

Study of Effects of Carbohydrates on the Body Under Stress and Fatigue

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N65-18595

The influence of nutrition on the capacity for physical work has been the subject of several extensive reviews (refs. 1 to 3). A belief that performance is in some way related to the foods consumed has led some enthusiasts to pursue the hope that a special state of muscular capacity might be achieved by the intake of certain diets (ref. 4). Such an optimistic view may be unwarranted. Although theoretical considerations favor the feeding of calories in order to maintain the blood sugar level and to provide fuel for the working muscles, and also favor special intake of vitamins because of their participation as coenzymes in energy-yielding reactions, research has failed to demonstrate an unequivocal effect of these substances on work capacity. Indeed, the demonstration with rats (ref. 5) that running capability is increased significantly during starvation, despite the relatively low levels of blood sugar coincident with food deprivation, leads one to question seriously the role played by diet in the performance of hard physical work.

Therefore, experiments have been undertaken to determine the influence of nutrition on performance in order to clarify the relationships between body metabolism and performance capabilities. These studies have been directed toward determining the influence of prolonged physical work on metabolism, with particular emphasis on the development of special dietary supplements to prevent fatigue and to improve work capability. Additionally, preliminary

studies have been undertaken to evaluate the utilization of body energy reserves during periods of food austerity, as well as to develop methods for enhancement of the use of the body energy stores.

EXPERIMENTS WITH ANIMALS

Preliminary evaluation of dietary effects on performance was obtained through studies with dogs. Six to eight animals were used for each test. The results to be described were obtained through experimentation with male, pure-bred beagle dogs, approximately 2 years of age and weighing 8 to 12 kg. The performance tests followed a common plan of exhaustive treadmill running at a speed of 3.6 mph, the grade varying between 9° and 13° of incline. Maximal work capacity has been expressed as energy expenditure measured in kilocalories.

The experiments were undertaken for three purposes:

- (1) To compare metabolism in sedentary and working animals with a view toward determining those responses which are likely to be associated with physical work.

- (2) To evaluate the immediate effect of specific nutrients on work capacity and to ascertain the effect of recency of food intake on performance.

- (3) To evaluate metabolism and performance in relationship to the level of blood sugar.

Early evidence of the relative ineffectiveness of carbohydrate supplements on work performance was obtained through a comparison of the effects of a carbohydrate supplement and a water supplement during exhaustive work. Experimental dogs were provided with either no supplement during treadmill running, or with water, or with carbohydrate pellets consisting largely of sucrose and dextrose and administered in an amount equal to 0.5 percent of body weight. The results are summarized in table I. While carbohydrate supplements tended to elevate the respiratory quotient and to minimize the decline in blood sugar during work, there was no obvious improvement in work capacity. The average total energy expenditure of animals without supplements was 1191 kilocalories; with carbohydrate supplements total energy expenditure was substantially similar, 1299 kilocalories. In contrast, animals given water during work showed a significant increase in performance, 2141 kilocalories, and a tendency to maintain their blood sugar at nearly normal levels.

Further studies of the influence of carbohydrate loading were undertaken. Animals were examined for their maximum work capability at 2, 4, 6, 17, and 120 hours after the last meal, which consisted largely of carbohydrate. The results are summarized in table II. During the first 6 hours following the intake of food, the average work capacity was 720 kilocalories; 17 hours after the last meal, work performance was 2200 kilocalories; 5 days after the last feeding performance capacity was increased to 4100 kilocalories. In these last tests, somewhat surprisingly, the blood sugars at the termination

TABLE II.—*Relationship Between Work Capacity and Recency of Food Intake^a in Dogs; Water Was Provided Ad Libitum During Work*

Time after last feeding, hr	Work capacity kcal ^b
2	850 ± 250
4	600 ± 275
6	700 ± 300
17	2200 ± 219
120	4100 ± 300

^a 200 g Purina Chow

^b Mean value ± standard deviation.

of work were 100 mg per 100 ml, or approximately 20 percent higher than the levels measured just prior to exhaustive treadmill running.

To investigate further the relationship between food intake and performance capabilities, animals were offered, during work, one of the following special nutrient supplements: water, milk, or aqueous solutions of either (a) carboxymethyl cellulose, (b) corn oil, (c) phospholipids, (d) lactalbumin, (e) glucose, or (f) water-soluble vitamins. With the exception of the supplement containing the cellulose derivative, the concentrations of protein, sugar, fat, vitamins, and phospholipids were similar to those found in milk. The results of these tests are shown in table III. Supplements of milk, corn oil, vitamins, phospholipids, and cellulose derivatives decreased performance approximately 40 percent; supplementation with glucose or lactalbumin was neither beneficial nor detrimental.

TABLE I.—*Effect of Water or Carbohydrate Supplementation on Work Capacity of Dogs*

	No supplement	Carbohydrate (52.4 ± 7.2 g)	Water (1520 ± 172 cc)
Work capacity kcal.....	1191	1299	* 2141
Respiratory quotient.....	0.77	* 0.85	0.77
Max. rectal temp., ° F.....	105.4	105.7	* 104.2
Δblood glucose, mg/100 ml.....	* -39.3	-20.2	-14.5
Δblood lactate, mg/100 ml.....	-.1	.8	-.7
Δblood acetone, mg/100 ml.....	.9	.5	1.3

* Differs significantly from both other treatments, $P < 0.05$.

TABLE III.—*Effect of Nutrient Intake During Treadmill Running on the Work Capacity of Dogs*

Nutrient	Percent change in work capacity*
Milk.....	-61
Corn oil.....	-38
Water-soluble vitamins.....	-37
Plant phospholipids.....	-40
Carboxymethyl cellulose.....	-60
Glucose.....	<1
Lactalbumin.....	4

* Compared with capacity when only water was consumed.

The apparent ineffectiveness of carbohydrate supplements on performance capabilities has been of special interest, and additional tests have been undertaken to evaluate the factors regulating the blood sugar level during work. Specifically, the level of blood sugar has been examined during physical work with and without starvation.

The effect of food deprivation combined with hard work is shown in table IV. During the first day of fasting, the level of blood sugar measured at rest was 86 mg per 100 ml; following treadmill running of 6 to 10 hours' duration the level declined to 47 mg per 100 ml. In contrast, on the third and fifth day of fasting the level of blood sugar measured at rest was 72 mg per 100 ml and 69 mg per 100 ml, respectively; during those periods, long sustained work did not further lower the level of the blood sugar.

TABLE IV.—*Blood Sugar in Dogs Following Prolonged Work^a During Fasting*

Day of fast	Resting blood glucose, mg percent	Postexercise blood glucose, mg percent
First.....	86 ± 6.0	47 ± 5.6
Third.....	72 ± 2.3	67 ± 20
Fifth.....	69 ± 7.0	64 ± 15

* Of 6 to 10 hours' duration.

Additionally, studies were undertaken to follow the blood sugar level during various periods of work. These results are shown in figure 1. In general the level of blood sugar tended to decrease systematically to 40 mg per 100 ml until a cumulative energy deficit of approximately 1200 kilocalories had been attained, but thereafter the level of the blood sugar tended to rise. In conjunction with these studies, the overall body metabolism was examined at rest and during prolonged physical work. A comparison of the responses of sedentary animals with those of active animals is shown in table V. Although the level of blood sugar was depressed in the physically active animals, the urinary nitrogen and acetone excretion were uninfluenced.

The results of the above investigations have led to a serious reevaluation of the nature of the metabolic substrate utilized during prolonged work. In effect, substantial degradation of body protein and fat was anticipated during the prolonged running tests, and significant increases in the blood ketones as well as in the urinary nitrogen and creatinine were ex-

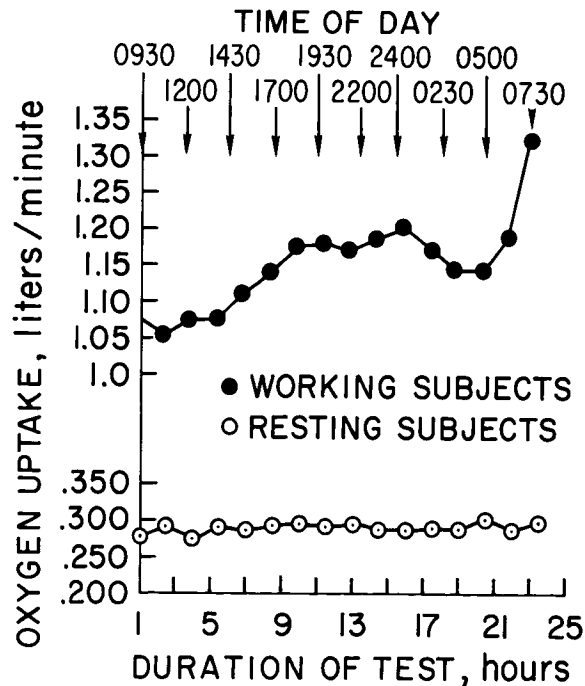


FIGURE 1.—Effect of work with ad libitum water intake on the blood glucose level.

TABLE V.—*Physiologic Characteristics of Work, Blood Chemistry, and Urinary Excretion in Post-absorptive Dogs*

	Sedentary, 20 hr ^a	Active, 12 hr ^a
Energy expenditure, kcal/min.....	0. 50 ± 0. 04	^b 3. 35 ± 0. 3
Gross energy expenditure, kcal.....	600 ± 30	^b 2100 ± 210
Heart rate/min.....	90 ± 15	^b 235 ± 12
Respiratory rate/min.....	25 ± 4. 0	^b 210 ± 15
Venous O ₂ , cc/100 ml blood.....	16. 0 ± 1. 0	15. 9 ± 0. 8
Oxygen debt.....	None	None
Blood glycogen, mg/100 ml.....	2. 2 ± 1. 5	2. 8 ± 1. 6
Blood glucose, mg/100 ml.....	72 ± 5. 0	^b 55 ± 6. 0
Blood fructose, mg/100 ml.....	3. 3 ± 0. 9	2. 8 ± 0. 6
Blood pyruvate, mg/100 ml.....	2. 1 ± 0. 5	2. 0 ± 0. 4
Blood lactate, mg/100 ml.....	3. 0 ± 1. 5	4. 0 ± 0. 8
Blood acetone, mg/100 ml.....	2. 0 ± 0. 7	3. 0 ± 1. 4
Urinary NPN, g.....	2. 2 ± 0. 7	1. 9 ± 0. 6
Urinary urea N, g.....	1. 7 ± 0. 4	1. 5 ± 0. 5
Urinary creatinine N, mg.....	75 ± 32	57 ± 13
Urinary acetone, mg.....	12 ± 5. 0	18 ± 7. 8
Urinary sodium, meq.....	22 ± 3. 0	24 ± 3. 0
Urinary potassium, meq.....	12 ± 2. 5	^b 18 ± 2. 5
Urinary phosphorus, mg.....	195 ± 44	183 ± 30

^a Mean value ± standard deviation.

^b Differs significantly from value obtained with sedentary dogs, $P \leq 0.01$.

pected. However, the results have failed to confirm this hypothesis. Therefore, it is postulated that carbohydrate is formed and utilized even during undernutrition; that the relative constancy of the blood sugar level during fasting with hard work and, again, the tendency of the blood sugar to increase during prolonged work are due to de novo synthesis of sugar. Finally, since no important variations in nitrogen metabolism have been observed, it is postulated that sugar may be synthesized from fat precursors.

EXPERIMENTS WITH HUMANS

A program has been undertaken with human subjects to test further the hypothesis of glucose synthesis. As a preliminary measure, investigations have been carried out to test the feasibility of walking for periods up to 24 hours, the time needed to develop an experimental situation suitable for studies of carbohydrate synthesis.

Studies are in progress with 20 male subjects, varying from 22 to 40 years of age. After 3 months of intensive physical conditioning, they are tested on the treadmill for periods of 24 hours or until the onset of exhaustion. The pace varies between 2.5 and 2.7 mph and the degree of incline is varied between 0° and 2° in order to attain a workload which is one-third of each individual's maximal work capacity. Additionally, each subject is tested during a 24-hour period of rest. All tests are conducted in the postabsorptive state. The physiologic characteristics of the tests are shown in table VI. Generally, heart rate and rectal temperature during work are 104 and 38.1° C, respectively. Blood lactic acid levels remain normal.

The oxygen uptake, the level of blood sugar and fatty acids, and the pattern of urinary excretion have been examined. Figure 2 shows the relationship between the duration of the test and the oxygen uptake. In general, the oxygen uptake measured at rest was relatively constant. During work, however, oxygen uptake tended to rise during the first 10 hours from 1.07 liters/min to 1.20 liters/min. The level of blood sugar declined during the first 9 hours and thereafter was relatively constant (fig. 3). Two points are

TABLE VI.—*Average Physiologic Responses at Rest and During Work in 13 Human Subjects*

	Treadmill walking	Resting
O ₂ uptake, liters/min.....	1. 151	0. 288
Percent of peak effort.....	32	8. 0
Heart rate/min.....	104	61
Rectal temp., °C.....	38. 1	37. 1
Serum lactate, mg/100 ml.....	13. 0	10. 5

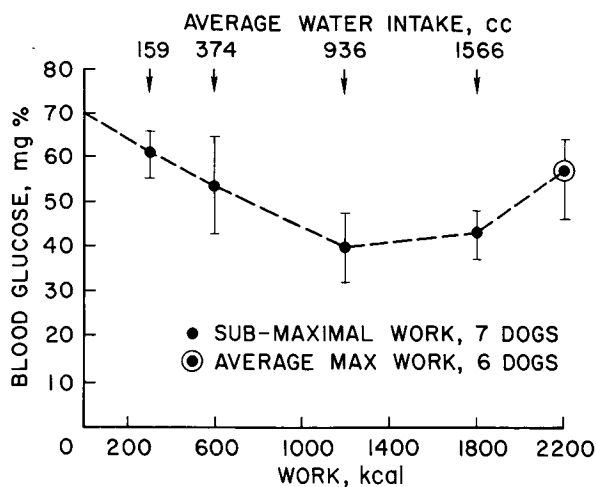


FIGURE 2.—Mean oxygen uptake at rest and during work in 13 human subjects.

noted in regard to the level of blood sugar. First, the level of sugar in the working subjects was only 10 mg per 100 ml lower than that observed in the resting subjects, despite the substantially greater energy deficits incurred during work. Second, we have noticed a tendency of the blood sugar to rise terminally after approximately 22 hours of treadmill walking. Serum free fatty acids also showed a tendency to rise (fig. 4). During the first 10 hours of work, the level of fatty acids increased from 0.65 m q/liter to 2.6 m q/liter.

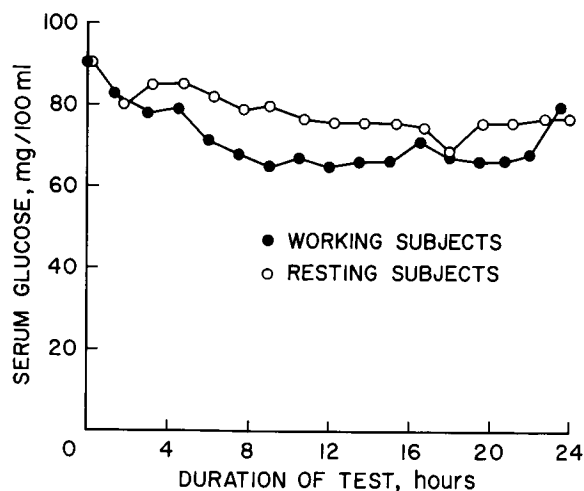


FIGURE 3.—Mean blood sugar at rest and during work.

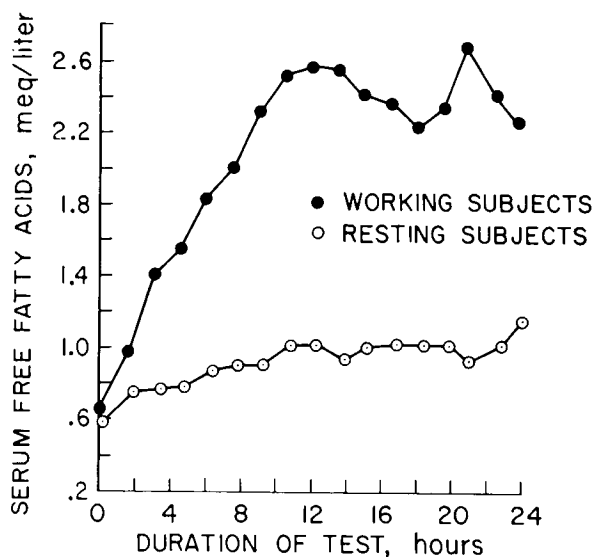


FIGURE 4.—Mean serum free fatty acids at rest and during work.

A preliminary examination of the blood and urine for nonprotein nitrogen content has shown that physical work does not increase protein breakdown in the body. Further biochemical tests are in progress to measure ketone-body production and to evaluate protein catabolism more fully.

Additional studies are being planned to test the hypotheses that (a) the relative constancy in the blood sugar level after 10 hours of treadmill walking is attributable, in part, to glucose synthesis which, accordingly, would be reflected in the body glycogen reserves; (b) the increased oxygen uptake shown during work is related to carbohydrate synthesis, particularly to the conversion of fats which are relatively poor in oxygen into oxygen-rich carbohydrates; and (c) increases in serum fatty acids are associated not only with the mobilization of lipids (palmitic and oleic) from the fat stores, but also with the production of short-chain (C_2 to C_7) fatty acids which may serve as direct precursors for carbohydrate synthesis. Furthermore, more sensitive psychological tests are being developed in order to assess the influence of progressive exhaustion and lack of sleep on reaction time, short-term memory, steadiness, and problem-solving ability and to correlate these with changes at the biochemical level.

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COMMENTS

DR. HELVEY: I am very much interested in the mechanism of this rise of the blood sugar content. Might it be that there is an irritation of the calamus scriptorius of the fourth ventricle liberating some reserves otherwise not acceptable in the liver?

DR. YOUNG: At the present time we are administering adrenalin. Presumably, if there is any liver glycogen there, it should be observed in the increase in blood sugar. These tests are only in process now and we have no data.

MR. ALLEN: What is being depleted in 24 hours of work?

DR. YOUNG: We do not measure body composition. We measure nitrogen excretion and there appears to be no unusual amount of nitrogen excretion so that must leave fat.

DR. JOHNSON: Were these men on a prescribed diet before these tests were given? If so, how long and what diet?

DR. YOUNG: We had no way of controlling the diet. We did provide a series of menus and make recommendations as to what they should eat but these individuals were from private contractors and private citizens and ate more or less what they wanted.

DR. VORIS: How many hours post-absorptive were tests made?

DR. YOUNG: The subjects ate at 7:00 in the evening. We started at 8:30 or 9:00 in the morning, so about 13 hours elapsed. They had no food during the day.

QUESTION: What was the approximate average weight loss during the course of the experiment?

DR. YOUNG: It varied from zero to as much as 5 pounds.

QUESTION: Did the subjects eat during the experiment?

DR. YOUNG: No, they had as much as 5 liters of water. We provided water and 5 grams of salt.