mainly fat. There is no explanation for the unchanged RQ in Christensen and Hansen's experiments, but an adaptation of the enzyme system due to the fat diet in favour of fat metabolism is probably not excluded. Under these conditions, it is quite possible that the glucose fatty acid cycle as proposed by Randle et al. (91) was operating, in which case the high fat metabolism would have suppressed oxidation of carbohydrate, which in turn could explain the unchanged RQ. Mager et al. (77), who studied men

over a seven-hour period of exercise at 5,6 km/hour on a treadmill, noted that the FFA level in blood rose five-fold when the men were in the fasting state and that intermittent ingestion of carbohydrate during the period of exercise prevented this rise in FFA level. Under these conditions it could be assumed that the oxidation of FFA was correspondingly decreased in the fed subjects as the turnover and oxidation of free fatty acids have been shown to be a function of their concentration in the blood (4,64,65,66,68,84). Havel et al. (52) showed that in a shorter period of work 25 g of sucrose fed at the end of each half hour suppressed the significant rise in blood FFA observed in the fasting state. They measured the turnover rate of palmitate-1-C¹⁴ and concluded that oxidation of FFA entering tissues accounted for 41 to 49 per cent of the energy metabolism during exercise in fasting subjects and 7 to 10 per cent in fed subjects. They stated further that "the decreased mobilization of FFA after the ingestion of carbohydrate seemed to account almost entirely for their decreased oxidation during muscular exercise".

Administration of sucrose caused an increased excretion of urinary ketones as well as a change in the ratio of 3-OH butyrate/acetoacetate. It was suggested that the ratio of these two substances in blood reflects the intra-mitochondrial dihydronicotinamide adenine dinucleotide/nicotinamide adenine dinucleotide (NADH/NAD) ratio (70). Depending on this ratio part of the acetoacetate is reduced to form 3-OH butyrate. It was

also suggested that the redox pair 3-OH butyrate/ acetoacetate acts as a hydrogen shuttle transferring reducing equivalents from cytoplasmic NADH to the intra-mitochondrial respiratory chain (39,70). It is obvious that the ketone bodies fulfill an important role in cellular metabolism and cannot be regarded as merely breakdown products of fat metabolism. The significance of change in ratio in the excretion of the ketone bodies is not known but could be indicative of a change in glucose and fructose metabolism at cellular level.

From the above it seems safe to conclude that the ingestion of 100 g or 200 g of sucrose during prolonged work of moderate intensity leads to a definite shift to carbohydrate metabolism. The early rise in the RQ after sucrose ingestion might be an overestimation of the carbohydrate metabolism due to the possible effect of insulin on RQ. Even if such an influence did exist, it should have little more effect than merely reducing the absolute value of RQ. This argument is substantiated by our finding on blood glucose values after sucrose ingestion. Blood insulin levels are known to follow blood glucose concentration after glucose ingestion (72,93,100). The difference in the fourth-hour value for blood glucose was only about 7mg% between the no sucrose experiment and the experiment when subjects received 200 g of sucrose. It is fair to assume then that the peak RQ value was reached at a stage when blood insulin levels had returned to about control levels and that insulin could have influenced the RQ only in the

early phases of the RQ rise.

5.4 Utilization of carbohydrate

These experiments showed that there is a significant dose-response effect with the ingestion of 100 and 200 g of sucrose. Calculation of carbohydrate utilization in the last three hours of work shows that, at the higher rate of work, 90 g of carbohydrate was oxidised during fasting, 155 g after administration of 100 g sucrose and 185 g after administration of 200 g sucrose. Comparable figures for carbohydrate utilisation at the lower work rates were 65, 120 and 150 g of carbohydrate, respectively. Thus, although there is a definite dose-response effect, the increase in carbohydrate utilisation at both levels of work was less when the dose of sucrose was increased from 100 g to 200 g than when it was increased from 0 g to 100 g. In practice the major effect of a mid-shift feed of sucrose on carbohydrate/fat metabolism would be obtained when a dose of 100 g of sucrose is fed.

5.5 Circulatory changes

The reduced carbohydrate utilisation during prolonged exercise in the fasting state is associated with a slow, continuous increase in heart rate and oxygen consumption. Cardiac output, measured in two subjects, was unchanged and the increase in oxygen consumption must therefore have been due to an increase in arterio-venous oxygen difference. The increase in heart rate, in conjunction with no change in cardiac output, points to

a decrease in stroke volume. The reason for the decrease in stroke volume is not obvious. Ekelund (43) in a study on 18 male subjects working at an average work load requiring about 50 per cent of the maximal oxygen uptake for one hour, also reported a decrease in stroke volume during the work period. Cobb and Johnson (32), Ahlborgh (1), and Olsson (82) reported similar findings.

Saltin and Stenberg (97) studying 4 well-trained subjects during 180 minutes of work on both a treadmill and a bicycle ergometer at an oxygen uptake of 75 per cent of the individuals maximum, reported a decrease in stroke volume with an increase in heart rate. They considered the increase in heart rate to be due to the dehydration of the subjects during exercise, which amounted to between three and five per cent of the body weight. The subjects in the present study ended the six-hour period with a water deficit of $\pm 1,5$ litres, but it is unlikely that the water deficits were responsible for the increase in heart rate. When the men received a mid-shift feed of sucrose they reached the same degree of water deficit without showing the increase in heart rate after the fourth hour. Rectal temperatures were also found to be similar in all experiments and could therefore be excluded as a possible explanation for the higher heart rate and lower stroke volumes observed in the no-sucrose experiments. The most reasonable explanation for the increase in heart rate appears to be that it is due to the increase in oxygen uptake. Such an association is well documented (5,7,8,28,30,71).

As indicated above, heart rate did not increase, nor did oxygen consumption, when sucrose was ingested mid-way during the six-hour period of work. There was no significant difference between the cardiac outputs in the fasting state and after feeding of sucrose, and thus stroke volume was higher after sucrose administration than in the fasting state. This finding supports the conclusion that the increased heart rate and decreased stroke volume observed in the fasting experiments, were due to the increase in fat metabolism, and not to dehydration.

Cardiac output was determined by a CO_2 rebreathing technique, which allows the estimation of the partial pressure of carbon dioxide in the mixed venous blood. The mixed venous P_{CO_2} obtained by rebreathing was found to be consistently higher in the sucrose experiments compared with the fasting experiments. With the unchanged arterial carbon dioxide concentrations in all experiments, it is felt that the higher mixed venous CO_2 concentrations in the sucrose experiments confirm the metabolic nature of the higher RQ and carbon dioxide production observed after sucrose ingestion.

5.6 Comparison of the results of the two work intensities

Apart from minor differences in the results of the two work intensities studied, it can be concluded that the results are comparable. The changes in heart rate and oxygen uptake during the lower work intensity in the fasting state were not as obvious as during the higher

work load. The effect of a mid-shift feed during the lower load, is also not as clear cut as that for the higher load. The differences in the results obtained on heart rate and oxygen uptake at the two work intensities are not easily explained. It is possible that the differences between fat and carbohydrate metabolism during exercise are better defined the higher the energy requirements for a particular task.

5.7 Validity of results obtained on four subjects

As can be seen from Tables 8 and 9, there were only small differences between the results of the four subjects obtained during the sucrose experiments. The results of each subject at any condition were also found to be highly reproducible. The relative uniformity of the results of the four subjects and the almost predictability of the course of events following ingestion of sucrose under the present conditions, suggest that the results could also be applied to a larger number of subjects.

CHAPTER 6

Summary and conclusions

The purpose of this study was to examine the effect of a mid-shift feed of sucrose on the proportions of fat and carbohydrate oxidized during prolonged work. Four well-trained, healthy young Bantu males receiving a standard compound diet, worked for fifty minutes of every hour for six hours on a bicycle ergometer. Two work loads were investigated: one requiring about 30 per cent and the other about 50 per cent of the subjects' maximal aerobic capacity. Respiratory, circulatory and some biochemical changes were studied when the men received only water and again when they were fed 100 g and 200 g sucrose.

It was found that:

- a) When men work continuously at a moderate (1,0 litres/min oxygen consumption) or hard rate (1,5 litres/min oxygen consumption) for six hours, the respiratory quotient decreased from 0,94 to 0,80. In classical concepts this indicates that 68 per cent of the caloric requirement comes from carbohydrates initially and that only 30 per cent comes from that source at the end of the work period. This change in metabolism is associated with an increase in oxygen consumption and heart rate, indicating that

the men were being less effective mechanically towards the end of the work period when they were using predominantly fat metabolism.

- b) A mid-shift feed of 100 or of 200 g of sucrose in water caused an immediate rise in RQ which persisted for the rest of the work period. This was associated with a lower rate of oxygen consumption than in the fasting state. While there may be some doubt about the immediate increase in RQ being due to a shift towards carbohydrate metabolism after the ingestion of sucrose, there can be little doubt that this is the case from the end of the first hour onwards, after the ingestion of sucrose.
- c) There was a significant dose-response effect with 100 and 200 g of sucrose. The increase in RQ was proportionally greater after administering 100 g than after 200 g of sucrose, from which it can be concluded that the major benefit of administering a mid-shift feed of sucrose is obtained with 100 g. Although some added benefit is obtained with an extra 100 g, the additional benefit is small. Men working at the higher work rate benefited more than when they worked at the lower rate.

Recommendation

The doubt about whether the rapid increase in RQ after the ingestion of sucrose is due to a change from fat to carbohydrate metabolism or whether it is due to an alteration in blood insulin level following the ingestion of sucrose, could be resolved by ingesting C^{14} sucrose and studying the output of $C^{14}O_2$ in expired air. In view of the practical importance to industry of showing whether or not carbohydrate given during a mid-shift feed is actually metabolised during the remainder of the shift, a study with C^{14} sucrose appears to be fully justified; its scientific value in solving the above problems is not in doubt.

ACKNOWLEDGEMENTS

I sincerely wish to thank: the Chamber of Mines of South Africa for the opportunity to use the data obtained during an official laboratory research project carried out for the South African Sugar Association. The South African Sugar Association for their highly appreciated permission to utilize the data obtained during the study and for their interest through their medical adviser Professor J.V.O. Reid.

Professor C.H. Wyndham and Professor N.B. Strydom for their guidance and advice during the study and their valuable suggestions and criticism during the preparation of this thesis.

Professor P.J. Pretorius of the Potchefstroom University for Christian Higher Education for his assistance and advice during the final stages of the preparation of this thesis.

The staff of the Human Sciences Laboratory for their excellent technical assistance with the analysis of blood and expired air samples: Mrs. J. Duke and Mr. J.J. Hitge for their help in expired air analyses; Mr. Hitge also performed some of the blood analysis; Mr. G.G. Rogers for his very able assistance with the experiments; Mrs. A. Margo for her patience in obtaining the references.

Mr. A.J. Heyns for performing the statistical analyses; Mr. D. Rabe for editing the manuscript; Mrs. F. Terblanche for her assistance, and patience during

the typing of the manuscript.

Finally my wife for her enduring patience and support.

REFERENCES

1. Ahlborg, B.
Capacity for prolonged exercise in man.
Försvarsmedicin 3 (Suppl. 1) 1, 1967.
2. Ahlborg, B., J. Bergström, L-G. Ekelund and E. Hultman.
Muscle glycogen and muscle electrolytes during prolonged physical exercise.
Acta Physiol. Scand. 70: 129, 1967.
3. Albrink, M.J., and R.S. Neuwirth.
Effect of previous starvation on the response of plasma lipids and free fatty acids to a fat meal.
J. Clin. Invest. 39: 441, 1960.
4. Armstrong, D.T., R. Steele, N. Altszuler, A. Dunn, J.S. Bishop and R.C. de Bodo.
Regulation of plasma free fatty acid turnover.
Amer. J. Physiol. 201: 9, 1961.
5. Asmussen, E.
Muscular Exercise.
In: Handbook of Physiology, Respiration
Section 3, Volume II, (ed W.O. Fenn, H. Rahn),
Baltimore, Maryland, Waverley Press, Inc., 1965.
6. Asmussen, E., and M. Nielsen.
Pulmonary ventilation and effect of oxygen breathing in heavy exercise.
Acta. Physiol. Scand. 43: 365, 1958.
7. Astrand, I.
Aerobic work capacity in men and women with special reference to age.
Acta. Physiol. Scand. 49, Supp. 169, 1960.
8. Astrand, P.O.
Experimental studies of physical working capacity in relation to sex and age.
Ejnar Munksgaard, Copenhagen, 1952.
9. Astrand, P.O.
Diet and athletic performance.
Federation Proceedings 26: 1772, 1967.

10. Astrand, P.O., and K. Rodahl.
Textbook of work physiology.
New York, Mc Graw-Hill, 1970.
11. Atkins, A.R. and J.D. Nicholson.
An accurate constant work rate ergometer.
J. Appl. Physiol. 18: 205, 1962.
12. Bachmann, G., and J. Haldi.
A comparative study of the respiratory quotient
following the ingestion of glucose and of fructose
as affected by the lactic acid and carbon dioxide
changes in the blood.
J. Nutr. 13: 157, 1937.
13. Barker, S.B., and W.H. Summerson.
The colorimetric determination of lactic acid in
biological material.
J. Biol. Chem. 138: 535, 1941.
14. Benade, A.J.S., N.B. Strydom and W.H. van der Walt.
A comparison of physical and chemical methods for
the determination of respiratory quotient.
Int. Z. angew. Physiol. 28, 193, 1970.
15. Benade, A.J.S., C.H. Wyndham, N.B. Strydom and
G.G. Rogers.
The physiological effects of a mid-shift feed of
sucrose.
S. Afr. Med. J. 45: 711, 1971.
16. Benedict, F., and E.P. Cathcart.
Muscular work: A metabolic study with special
reference to the efficiency of the human body
as a machine.
Carnegie Inst. Wash. Publ. 187, 1913.
17. Bergström, J., L. Hermansen, E. Hultman, and
B. Saltin.
Diet, muscle glycogen and physical performance.
Acta. Physiol. Scand. 71: 140, 1967.
18. Bergström, J., and E. Hultman.
The effect of exercise on muscle glycogen and
electrolytes in normals.
Scand. J. Clin. & Lab. Invest. 18: 16, 1966.

19. Bergström, J., E. Hultman, L. Jarfeldt, B. Pernow, and J. Wahren.
Effect of nicotinic acid on physical working capacity and on metabolism of muscle glycogen in man.
J. Appl. Physiol. 26: 170, 1969.
20. Bock, A.V., C. Vancaulaert, D.B. Dill, A. Fölling, and L.M. Hurxthal.
Studies in muscular activity.
IV The steady state and respiratory quotient during work.
J. Physiol. London 66: 162, 1928.
21. Carlson, L.A., J. Havel, L-G. Ekelund, and A. Holmgren.
Effect of nicotinic acid on the turnover rate and oxidation of the free fatty acids of plasma in man during exercise.
Metabolism 12: 837, 1963.
22. Carpenter, T.M., and R.C. Lee.
The effect of glucose and of fructose on the human respiratory quotient and alveolar air.
J. Nutrition 6: 55, 1933.
23. Cathcart, E.P. and W.A. Burnett.
Influence of muscle work on metabolism in varying conditions of diet.
Proc. Roy. Soc. (Biol.) 99: 405, 1926.
24. Cathcart, E.P., and J. Markowitz.
The influence of various sugars on the respiratory quotient.
J. Physiol. 63: 309, 1927.
25. Christensen, E.H.
Das essen und trinken des sportlers.
Sportmedizinische Schriftenreihe. Bern. Wanderer 1958.
26. Christensen, E.H., and O. Hansen.
Zur Methodik der Respiratorischen Quotient-Bestimmungen in Ruhe und bei Arbeit.
Skand. Arch. Physiol. 81: 137, 1939.
27. Christensen, E.H., and O. Hansen.
Untersuchungen über die Verbrennungsvorgänge bei langdauernder, schwerer Muskelarbeit.
Skand. Arch. Physiol. 81: 152, 1939.

28. Christensen, E.H., and O. Hansen.
Arbeitsfähigkeit und Ernährung.
Skand. Arch. Physiol. 81: 160, 1939.
29. Christensen, E.H., and O. Hansen.
Hypoglykämie, Arbeitsfähigkeit und Ermüdung.
Skand. Arch. Physiol. 81: 172, 1939.
30. Christensen, E.H., and O. Hansen.
Respiratorischer Quotient und O₂-aufnahme.
Skand. Arch. Physiol. 81: 180, 1939.
31. Christophe, J., and J. Mayer.
Effect of exercise on glucose uptake in rats and men.
J. Appl. Physiol. 13: 269, 1958.
32. Cobb, L.A., and W.P. Johnson.
Hemodynamic relationships of anaerobic metabolism and plasma free fatty acids during prolonged, strenuous exercise in trained and untrained subjects.
J. Clin. Invest. 42: 800, 1963.
33. Courtice, F.C. and C.G. Douglas.
The effects of prolonged muscular exercise on the metabolism.
Proc. Roy. Soc. G.B. 119: 381, 1936.
34. Courtice, F.C., C.G. Douglas and J.G. Priestley.
Adrenaline and muscular exercise.
Proc. Roy. Soc. 127: 288, 1939.
35. Courtice, F.C., C.G. Douglas and J.G. Priestley.
Carbohydrate metabolism and muscular exercise.
Proc. Roy. Soc. B. 127: 41, 1939.
36. Crane, R.K., and A. Sols.
The association of hexokinase with particulate fractions of brain and other tissue homogenates.
J. Biol. Chem. 203: 273, 1953.
37. Davidson, P.C., Shane S.R., and M.J. Albrink.
Decreased glucose tolerance following a physical conditioning program.
Circulation (Suppl III), 33: 7, 1966.

38. Defares, J.G.
Determination of $PVCO_2$ from the exponential CO_2 rise during re-breathing.
J. Appl. Physiol. 13: 159, 1958.
39. Devlin, T.M., and B.H. Bedell.
Effect of acetoacetate on the oxidation of reduced diphosphopyridine nucleotide by intact rat liver mitochondria.
J. Biol. Chem. 235: 2134, 1960.
40. Dill, D.B., H.T. Edwards, and R.H. de Meio.
Effects of adrenaline injection on moderate work.
Am. J. Physiol. 3: 9, 1935.
41. Dulin, W.E., and J.J. Clark.
Studies concerning a possible humoral factor produced by working muscles. Its influence on glucose utilization.
Diabetes 10: 289, 1961.
42. Edwards, H.T., E.H. Bensley, D.B. Dill, and T.M. Carpenter.
Human respiratory quotients in relation to alveolar carbon dioxide and blood lactic acid after ingestion of glucose, fructose or galactose.
J. Nutr. 27: 241, 1944.
43. Ekelund, L-G.
Circulatory and respiratory adaption during prolonged exercise.
Acta. Physiol. Scand. 70 (Suppl, 292): 1, 1967.
44. Evans, C.L.
Effect of muscular work on metabolism.
In: Principles of Human Physiology.
11th Edition, p. 812, J. & A. Churchill Ltd., London, 1952.
45. Fleming, P.W.
Some aspects of the nutrition of Bantu miners.
Research Report No. 55/65, Chamber of Mines of South Africa, 1965.
46. Fleming, P.W.
Unpublished report to Chamber of Mines, 1961.

47. Foerstner, B.
Über die wirkung des Insulins auf die Kohlehydrat-
verbrennung im Hungertier.
Biochem. Ztschr. 194: 422, 1928.
48. Fritz, I.B.
Factors influencing the rates of long-chain fatty
acid oxidation and synthesis in mammalian systems.
Physiol. Rev. 41: 52, 1961.
49. Goldstein, M.S.
Humoral nature of hypoglycemia in muscular exercise.
Am. J. Physiol. 200: 67, 1961.
50. Hagenfeldt, L., and J. Wahren.
Human forearm muscle metabolism during exercise.
III. Uptake, release and oxidation of B-
hydroxybutyrate and observations on the B-
hydroxybutyrate/acetoacetate ratio.
Scand. J. Clin. Lab. Invest. 21: 314, 1968.
51. Havel, R.J., L.A. Carlsson, L.G. Ekelund, and
A. Holmgren.
Turnover rate and oxidation of different free fatty
acids in man during exercise.
J. Appl. Physiol. 19: 613, 1964.
52. Havel, R.J., A. Naimark, and C.F. Borchgrevink.
Turnover rate and oxidation of free fatty acids of
blood plasma in man during exercise: Studies
during continuous infusion of palmitate-1-C¹⁴.
J. Clin. Invest. 42: 1054, 1963.
53. Hedman, R.
The available glycogen in man and the connection
between rate of oxygen intake and carbohydrate
usage.
Acta. Physiol. Scand. 40: 305, 1957.
54. Henschel, A., H.L. Taylor, and A. Keys.
Performance capacity in acute starvation with hard
work.
J. Appl. Physiol. 6: 624, 1954.
55. Hermansen, L., E. Hultman, and B. Saltin.
Muscle glycogen during prolonged severe exercise.
Acta. Physiol. Scand. 71: 129, 1967.

56. Hermansen, L., and B. Saltin.
Blood lactate concentration during exercise at acute exposure to altitude.
R. Margaria (ed). "Exercise at altitude"
Excerpta Medica Foundation, New York, 1967.
57. Hullin, R.P., and R.L. Noble.
The determination of lactic acid in micro quantities.
Biochem. J. 55: 289, 1953.
58. Hultman, E.
Studies on muscle metabolism of glycogen and active phosphate in man with special reference to exercise and diet.
Scand. J. Clin. Lab. Invest. 19: 1, 1967.
59. Hultman, E., J. Bergström, and N. McLennan Anderson.
Breakdown and resynthesis of phosphorylcreatine and adenosine triphosphate in connection with muscular work in man.
Scand. J. Clin. Lab. Invest. 19: 56, 1967.
60. Hunter, W.M., and M.Y. Sukka.
Changes in plasma insulin levels during muscular exercise.
J. Physiol. 196: 110, 1968.
61. Huxley, H.E., and J. Hanson.
The molecular basis of contraction in cross-striated muscles.
In: Structure and function of muscle, G.H. Bourne (ed.) Vol. 1, pl, Academic Press Inc. New York, 1960.
62. Hyvarinen, A., and E.A. Nikkila.
Specific determination of blood glucose with o-toluidine.
Clin. Chem. Acta. 7: 140, 1962.
63. Issekutz, B., N.C. Brikhead and K. Rodahl.
Effect of diet on work metabolism.
J. Nutrition 79: 109, 1963.
64. Issekutz, B. Jr., H.I. Miller, P. Paul and K. Rodahl.
Source of fat oxidation in exercising dogs.
Amer. J. Physiol. 207: 583, 1964.

65. Issekutz, B., Jr., H.I. Miller, P. Paul, and K. Rodahl.
Aerobic work capacity and plasma FFA turnover.
J. Appl. Physiol. 20: 293, 1965.
66. Issekutz, B. Jr., H.I. Miller, and K. Rodahl.
Lipid and carbohydrate metabolism during exercise.
Fed. Proc. 25: 1415, 1966.
67. Issekutz, B., P. Paul, and H.I. Miller.
Metabolism in normal and pancreatectomized dogs during steady-state exercise.
Am. J. Physiol. 213(4): 857, 1967.
68. Issekutz, B. Jr., P. Paul, H.I. Miller, and W.M. Borz.
Oxidation of plasma FFA in lean and obese humans.
Metabolism 17: 62, 1968.
69. Issekutz, B., and K. Rodahl.
Respiratory quotient during exercise.
J. Appl. Physiol. 16: 606, 1961.
70. Klingenberg, M., and H. v. Hafen.
Wege des Wasserstoffs in Mitochondrien.
I. Die Wasserstoffübertragung von Succinat zu Acetoacetat.
Biochem Z. 337, 120, 1963.
71. Kok, R.
Physiological changes during prolonged work on a bicycle ergometer.
M.Sc. Thesis, Potchefstroom University for C.H.E. 1970.
72. Kraegen, E.W., D.J. Chisholm, J.D. Young and L. Lazarus.
The gastrointestinal stimulus to insulin release.
J. Clin. Invest. 48: 1453, 1969.
73. Krogh, A., and J. Lindhard.
The relative value of fat carbohydrate as sources of muscular energy. With appendices on the correlation between standard metabolism and the respiratory quotient during rest and work.
Biochem. J. 14: 290, 1920.

74. Lusk, G.
Animal calorimetry. XXIV Analysis of the oxidation
of mixtures of carbohydrate and fat.
J. Biol. Chem. 49: 41, 1924.
75. Lusk, G.
The elements of the science of nutrition.
4th ed., W.B. Saunders Company, Philadelphia,
1928.
76. MacLeod, J.J.R.
The control of carbohydrate metabolism.
Bull. Johns Hopkins Hosp. 54: 79, 1934.
77. Mager, M., P.F. Iampietro, and R.F. Goldman.
The effect of supplementary feeding on plasma free
fatty acids during work.
Metabolism 13: 823, 1964.
78. Margaria, R., H.T. Edwards, and D.B. Dill.
The possible mechanism of contracting and paying
the oxygen debt and the role of lactic acid in
muscular contraction.
Am. J. Physiol. 106: 689, 1933.
79. Margaria, R., and P. Foa.
Der Einfluss von Muskularbeit auf den
Stickstoffwechsel, die Kreatin- und
Säureausscheidung.
Arbeitsphysiol. 10: 553, 1939.
80. Michaels, G.D., S. Margen, G. Liebert, and
L.W. Kinsell.
Studies in fat metabolism. I. The calorimetric
determination of ketone bodies in biological
fluids.
J. Clin. Invest. 30: 1483, 1951.
81. Nikkila, E.A., M-R. Taskinen, A. Miettinen,
R. Pelkonen, and H. Poppius.
Effect of muscular exercise on insulin secretion.
Diabetes 17: 209, 1968.
82. Olsson, K-E.
Total body water and water exchange during
prolonged physical work.
Försvarsmedicin 6: 221, 1970.

83. Passmore, R., and Y.E. Swindel.
Observations on the respiratory quotients and weight gain of man after eating large quantities of carbohydrate.
Brit. J. Nutrition 17: 33, 1963.
84. Paul, P.
FFA metabolism of normal dogs during steady-state exercise at different work loads.
J. Appl. Physiol. 28: 127, 1970.
85. Paul, P., B. Issekutz, Jr., and H.I. Miller.
Interrelationship of free fatty acid and glucose metabolism in the dog.
Am. J. Physiol. 211: 1313, 1966.
86. Pettenkofer, M., von, and C. Voit.
Betrachtung der 24 stundigen Versuche bei Hunger und mittlerer Kost mit Arbeit.
Z. Biol. 2: 537, 1866.
87. Pruett, E.D.R.
Glucose and insulin during prlonged work stress in men living on different diets.
J. Appl. Physiol. 28: 199, 1970.
88. Pruett, E.D.R.
Fat and carbohydrate metabolism in exercise and recovery, and its dependence upon work load severity.
Doctorate Thesis, Institute of Work Physiology, Oslo, 1971.
89. Pruett, E.D.R., and S. Oseid.
Effect of exercise on glucose and insulin response to glucose infusion.
Scand. J. Clin. Lab. Invest. 26, 277, 1970.
90. Rabinovitch, I.M., and E.V. Basin.
Blood sugar and respiratory metabolism time curves of normal individuals, following simultaneously administered glucose and insulin.
J. Biol. Chem. 80: 723, 1928.
91. Randle, P.J., P.B. Garland, E.A. Newsholme, and C.N. Hales.
THE GLUCOSE FATTY ACID CYCLE. Its role in insulin sensitivity and the metabolic disturbances of diabetes mellitus.
The Lancet 1: 785, 1963.

92. Reichard, G.A., B. Issekutz, P. Kimbal, R.C. Putnam, N.J. Hochella, and S. Weinhouse
Blood glucose metabolism in man during muscular work.
J. Appl. Physiol. 16: 100, 1961.
93. Reinheimer, W., P.C. Davidson, and M.J. Albrink.
Effect of moderate exercise on plasma, insulin, and free fatty acids during oral glucose tolerance tests.
J. Lab. Clin. Med. 71: 1968.
94. Robinson, S.
Experimental studies of physical fitness in relation to age.
Arbeitsphysiologie 10: 251, 1938.
95. Rudolph, W., D. Maas, J. Richter, F. Hasinger, H. Hofmann and P. Dohan.
Über die Bedeutung von Acetacetat und B-hydroxybutyrat im Stoffwechsel des menschlichen Herzens.
Klin. Wschr. 43: 445, 1965.
96. Saltin, B., and J. Karlsson.
Muscle ATP, CP, and lactate during exercise after physical conditioning.
In: Muscle metabolism during exercise.
eds. B. Pernow and B. Saltin, New York, Plenum Press. 1971.
97. Saltin, B., and J. Stenberg.
Circulatory response to prolonged severe exercise.
J. Appl. Physiol. 19: 833, 1964.
98. Saltzman, H.A., and J.V. Salzano.
Effects of carbohydrate metabolism upon respiratory gas exchange in normal men.
J. Appl. Physiol. 30: 228, 1971.
99. Sanders, C.A., G.E. Levinson, W.H. Abelmann and N. Freinkel.
Effect of exercise on the peripheral utilization of glucose in man.
New. Eng. J. Med. 271: 220, 1964.
100. Seltzer, H.S., E.W. Allen, A.L. Herron, Jr., and M.T. Brennan.
Insulin secretion in response to glycemic stimulus: Relation of delayed initial release to carbohydrate intolerance in mild diabetes mellitus.
J. Clin. Invest. 46: 323, 1967.

101. Strydom, N.B., H.M. Cooke, H.D. Miller, and P. Winer.
Errors in respiratory gas analysis. A comparison
of the Haldane and Pauling gas analysers.
Int. Z. angew. Physiol. 21: 13, 1965.
102. Wells, F.G., B. Balke, and D.D. van Fossau.
Lactic acid accumulation during work. A
suggested standardization of work classification.
J. Appl. Physiol. 10: 51, 1957.
103. Whichelow, N.G. W.J.H. Butterfield, M.E. Abrams,
G. Sterky and C.J. Garratt.
The effect of mild exercise on glucose uptake in
human forearm tissues in the fasting state and
after oral glucose administration.
Metabolism XVII (1): 84, 1968.
104. Williams, C.G., C.H. Wyndham, R. Kok, and
M.J.E. von Rahden.
Effect of training on maximum oxygen intake
and an anaerobic metabolism in man.
Int. Z. angew. Physiol. 24: 18, 1967.
105. Wrightington, M.
Effect of glucose and sucrose on respiratory
quotient and muscular efficiency of exercise.
J. Nutrition 24: 307, 1942.
106. Wyndham, C.H., C.G. Williams, and M. von Rahden.
A physiological basis of the optimum level of
energy capacities.
Nature 195: 1210, 1962.
107. Young, D.R., R. Pelligra, J. Shapira, R.R. Adachi
and K. Skrettingland.
Glucose oxidation and replacement during
prolonged exercise in man.
J. Appl. Physiol. 23: 734, 1967.
108. Zunts, N.
Betrachtungen über die beziehungen zwischen
nährstoffen und leistungen des Körpers.
Oppenheimers Handbuch der Biochemie 4: 849, 1911.

TABLE 2
BODY WEIGHT CHANGES KG

Work load	Sucrose	Time							Total wt. loss	Wt. loss as %
		R	1	2	3	4	5	6		
$\dot{V}O_2$ 1,5 l/min	0	65,44	65,28	64,93	64,63	64,38	64,18	63,90	1,54	2,35%
	100	65,65	65,37	64,98	64,70	64,53	64,29	64,00	1,65	2,51%
	200	65,21	64,96	64,63	64,30	64,36	64,10	63,38	1,38	2,12%
$\dot{V}O_2$ 1,0 l/min	0	65,36	65,39	65,23	65,03	65,00	64,79	64,64	0,72	1,10%
	100	65,95	65,97	65,76	65,58	65,58	65,42	65,12	0,83	1,26%
	200	65,74	65,77	65,53	65,34	65,50	65,33	65,22	0,52	0,79%

TABLE 3
RECTAL TEMPERATURES °C

Work load	Sucrose	Time						
		R	1	2	3	4	5	6
$\dot{V}O_2$ 1,5 l/min	0	36,9	37,7	37,8	37,8	37,8	37,9	37,9
	100	36,8	37,7	37,7	37,7	37,8	37,9	37,9
	200	36,8	37,7	37,7	37,7	37,8	37,9	37,9
$\dot{V}O_2$ 1,0 l/min	0	36,9	37,4	37,4	37,4	37,4	37,5	37,5
	100	36,6	37,3	37,4	37,4	37,5	37,5	37,6
	200	36,8	37,4	37,6	37,6	37,7	37,7	37,7

TABLE 4
PULMONARY VENTILATION

Work rate	Hour	Between no sucrose and 100 grams of sucrose	Between no sucrose and 200 grams of sucrose	Between 100 grams and 200 grams of sucrose
5000	4	S	S	S
	5	N.S.	S	S
	6	N.S.	N.S.	N.S.
3000	4	S	S	S
	5	S	S	S
	-	N.S.	N.S.	S

TABLE 5
OXYGEN CONSUMPTION

Work rate	Hour	Between no sucrose and 100 grams of sucrose	Between no sucrose and 200 grams of sucrose	Between 100 grams and 200 grams of sucrose
5000	4	S	S	N.S.
	5	S	S	S
	6	S	S	N.S.
3000	4	N.S.	S	S
	5	N.S.	S	S
	6	N.S.	N.S.	S

S = Significantly different

N.S.= Not significantly different

TABLE 6
RESPIRATORY QUOTIENT

Work rate	Hour	Between no sucrose and 100 grams of sucrose	Between no sucrose and 200 grams of sucrose	Between 100 grams and 200 grams of sucrose
5000	4	S	S	N.S.
	5	S	S	S
	6	S	S	S
3000	4	S	S	S
	5	S	S	S
	6	S	S	S

TABLE 7
HEART RATE

Work rate	Hour	Between no sucrose and 100 grams of sucrose	Between no sucrose and 200 grams of sucrose	Between 100 grams and 200 grams of sucrose
5000	4	N.S.	N.S.	N.S.
	5	S	N.S.	S
	6	S	S	N.S.
3000	4	S	S	S
	5	N.S.	S	S
	6	N.S.	N.S.	S

S = Significantly different
N.S. = Not significantly different

TABLE 8
WORK RATE 1.5 LITRES O₂/MIN

Subject	Sucrose Load	Pulmonary Ventilation			Oxygen Consumption			Respiratory Quotient			Heart Rate		
		4th Hour	5	6	4	5	6	4	5	6	4	5	6
Fa	100	95	97	99	93	88	93	111	110	107	96	92	92
	200	106	101	94	93	93	92	112	110	105	97	96	91
J	100	111	96	95	97	95	94	115	108	105	101	95	94
	200	110	108	102	99	97	93	113	115	112	102	98	94
Fe	100	104	99	96	96	94	94	111	106	104	98	93	93
	200	108	112	96	98	95	92	115	118	111	98	98	97
Ar	100	100	102	102	99	96	95	110	104	108	104	96	93
	200	115	113	103	100	97	95	114	118	109	108	101	93
Average	100	105	98	98	96	93	94	112	107	106	100	94	93
	200	110	108	99	98	96	93	114	115	109	101	98	94

Figures for sucrose loads of 100 and 200 expressed as percentages of those for no sucrose load

TABLE 9
WORK RATE 1.0 LITRE O₂/MIN

Figures for sucrose loads of 100 and 200 expressed as percentages of those for no sucrose load

Subject	Sucrose Load	Pulmonary Ventilation			Oxygen Consumption			Respiratory Quotient			Heart Rate		
		4th Hour	5	6	4	5	6	4	5	6	4	5	6
Pa	100	103	103	86	97	100	93	115	114	106	100	97	95
	200	114	110	100	102	104	98	112	121	116	110	106	105
J	100	110	109	102	104	102	98	114	111	107	105	110	101
	200	114	119	105	103	103	96	117	120	114	101	109	99
Fe	100	103	104	93	100	103	98	113	111	107	103	102	102
	200	116	125	98	105	112	102	113	116	105	115	118	115
Ar	100	110	107	102	108	100	102	111	109	106	103	100	98
	200	114	115	107	110	108	106	115	120	112	114	108	95
Average	100	106	106	96	102	101	98	113	111	106	103	102	99
	200	114	117	102	105	107	100	117	119	112	110	110	104

Fig.1

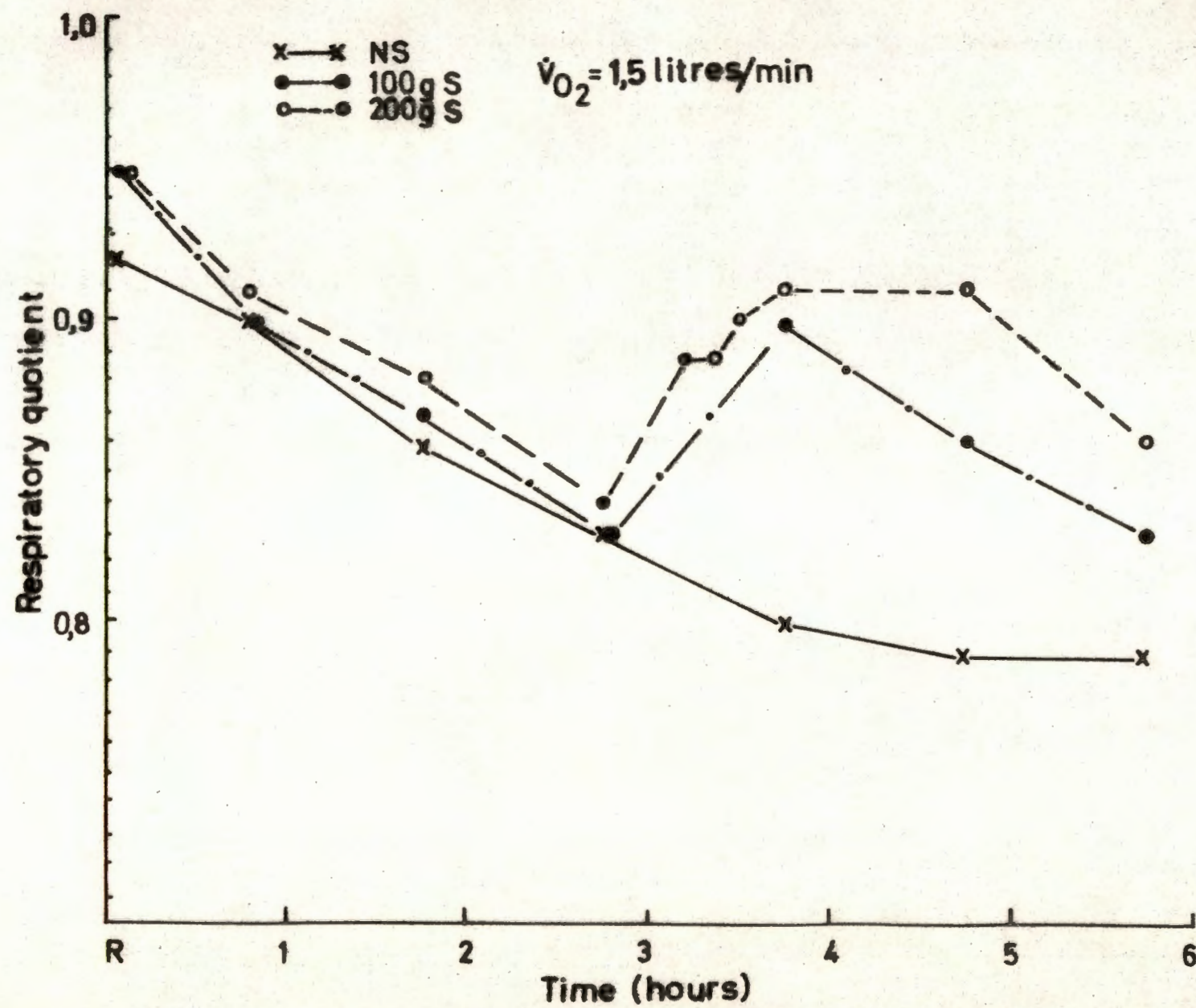


Fig. 2

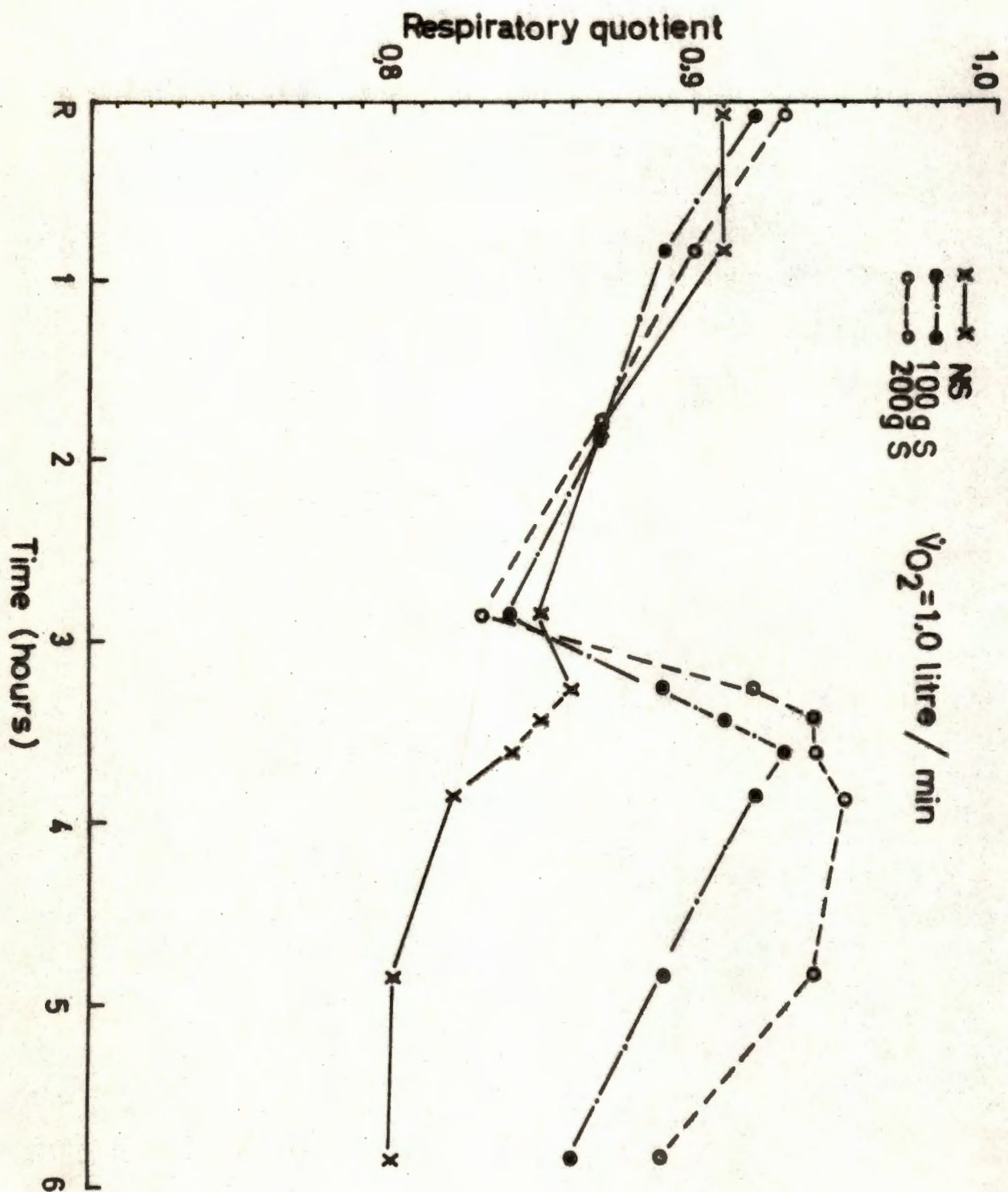


Fig.3

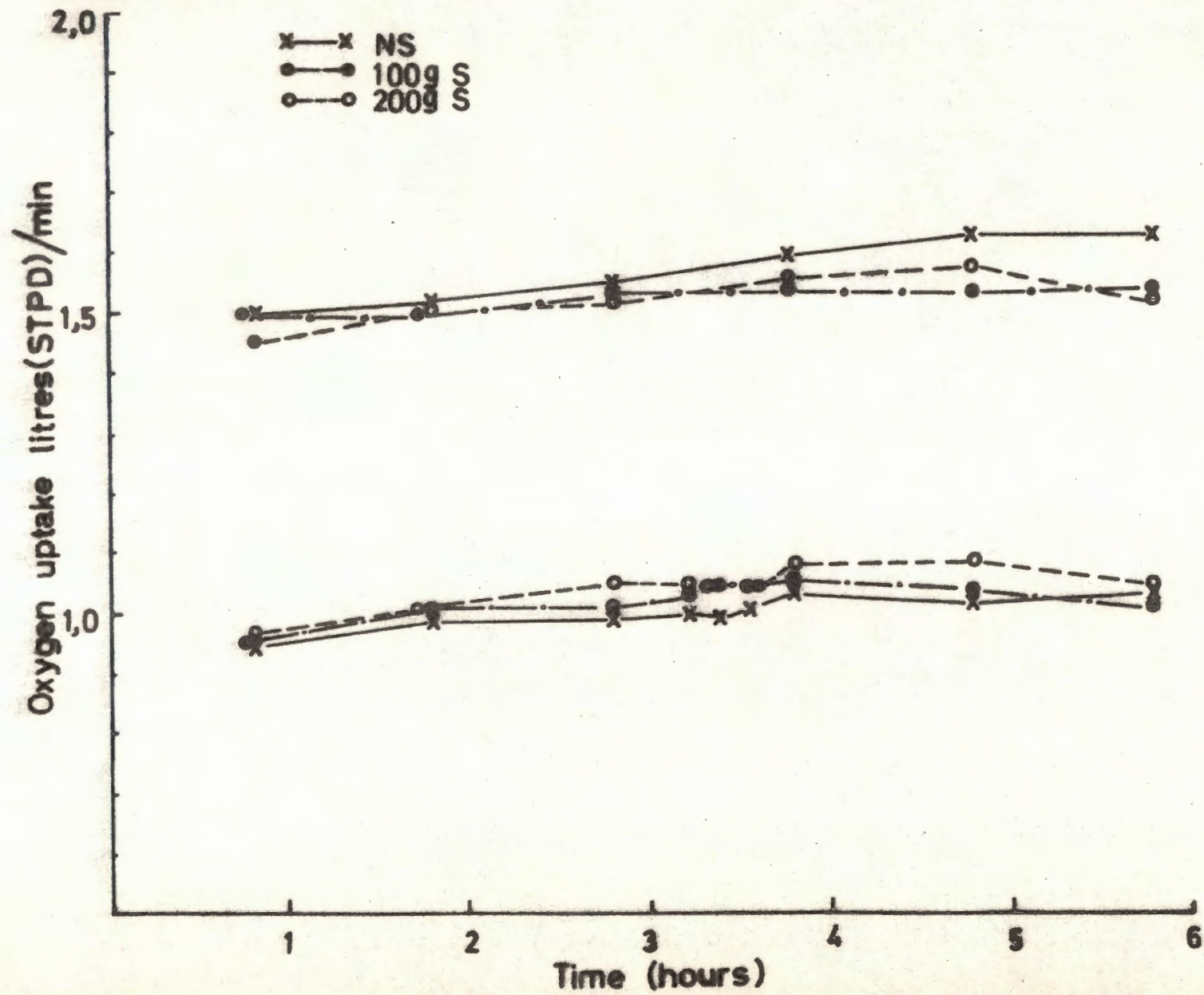


Fig.4

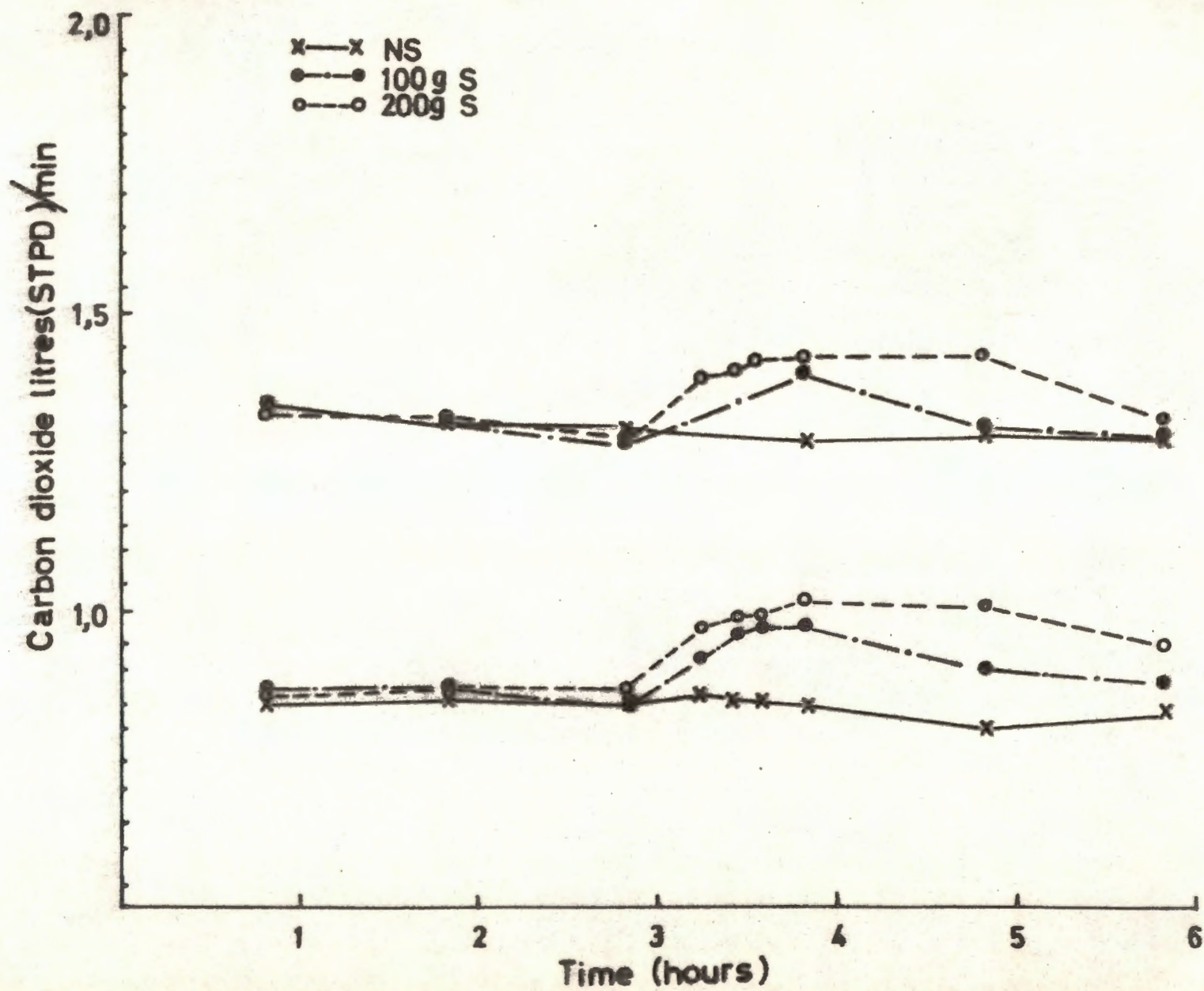


Fig. 5

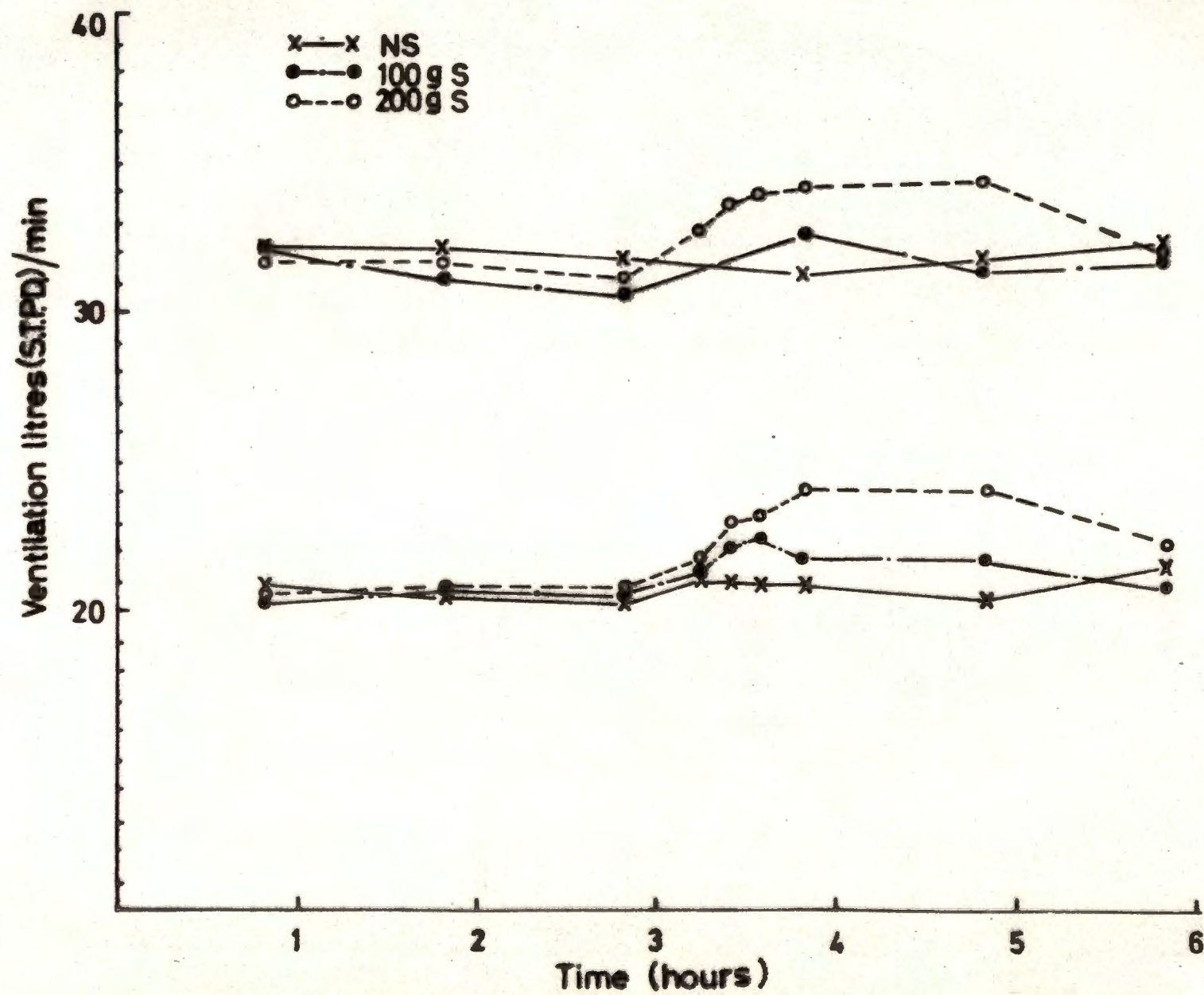


Fig.6

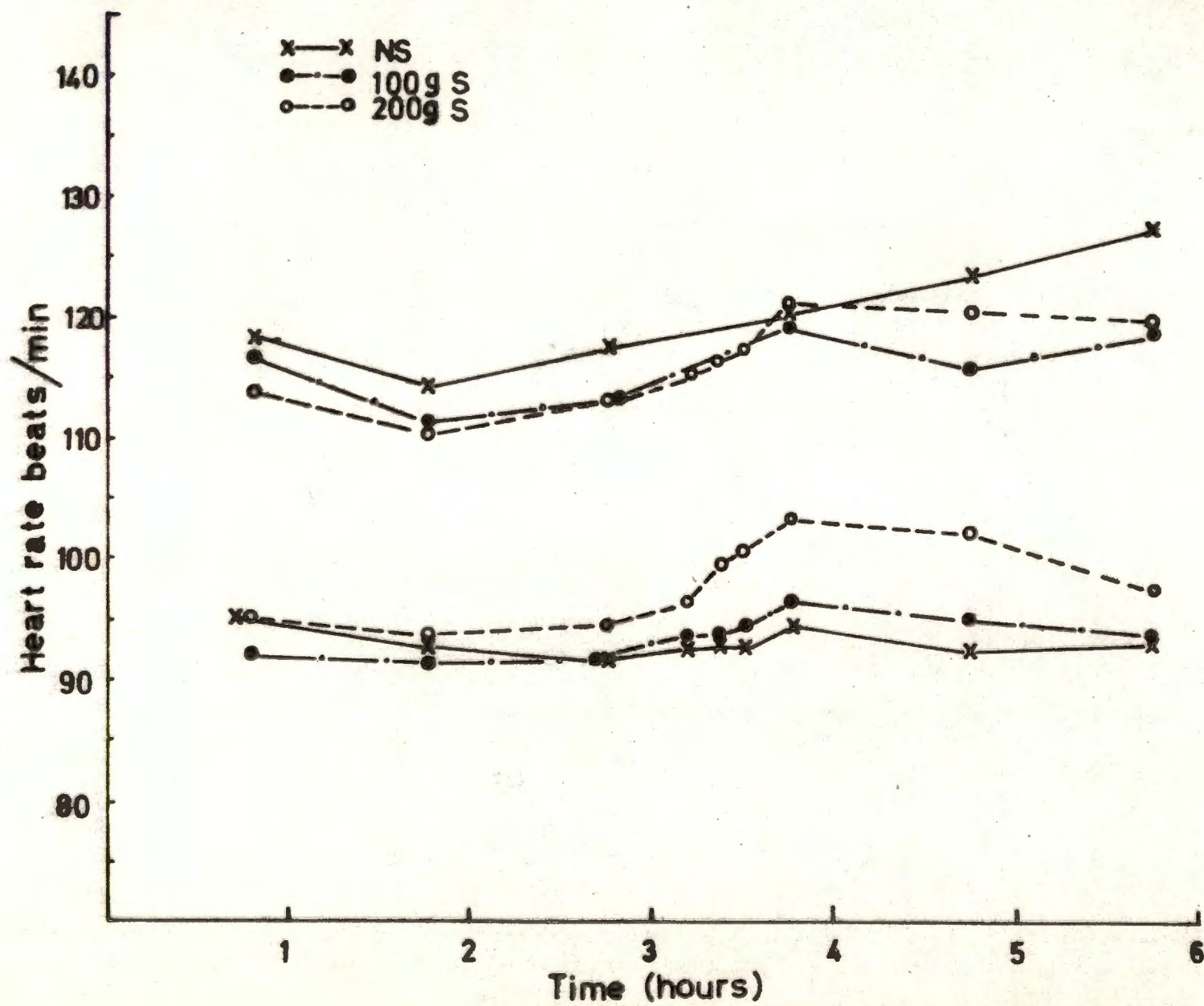


Fig. 7

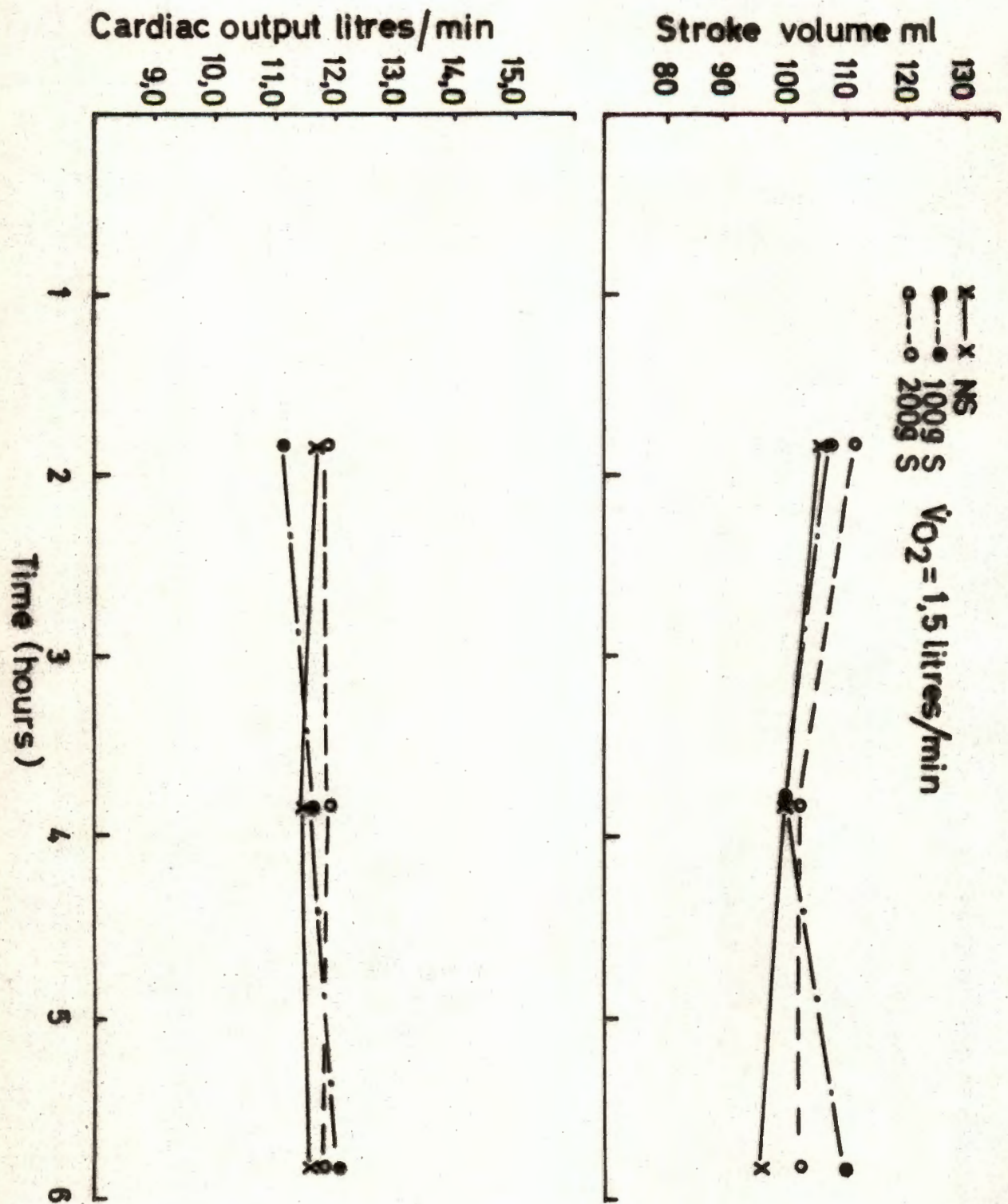


Fig. 8

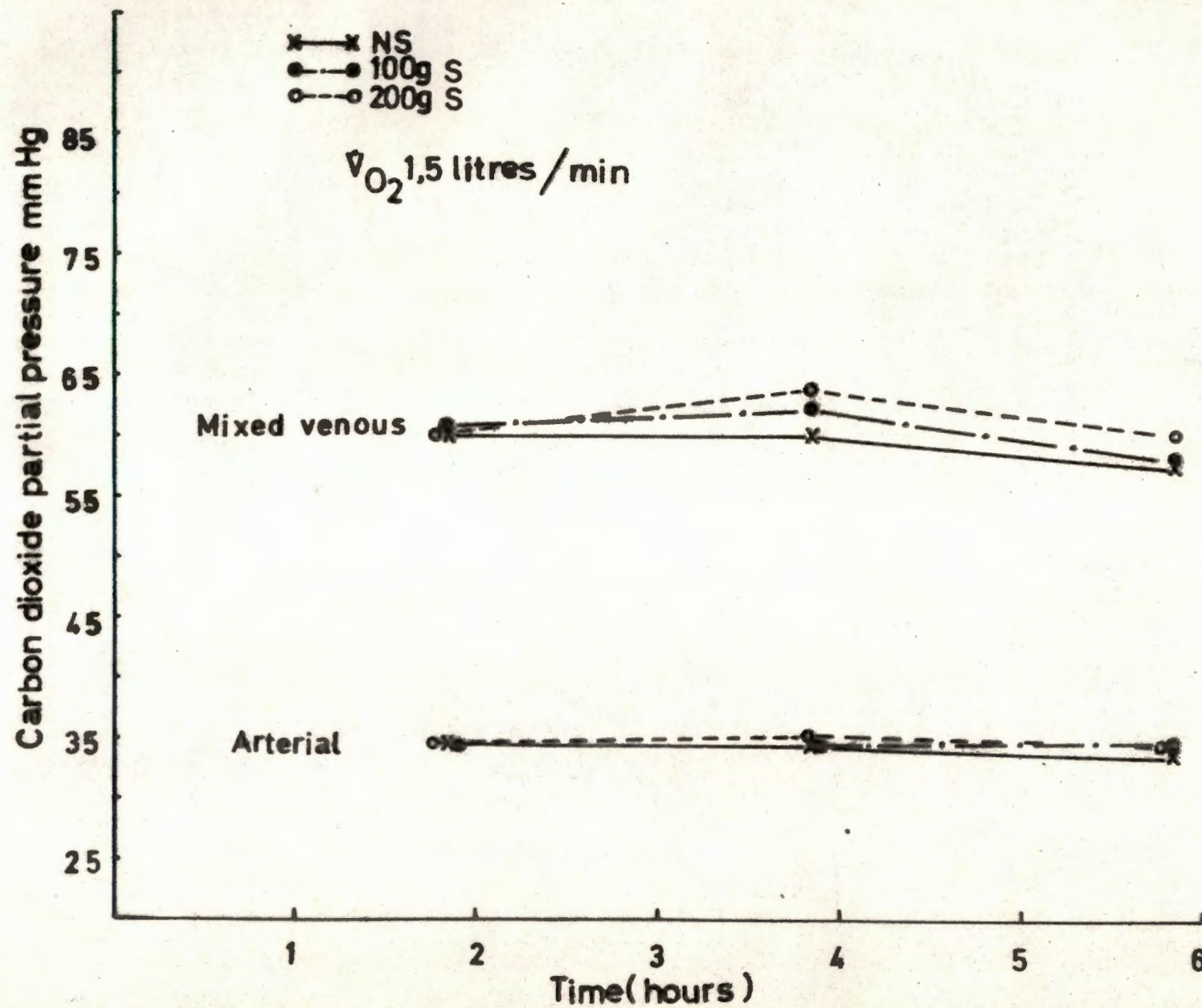


Fig. 9

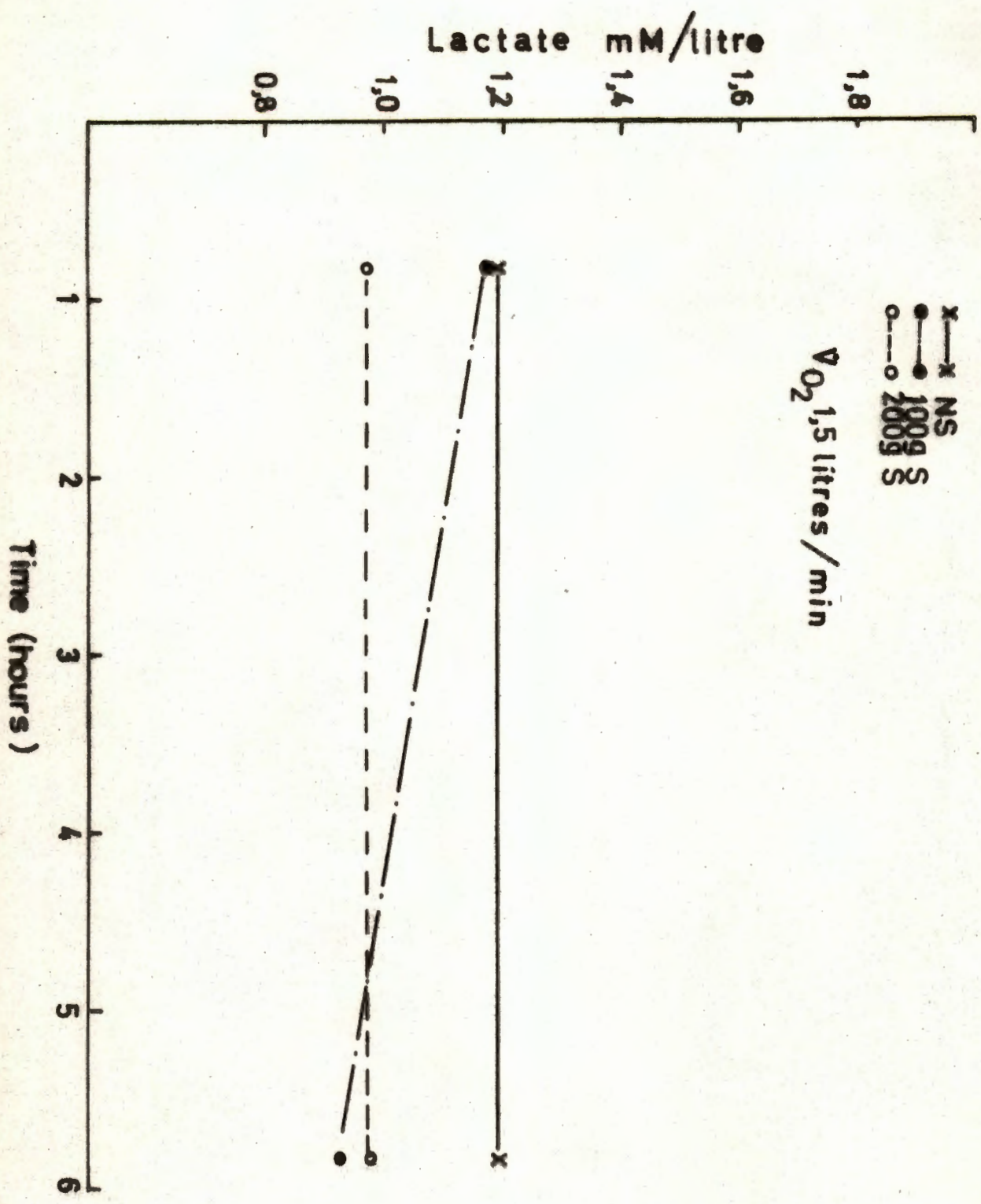


Fig. 10

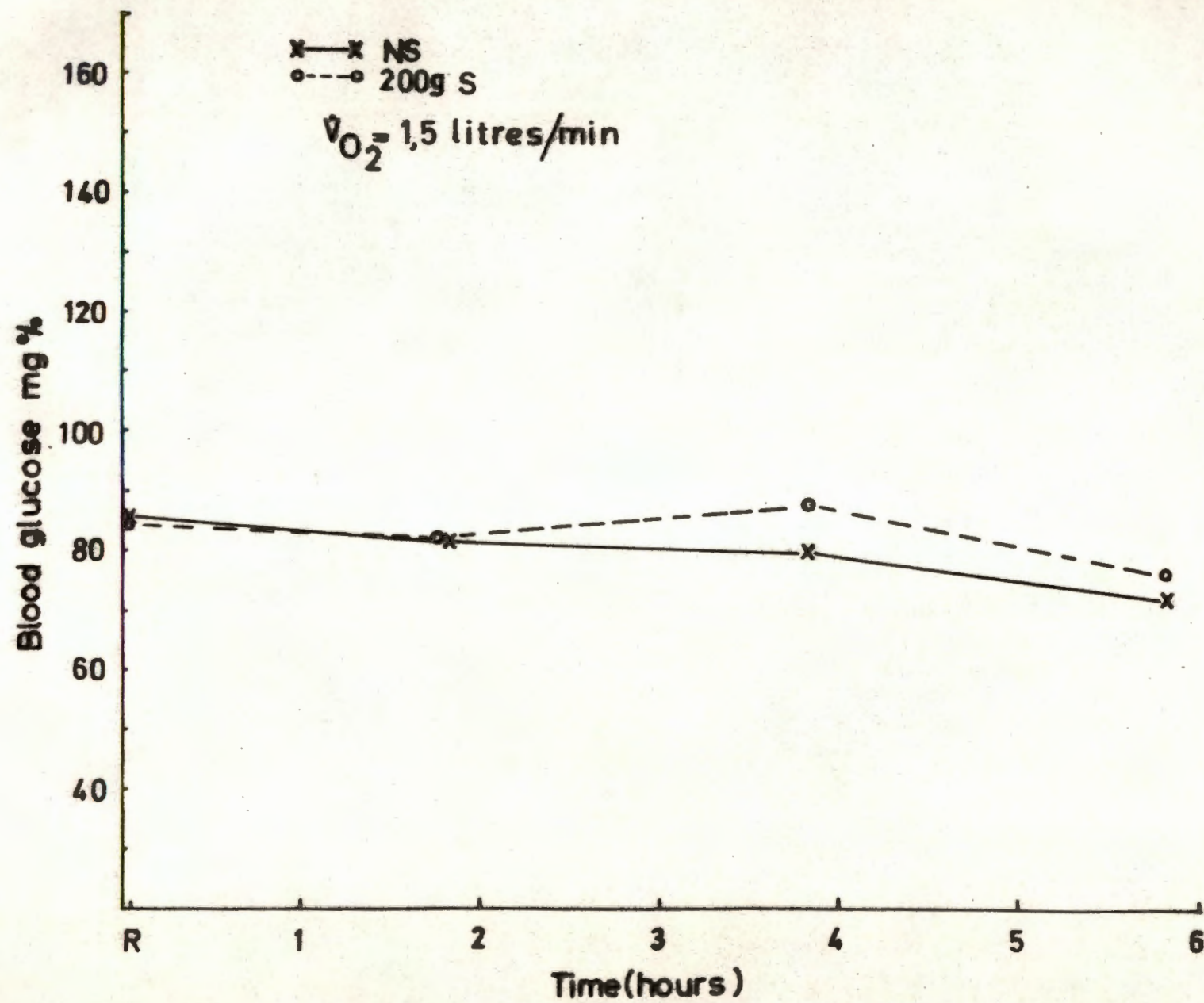


Fig. 11

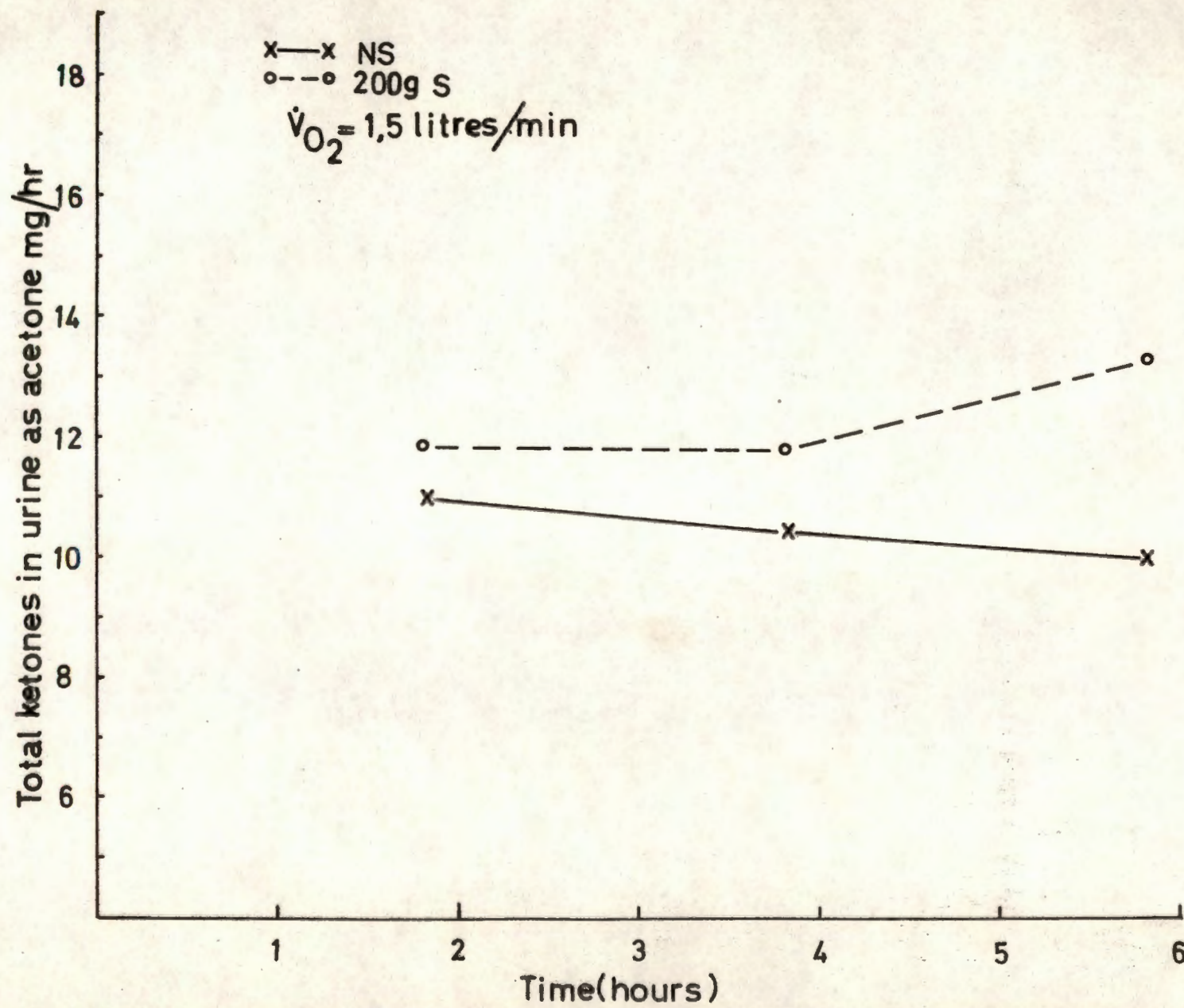


Fig. 12

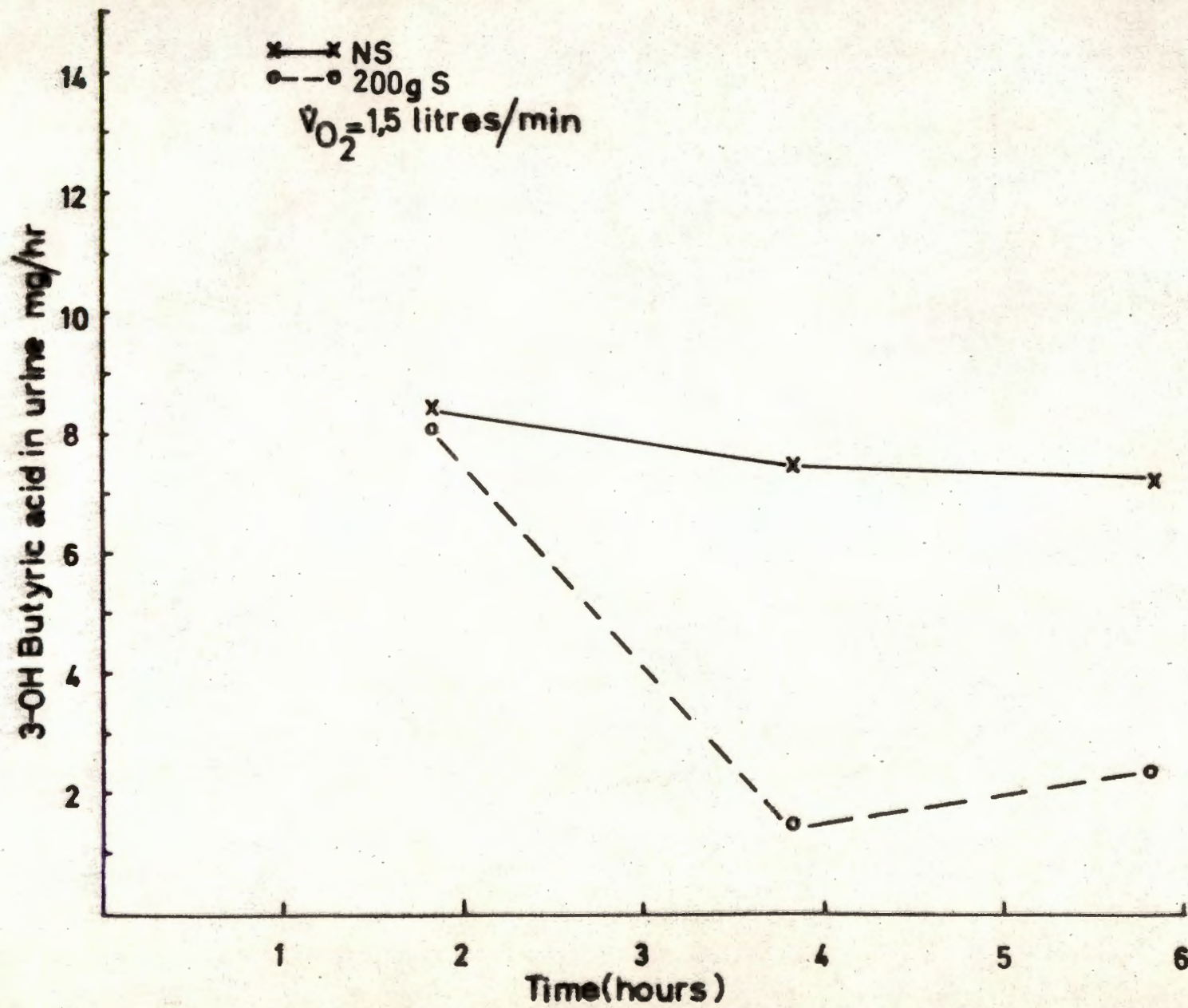


Fig. 13

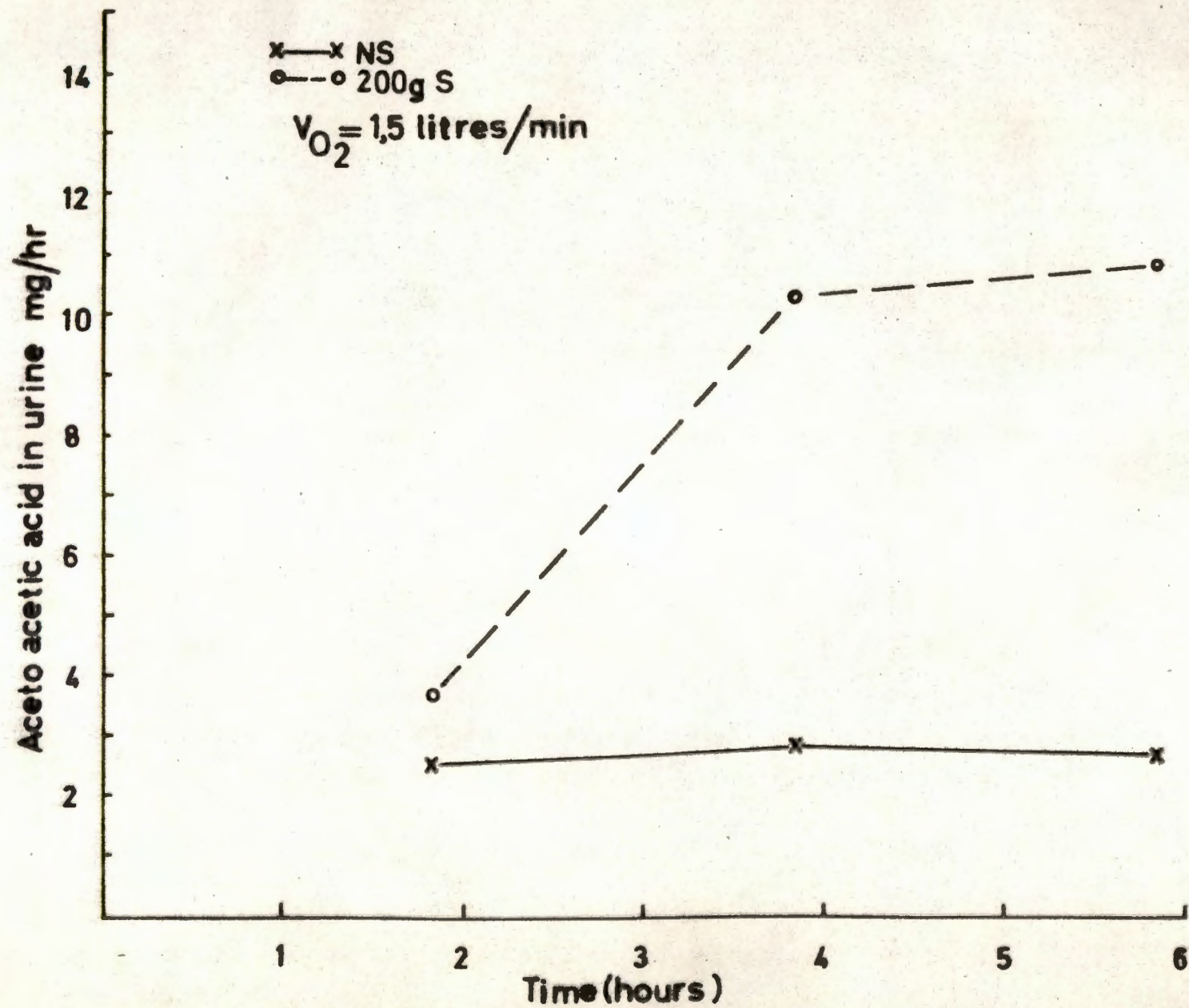


Fig.14

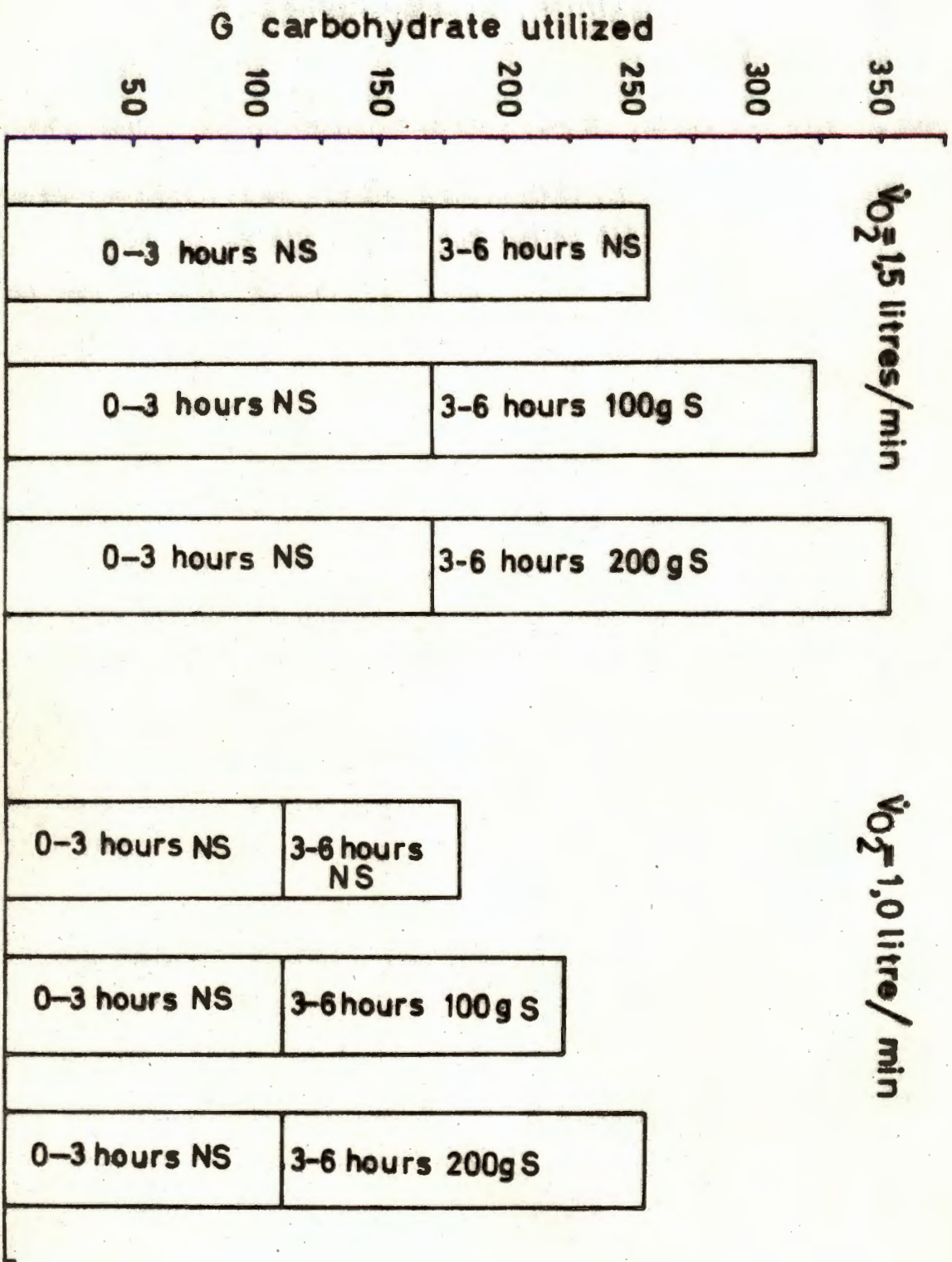


Fig.15

