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Effectiveness of Carbohydrate Feeding in Delaying Fatigue during Prolonged Exercise

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Summary

Prolonged exercise in the fasted state frequently results in a lowering of blood glucose concentration, and when the intensity is moderate (i.e. 60-80% of $\dot{V}O_{2\max}$), muscle often becomes depleted of glycogen. The extent to which carbohydrate feedings contribute to energy production, and their effectiveness for improving endurance during prolonged exercise, are reviewed in this article.

Prolonged exercise (i.e. > 2 hours) results in a failure of hepatic glucose output to keep pace with muscle glucose uptake. As a result, blood glucose concentration frequently declines below 2.5 mmol/L. Despite this hypoglycaemia, fewer than 25% of subjects display symptoms suggestive of central nervous system dysfunction. Since fatigue rarely results from hypoglycaemia alone, the effectiveness of carbohydrate feeding should be judged by its potential for muscle glycogen sparing.

Carbohydrate feeding during moderate intensity exercise postpones the development of fatigue by approximately 15 to 30 minutes, yet it does not prevent fatigue. This observation agrees with data suggesting that carbohydrate supplementation reduces muscle glycogen depletion. It is not certain whether carbohydrate feeding increases muscle glucose uptake throughout moderate exercise or if glucose uptake is higher only during the latter stages of exercise.

In contrast to moderate intensity exercise, carbohydrate feeding during low intensity exercise (i.e. < 45% of $\dot{V}O_{2\max}$) results in hyperinsulinaemia. Consequently, muscle glucose uptake and total carbohydrate oxidation are increased by approximately the same amount. The amount of ingested glucose which is oxidised is greater than the increase in total carbohydrate oxidation and therefore endogenous carbohydrate is spared. The majority of sparing appears to occur in the liver, which is reasonable since muscle glycogen is not utilised to a large extent during mild exercise.

Although carbohydrate feedings prevent hypoglycaemia and are readily used for energy during mild exercise, there is little data indicating that feedings improve endurance during low intensity exercise. When the reliance on carbohydrate for fuel is greater, as during moderate intensity exercise, carbohydrate feedings delay fatigue by apparently slowing the depletion of muscle glycogen.

During the past half-century it has been repeatedly demonstrated that exercise of a moderate intensity (i.e. 60-80% of maximal oxygen uptake, $\dot{V}O_{2\max}$) cannot be maintained when carbohydrate stores within the body become depleted (Bergström et al., 1967; Christensen and Hansen, 1939). Fatigue usually occurs when the muscle glycogen concentration in the exercising musculature reaches a critically low level (Bergström et al., 1967). Occasionally, fatigue may occur before muscle glycogen is depleted due to the development of central nervous system distress (i.e. lightheadedness, weakness, nausea) in individuals who are sensitive to the lowering of blood glucose concentration during exercise (Christensen and Hansen, 1939; Coyle et al., 1983).

Since fatigue during exercise often results from carbohydrate depletion, there has been much interest in determining the extent to which carbohydrate feedings improve endurance. Recent studies have indicated that carbohydrate feedings can be of some value in delaying fatigue (Coyle et al., 1983; Ivy et al., 1983). The effectiveness of carbohydrate feedings will be discussed in terms of what is known about their ability to spare muscle and liver glycogen usage during exercise. Since few studies have directly measured muscle glycogen utilisation with and without carbohydrate feedings, it is necessary to discuss the effects of carbohydrate ingestion on glucose uptake and oxidation by muscle and theorise about the potential for glycogen sparing. The extent to which low blood glucose concentration, in itself, causes fatigue will also be reviewed.

1. Fatigue Due to Muscle Glycogen Depletion

In rested and well fed persons, a sufficient amount of muscle glycogen is available to fuel moderately intense exercise (i.e. 60-80% of $\dot{V}O_{2\max}$) for a duration of approximately 2 hours (Essen, 1977). Therefore, activities of shorter duration should not require carbohydrate supplementation. Exercise performed at higher intensities (i.e. 80-100% of $\dot{V}O_{2\max}$) can produce glycogen depletion

within a relatively brief period of time (Thomson et al., 1979). Such rapid muscle glycogenolysis also creates lactic acidosis and other metabolic imbalances which appear to be the primary causes of fatigue (Fitts and Holloszy, 1976). Therefore, in order for muscle glycogen depletion to be the primary cause of fatigue, exercise must be moderately intense and performed for 2 to 4 hours. It is during prolonged activities such as competitive road cycling, cross-country ski racing and distance running that carbohydrate feedings would have the greatest endurance-enhancing effect.

Endurance during moderate intensity exercise can be increased by raising muscle glycogen stores and decreased by lowering muscle glycogen (Bergström et al., 1967). The increased endurance results from the ability to exercise for a longer period of time before fatiguing and not from an ability to exercise at a higher steady-state intensity.

Low intensity exercise (i.e. 30-50% of $\dot{V}O_{2\max}$) relies predominantly upon fat for fuel and muscle glycogen is consumed at a slow rate (Essen, 1977; Pernow and Saltin, 1971). If muscle glycogen were to become depleted, it most probably would not occur during the first 5 to 10 hours of activity (Essen, 1977). Therefore, muscle glycogen-sparing treatments would not be required during low intensity exercise which does not rely heavily upon muscle glycogen.

2. Fatigue Associated with Liver Glycogen Depletion and Hypoglycaemia

2.1 Prevalence of Hypoglycaemia

More than 60 years ago Levine et al. (1924) observed that the blood glucose concentration can decline following prolonged and intense running to levels below 2.5 mmol/L (i.e. 45 mg/dl), which is considered to be 'frank' hypoglycaemia. This is not uncommon during prolonged exercise, especially cycling, performed in the fasted state. When exercise at 60 to 75% of $\dot{V}O_{2\max}$ is maintained for 2.5 to 3.5 hours, approximately half of the subjects studied have displayed frank hypoglycaemia (Ahlborg and Felig, 1982; Coyle et al., 1983; Felig et al., 1982). The extent to which this low blood glu-

cose deprives the central nervous system (CNS) of energy and causes severe stress and exhaustion has not been totally resolved.

2.2 Cause of Hypoglycaemia during Prolonged Exercise

Blood glucose concentration is dependent upon a balance between the rate at which glucose enters the blood and is removed by tissues in the body. Blood glucose concentration can decline as a result of a disproportionate uptake by tissue or a reduced entry of glucose into blood. Blood glucose concentration remains stable during the early portions of moderately intense exercise because glucose uptake by muscle and glucose output by the liver are comparable. The majority of glucose output by the liver is derived from the breakdown of liver glycogen (Wahren, 1977). The amount of glycogen stored in the liver in the postabsorptive state is relatively small (i.e. 70g) [Hultman and Nilsson, 1971]. As liver glycogen stores become depleted during prolonged exercise, liver glucose output declines, yet muscle glucose uptake is maintained. As a result of this imbalance, blood glucose levels decline (Ahlborg and Felig, 1982). Gluconeogenesis is accelerated during prolonged exercise, but this generally cannot totally compensate for the decline in liver glycogenolysis, at least during moderate exercise.

Glucose uptake by muscle and glucose output by liver both increase, as the intensity of exercise increases, at least up to 50 to 70% of $\dot{V}O_{2\text{max}}$ (Ahlborg and Felig, 1982; Pirnay et al., 1982; Wahren, 1977). This should accelerate liver glycogen depletion and hasten the time at which declining liver glucose output precipitates the fall in blood glucose concentration. Indeed, blood glucose concentration declines to within the range of frank hypoglycaemia (i.e. 2.5 mmol/L) after 3.5 hours of cycling at 58% of $\dot{V}O_{2\text{max}}$ compared with after 2.5 hours of exercise at 74% of $\dot{V}O_{2\text{max}}$ (Ahlborg and Felig, 1982; Coyle et al., 1983).

The development of hypoglycaemia during mild exercise is different from the pattern of blood glucose decline during more intense exercise. Blood

glucose declines later during low intensity exercise (i.e. 30-40% of $\dot{V}O_{2\text{max}}$) while the rate of decline is not as great and levels rarely drop below 2.8 mmol/L (Ahlborg and Felig, 1976; Young et al., 1967). Apparently, during low intensity exercise when the rate of glucose uptake is low, blood glucose levels can be maintained above 2.8 mmol/L through gluconeogenesis. Gluconeogenesis can account for almost half of the glucose output from the liver during prolonged low intensity exercise (Wahren, 1977).

2.3 Fatigue Caused by Hypoglycaemia

The classic work of Christensen and Hansen (1939) is often cited as providing evidence that frank hypoglycaemia can result in fatigue which appeared to be due to CNS dysfunction. They suggested CNS dysfunction because of the associated subjective symptoms which included lightheadedness, weakness and nausea. Apparently, exhaustion during moderate intensity exercise in the fasted state coincided with the development of hypoglycaemia, at which time their subjects displayed subjective symptoms which they interpreted to indicate CNS dysfunction (Åstrand and Rodahl, 1977). After ingesting 200g of glucose and resting for 15 minutes, blood glucose rose, the subjective symptoms disappeared, and the subjects were capable of exercising for another hour. Other investigators have reported that some hypoglycaemic individuals, when fatigued, display similar symptoms. When the symptoms are prevented through carbohydrate feedings, these individuals are able to continue exercising. These subjects generally represent fewer than 25% of the subjects studied (Coyle et al., 1983; Rodahl et al., 1964). Of the 7 subjects who became hypoglycaemic during exercise in a recent investigation (Felig et al., 1982), none displayed the symptoms indicative of CNS dysfunction when they became fatigued.

Therefore, it appears that the development of frank hypoglycaemia can produce subjective symptoms which may cause premature fatigue, only in some individuals who appear to be more sensitive to the lowering of blood glucose during exercise.

Although frank hypoglycaemia occurs frequently during prolonged intense exercise in the fasted state, these recent studies suggest that it does not frequently result in subjective symptoms severe enough to prevent the continuation of exercise.

Exercise-induced hypoglycaemia can also occur during the early stages of exercise begun with elevated blood insulin levels (Costill et al., 1977; Koivisto et al., 1981). Despite a rapid lowering of blood glucose concentration, the subjects appear to have remained asymptomatic of the subjective feelings of hypoglycaemia. Again, this indicates that a lowering of blood glucose during exercise, by itself, does not consistently cause fatigue due to CNS distress.

Fatigue during prolonged intense exercise often occurs at a time when blood glucose levels are low (Coyle et al., 1983; Levine et al., 1924). Since exhaustion rarely results from hypoglycaemia alone, and usually results from muscle glycogen depletion, it is likely that hypoglycaemia simply coincides with exhaustion due to the depletion of endogenous carbohydrate stores.

3. General Principles of Carbohydrate Feeding

3.1 Rationale

The purpose of carbohydrate ingestion during exercise is to provide a supplementary fuel source which can be oxidised in sufficient quantities to delay the time of carbohydrate depletion and fatigue. This implies that in order for carbohydrate feeding to be beneficial, the exercise task must normally result in fatigue due to muscle or liver glycogen depletion.

Clearly, dietary carbohydrate consumption and the type of exercise performed during previous days are the major determinants of muscle and liver glycogen concentration at the onset of exercise (Costill and Miller, 1981; Sherman, 1983). After maximising endogenous glycogen stores prior to exercise, carbohydrate feeding should be planned in an attempt to spare glycogen utilisation. Factors to consider in planning feedings are the type of carbohydrate and the timing of feedings.

3.2 Type of Carbohydrate Feeding

Various carbohydrate supplements have been studied, yet presently none have been found to be more effective than glucose or glucose polymers. Pyruvate and lactate have been infused into exercising rats because these carbohydrates readily diffuse across the sarcolemma. They can also serve as gluconeogenic precursors (Bagby et al., 1978). These substances actually accelerated muscle and liver glycogen depletion and hastened exhaustion due to a suppression of plasma free fatty acids and fat oxidation. Ingested glycerol, although not directly oxidisable by muscle, can be effectively converted to glucose within the liver of rats and the newly formed glucose can be used to spare muscle and liver glycogen and delay fatigue (Terblanche et al., 1981). However, glycerol ingestion is ineffective in humans because the human does not possess the ability to rapidly convert glycerol into glucose. Thus, the ingested glycerol accumulates within the body (Miller et al., 1983).

Fructose or sucrose (i.e. simple table sugar which is a disaccharide or glucose + fructose) ingestion during exercise probably does not offer any advantages over glucose ingestion since these substances are generally converted to glucose and metabolised as such. Ingested fructose enters the portal circulation where 70 to 90% is converted to glucose (Chen and Whistler, 1977) and thus little fructose is usually presented to the musculature for metabolism.

3.3 Time of Feedings

Glucose ingestion during the hour immediately prior to exercise leads to an elevation of insulin at the onset of exercise which has adverse effects on metabolism during the early stages of moderate to high intensity exercise (Costill et al., 1977; Koivisto et al., 1981). Under these conditions, blood glucose declines rapidly due to an insulin-potentiated and exercise-stimulated glucose uptake by muscle and prevention of an adequate rise in hepatic glucose output. Fat oxidation is also depressed and the exercising musculature relies more

heavily upon muscle glycogen due to the reduced availability of blood-borne substrates (Costill et al., 1977; Levine et al., 1983). Fatigue during prolonged exercise at 80% of $\dot{V}O_{2\max}$ occurs 19% sooner when glucose is ingested prior to exercise compared to water ingestion (Foster et al., 1979). These authors suggested that the more rapid fatigue may be due to a more rapid depletion of muscle glycogen, although muscle glycogen was not measured (Foster et al., 1979).

In contrast to moderate intensity exercise, glucose feeding prior to low intensity exercise does not appear to stress muscle metabolism since the availability of blood-borne substrates are not greatly affected (Ahlborg and Felig, 1977; Costill et al., 1977). First, hyperinsulinaemia at the onset of exercise at 30 to 50% of $\dot{V}O_{2\max}$ does not result in as great a decline in blood glucose, probably because less muscle is activated to clear the blood of glucose (Ahlborg and Felig, 1977; Jandrain et al., 1984). Secondly, the suppression of fat oxidation is compensated for by increased blood glucose oxidation and therefore muscle glycogen utilisation may not be accelerated.

The hyperinsulinaemia which is normally associated with glucose ingestion can be avoided or dramatically blunted if the glucose feeding is not given until exercise has been initiated (Coyle et al., 1983; Ivy et al., 1979). This is due to a catecholamine suppression of insulin release from the pancreas which is proportional to the intensity of exercise (Wright and Malaisse, 1968). Therefore, glucose feeding will have less of an effect upon suppressing fat oxidation, especially during moderate intensity exercise, if begun during exercise when catecholamines are elevated.

Fructose ingestion does not cause hyperinsulinaemia and when taken before exercise does not cause large perturbations in fuel homeostasis (Kõivisto et al., 1981; Levine et al., 1983). As discussed, however, the majority of ingested fructose is converted to and metabolised as glucose and there would be no expected benefit in ingesting fructose prior to exercise compared with ingesting glucose during exercise. If it were not possible to ingest glucose during exercise, fructose ingestion prior to ex-

ercise may aid in maintaining blood glucose concentration during exercise. Whether this actually spares muscle glycogen usage during exercise is controversial (Hargreaves et al., 1984a; Hughes et al., 1984; Levine et al., 1983).

3.4 Appearance of Ingested Glucose in Blood

When labelled glucose is ingested during exercise, small amounts of C^{14} appear in blood within 5 to 7 minutes (Costill et al., 1973). The contribution to the total blood glucose pool (which totals approximately 25 mmol or 4.5g) is initially quite small. The relative fraction of blood glucose which is derived from the ingested glucose increases with time and in proportion to the amount of the feeding (Costill et al., 1973; Van Handel et al., 1980). Peak concentration of labelled C^{14} glucose is reached within 30 minutes after ingesting a small load, but not until 90 minutes after ingesting larger loads. The relative fraction derived from the ingested glucose is 27, 42, and 67% after 10, 32 and 42g glucose loads. Whether larger doses result in blood glucose replacement which is predominantly supplied exogenously has not been determined. This is likely, however, because feedings suppress liver glycogenolysis (Bagby et al., 1978) and gluconeogenesis (Ahlborg and Felig, 1976), the pathways by which glucose normally enters into blood. Collectively, these studies indicate that after 60 to 90 minutes of exercise, ingested glucose can functionally replace the liver, to a large extent, in supplying blood glucose for exercise.

4. Evidence that Carbohydrate Feeding Can Delay Fatigue

4.1 During Exercise at 60 to 75% of $\dot{V}O_{2\max}$

There have been a number of previous studies of the effects on endurance of carbohydrate administration during exercise. One approach has been to give glucose after fatigue has developed. This procedure has not, in the absence of hypoglycaemia, resulted in a reversal of fatigue during mod-

erately strenuous exercise (Galbo et al., 1979; Nazar et al., 1972). This finding provides evidence that glucose uptake into muscle is too slow for blood glucose to serve as the major source of carbohydrate for muscle during exercise requiring 70% or more of $\dot{V}O_{2\max}$. It is also in keeping with the concept that strenuous exercise cannot be continued after muscle glycogen is depleted (Bergström et al., 1967; Hermansen et al., 1967).

Another approach has been to begin glucose polymer feedings during the early stages and continue feeding throughout exercise at 70 to 74% of $\dot{V}O_{2\max}$ (Coyle et al., 1983; Ivy et al., 1979). As a result, hyperinsulinaemia is avoided and blood glucose and insulin are maintained at basal levels throughout exercise with feedings. Since blood glucose and insulin decline during exercise in the fasted state, this results in a 20 to 50% higher blood glucose and plasma insulin concentration when carbohydrate feedings are provided. The blood glucose differences are greatest during the latter portions of exercise.

Using this approach, Ivy et al. (1979) had cyclists attempt to maximise work output during 2 hours of isokinetic cycling. Although no difference in total work output was observed, they noted that during the last 30 minutes of exercise, the subjects were able to maintain or even increase their initial work rate when fed carbohydrate, yet they began to fatigue during this period when fasted. Therefore, 11% more work was performed during the 90- to 120-minute period of exercise when fed. These findings indicate that feedings begin to exert a beneficial influence upon endurance during the 90- to 120-minute period of intense exercise and prompted Coyle et al. (1983) to study subjects for longer periods.

Coyle et al. (1983) asked experienced cyclists to exercise at 74% of $\dot{V}O_{2\max}$ for as long as possible. When they were no longer able to maintain this work rate, they were permitted to reduce the exercise intensity and select the highest work rate they thought they could maintain for at least another 10 minutes. As shown in figure 1 (top panel: subgroup A), the initial exercise intensity was maintained during the first 90 to 120 minutes of exercise, after

which the work rate began to decline when the subjects were fed placebo solutions. In contrast, carbohydrate feeding (CHO) allowed these subjects to maintain their initial work rate for a longer period of time. Fatigue was defined as the time at which work rate declined 10% below the initial intensity.

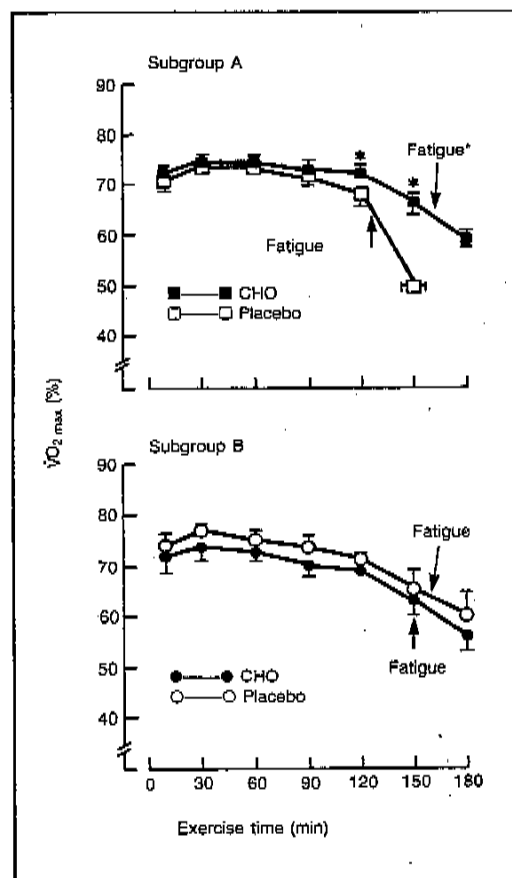


Fig. 1. Work Intensity (% $\dot{V}O_{2\max}$) that could be maintained during exercise with (CHO) and without (placebo) carbohydrate feeding in subjects who displayed a decline in blood glucose concentration during exercise without carbohydrate feeding (subgroup A) and those who did not (subgroup B). Arrows denote mean time to fatigue (i.e. reduction in work rate by 10% of $\dot{V}O_2$). Significantly different from placebo ($p < 0.01$) [from Coyle et al. (1983)].

In the entire group, fatigue occurred after 134 minutes in the placebo trial compared with 157 minutes when carbohydrate feedings were provided ($p < 0.01$). As in the study of Ivy et al. (1979), work output at 120 minutes was not significantly different, yet because divergences occurred after this time, the carbohydrate-fed group performed progressively more work with increasing duration. After 150 minutes, the subjects had performed 6.6% more work when fed carbohydrate compared with placebo.

The findings of Coyle et al. (1983) indicate that carbohydrate feedings can delay the development of fatigue during moderate exercise which is longer than 2 hours in duration. The observation that carbohydrate feedings do not prevent fatigue is consistent with the concept that blood glucose cannot be utilised at a fast enough rate to provide all the carbohydrate requirements for exercise of this intensity. Of the 10 subjects studied by Coyle et al. (1983), the 7 subjects who benefited from the carbohydrate feeding displayed a lowering of blood glucose during exercise when fasted. Fatigue was associated with symptoms of hypoglycaemia in only 2 of these subjects while the remainder complained primarily of severe weariness in the working muscles, which is suggestive of glycogen depletion. This indicates that carbohydrate feeding may have delayed fatigue in these subjects by slowing muscle glycogen depletion.

Blood glucose did not decline in the other 3 subjects during exercise when fasted. The exercise time to fatigue in these same 3 subjects (denoted as subgroup B in figure 1) was not affected by the carbohydrate feedings. This indicates that a 20 to 40% elevation of blood glucose and the maintenance of insulin at resting basal levels (which is 20-50% higher than observed during prolonged exercise) may not spare muscle glycogen unless it is compared with exercise which results in a lowering of blood glucose. It is possible that the lowering of blood glucose accelerates muscle glycogen usage and hastens fatigue. It is also possible that fatigue can be delayed if blood glucose is maintained during the latter stages of exercise when muscle glycogen concentration is already low.

Other investigators have measured endurance during exercise with and without carbohydrate feeding. Brooke et al. (1975) found that cyclists were capable of exercising for 19% longer (180 vs 214 min) when fed glucose syrup, compared with low energy drinks (which did not elevate blood glucose). Oxygen consumption, however, was 7% lower when the glucose feedings were provided, making the significance of these findings difficult to interpret.

Felig et al. (1982) recently concluded that glucose feeding during bicycle ergometer exercise at 60 to 65% of $\dot{V}O_{2\max}$ does not consistently delay exhaustion. The subjects in this study were not experienced cyclists and there was a large amount of variability in response due to motivation and learning. This was apparent in that 13 of 19 subjects increased their endurance on the second trial when provided with a monetary incentive. However, in each of the comparisons, the exercise times were longer with glucose feeding; the average increases in exercise time ranged from 7 to 13 minutes. Due to the tremendous variability in response, it is not surprising that these differences were not statistically significant.

4.2 During Exercise at 30 to 50% of $\dot{V}O_{2\max}$

In contrast to the heavy reliance on muscle glycogen during strenuous exercise, most of the energy for exercise requiring less than 50% of $\dot{V}O_{2\max}$ is provided by oxidation of fat and blood glucose, while muscle glycogen plays a minor role and undergoes minimal depletion (Essen, 1977). Additionally, there is little evidence to indicate that low intensity exercise is limited due to a lowering of blood glucose (Young et al., 1967). Although liver glycogen stores are lowered, gluconeogenesis can account for almost half of the glucose output by the liver and therefore frank hypoglycaemia is rarely encountered (Ahlborg and Felig, 1976; Wahren, 1977; Young et al., 1967). After 13 hours of walking at 33% of $\dot{V}O_{2\max}$, men can still supply sufficient quantities of endogenous glucose to maintain the carbohydrate requirements of exercise (Young

et al., 1967). As discussed below, there is much evidence indicating that carbohydrate feeding during mild exercise increases the amount of energy derived from blood glucose with a proportional lowering of fat oxidation (Ahlborg and Felig, 1976). Whether carbohydrate feedings, which generally replace fat oxidation with glucose oxidation, are required to maintain very prolonged (i.e. > 13h) mild exercise (i.e. < 40% of $\dot{V}O_{2\max}$) remains to be determined.

Ivy et al. (1983) recently demonstrated that the length of time that subjects can walk uphill is increased from 4.5 hours when fasted to 5.0 hours when fed glucose polymers. Although the subjects were exercising at only 47% of $\dot{V}O_{2\max}$ (measured while running), they relied predominantly upon carbohydrate for energy as reflected by the respiratory exchange ratio. The authors suggested that the work may have been isolated to a relatively small muscle mass, unlike during running, and that muscle glycogenolysis was stimulated to a greater extent than predicted from the percentage of $\dot{V}O_{2\max}$. Assuming that local muscular glycogen depletion resulted in fatigue in these subjects, these findings agree with the findings during exercise at 70% of $\dot{V}O_{2\max}$ and suggest that carbohydrate feedings delay fatigue by sparing muscle glycogen utilisation. These findings also indicated that the potential of carbohydrate feeding in delaying fatigue should be judged by the degree to which the activity relies upon carbohydrate for fuel, especially when isolated to a relatively small muscle mass.

5. Evidence that Carbohydrate Supplementation Spares Muscle Glycogen Utilisation

To our knowledge, there have been only 2 full investigations of glycogen utilisation in men during exercise with and without carbohydrate supplementation. Bergström and Hultman (1967) infused glucose during intermittent high intensity one-legged cycling which normally resulted in glycogen depletion within 60 minutes. Glucose was infused at a high rate (18.5 mmol/min), which was in ex-

cess of the total energy requirements of exercise and which produced a 6-fold increase in blood glucose concentration. This large glucose load resulted in 25% less glycogen utilisation compared with exercise without glucose infusion. At the time of this investigation, a 25% sparing of muscle glycogen was not considered impressive, especially since a purpose of this study was to determine whether the total carbohydrate requirements of intense exercise could be provided from blood glucose. A slowing of glycogen depletion by this amount, however, would theoretically have the effect of postponing the time of glycogen depletion from 60 minutes to approximately 85 minutes during their exercise bout (Bergström and Hultman, 1967; fig. 1). This amount of glycogen sparing and the theorised extent to which fatigue would be postponed, generally agrees with the observations of Coyle et al. (1983) and Ivy et al. (1983) who observed that carbohydrate feeding delayed fatigue during prolonged exercise.

Recently, Hargreaves et al. (1984b) measured glycogen utilisation during 4 hours of cycling with and without hourly feedings of sucrose. The exercise involved 8 repetitions of 20 minutes of exercise at 50% of $\dot{V}O_{2\max}$, followed by 10 minutes of intense intermittent exercise (30 sec at 100% $\dot{V}O_{2\max}$, followed by 2 min of rest). Glycogen concentration after 1 hour of exercise was actually 20% lower when feedings were provided; this difference was greater than what can be attributed to differing initial muscle glycogen levels. This suggests that feedings are not effective in sparing muscle glycogen use during the early portions of this type of prolonged exercise. However, glycogen consumption during the 1- to 4-hour period of exercise with the feedings was much lower and therefore the total glycogen reduction was lower. In terms of performance, the subjects were able to exercise at 100% of $\dot{V}O_{2\max}$ for 45% longer (i.e. 126.8 sec vs 87.2 sec; feeding vs water, respectively) when carbohydrate was ingested.

These 2 studies indicate that elevation of blood glucose during intermittent exercise results in less net glycogen depletion during the entire bout of exercise and they suggest that this sparing effect may occur during the latter stages of exercise

(Bergström and Hultman, 1967; Hargreaves et al., 1984b). It is possible that the net glycogen reduction with carbohydrate supplementation could be lower in both of these studies due to glycogen re-synthesis during the rest periods when fed. Although there is no direct information in humans during continuous exercise, Bagby et al. (1978) have provided strong evidence in rats which indicates that carbohydrate supplementation during continuous exercise results in a slowing of muscle glycogen depletion.

6. Blood Glucose Uptake and Oxidation during Exercise

Since direct measurements in humans of glycogen usage during continuous exercise with and without carbohydrate supplementation are not yet available, we must rely upon indirect information regarding the potential carbohydrate-sparing effects of glucose feedings. With this approach, we will review studies which have traced the fate of glucose ingested during exercise and determine the extent to which this exogenous glucose contributes directly to energy metabolism and then calculate whether this might spare endogenous muscle and liver glycogen stores.

6.1 Low Intensity Exercise ($< 50\%$ of $\dot{V}O_{2\max}$)

Glucose feeding during exercise at 30 to 50% of $\dot{V}O_{2\max}$ results in a 60% elevation of blood glucose and more than a 2-fold increase in plasma insulin concentration (Ahlborg and Felig, 1976). Ahlborg and Felig (1977) observed hyperinsulinaemia to result in a 2.5-fold greater glucose uptake by the exercising leg at a time when blood glucose was at normal fasting levels. On the other hand, marked hyperglycaemia in the absence of hyperinsulinaemia does not increase leg glucose uptake during exercise (Wahren et al., 1975). These findings indicate that the hyperinsulinaemia accompanying glucose feeding is the major factor responsible for increasing leg glucose uptake during low intensity exercise.

Total carbohydrate oxidation normally contributes less than one-third of the energy for low intensity exercise, yet following carbohydrate feeding as much as 50 to 65% of the energy is obtained from carbohydrate oxidation (Ahlborg and Felig, 1976; Benade et al., 1973a). This increase in carbohydrate oxidation is derived by increasing leg glucose uptake from a normal fasting value of approximately 2.0 mmol/min up to 3.5 mmol/min (Ahlborg and Felig, 1976). With the increase in blood glucose uptake there is a concomitant decline in fat oxidation and therefore muscle glycogen usage should not be affected.

Other studies which have simultaneously determined both total and exogenous carbohydrate oxidation following carbohydrate feeding have observed exogenous utilisation to increase more than total oxidation (Pirnay et al., 1977). This indicates that endogenous carbohydrates are being spared at a rate of roughly 1.7 to 2.8 mmol/min (Pirnay et al., 1977). These calculations are based upon whole body respiratory measurements. Thus, it is not possible to distinguish between a sparing of liver or muscle glycogen. Since the additional glucose which is taken up by the legs appears to provide for the increased total oxidation, it is unlikely that muscle glycogen is spared to a significant extent (Ahlborg and Felig, 1976). It is more likely, however, that the ingested glucose replaces liver glycogen as the carbohydrate source which maintains blood glucose concentration. This seems possible since the normal rate of glucose output by the liver during low intensity exercise is approximately 2.0 mmol/min, which, if suppressed through feedings, would agree with the rate of endogenous carbohydrate sparing reported by Pirnay et al. (1977).

When 100g of glucose or sucrose are ingested during exercise at 50% of $\dot{V}O_{2\max}$, approximately half of the ingested amount is oxidised during the 2-hour period following ingestion, irrespective of when during exercise the feeding was consumed (Benade et al., 1973; Krzentowski et al., 1984; Pirnay et al., 1977). Peak oxidation occurs during the second hour following ingestion. When 200g are ingested, the rate of glucose presentation to muscle does not increase proportionately suggesting that

the splanchnic bed (primarily the liver) retains a large portion of an ingested glucose meal for disposal at a later time (Ahlborg and Felig, 1976). By the fourth hour following ingestion of 100g of glucose, almost all of the ingested glucose is apparently oxidised (Krzentowski et al., 1984; Pirnay et al., 1977). Less of the ingested glucose appears as expired CO_2 when small amounts are consumed (10-42g) and the collection period is only 1 hour long (Costill et al., 1973; Van Handel et al., 1980).

Based upon a collective interpretation of the data currently available, it appears that carbohydrate feeding during low intensity exercise (i.e. 30-50% of $\dot{V}\text{O}_{2\text{max}}$) spares liver glycogen utilisation and increases total carbohydrate oxidation by increasing leg glucose uptake. However, the amount of muscle glycogen sparing is probably small. This is logical since muscle glycogen is not utilised to a large extent during this type of exercise. The rationale for carbohydrate feeding during mild exercise would be to maintain liver glycogen and elevate blood glucose concentration. This may not affect endurance, however, since hypoglycaemia is not usually a concern during this type of exercise (Young et al., 1967).

6.2 Moderate Intensity Exercise (50-80% of $\dot{V}\text{O}_{2\text{max}}$)

As the intensity of exercise increases from 50 to 70% of $\dot{V}\text{O}_{2\text{max}}$, total carbohydrate oxidation increases predominantly through increased muscle glycogenolysis. There is less information regarding the extent to which blood glucose uptake and oxidation are increased. Wahren et al. (1971) observed leg glucose uptake to increase with increasing exercise intensity with peak uptake values of 4 mmol/min. During prolonged exercise at 58% of $\dot{V}\text{O}_{2\text{max}}$ when fasted, leg glucose uptake is approximately 3.6 mmol/min compared to 2.5 mmol/min during exercise at 30% of $\dot{V}\text{O}_{2\text{max}}$ (Ahlborg and Felig, 1982). Interestingly, this value is similar to the rate of glucose uptake during low intensity exercise when blood glucose and insulin are elevated (Ahlborg and Felig, 1976). There have been no studies of leg glucose uptake during moderate

intensity exercise when glucose is ingested. It can not be very high since the total carbohydrate requirements of exercise at 70% of $\dot{V}\text{O}_{2\text{max}}$ can not be provided from blood glucose alone.

Along these lines, Pirnay et al. (1982) observed that the rate of oxidation of ingested glucose did not increase as exercise intensity increased from 51 to 64% of $\dot{V}\text{O}_{2\text{max}}$. This may indicate that the maximal rate of glucose entry into, and oxidation by muscle does not increase with this increase in exercise intensity. It is also possible, however, that less of the ingested glucose was made available to muscle for oxidation with increasing exercise intensity. The maximal rate of total exogenous glucose oxidation was approximately 4 mmol/min. Assuming the large majority of glucose in the blood was derived from the ingested glucose, it is interesting that the maximal reported rates of leg glucose uptake (Ahlborg and Felig, 1976, 1982; Wahren et al., 1971) agree fairly well with this maximal rate of oxidation (Pirnay et al., 1982).

Carbohydrate feeding during exercise at 70% or more of $\dot{V}\text{O}_{2\text{max}}$ does not cause hyperinsulinaemia (Coyle et al., 1983; Ivy et al., 1979). Insulin concentration remains at fasting basal levels instead of declining 20 to 50% as occurs during prolonged exercise when fasted. Additionally, there is only a modest reduction in the exercise-induced increase in plasma free fatty acids. In contrast to low intensity exercise, there is no change in the proportion of energy derived from carbohydrate oxidation, as reflected in the respiratory exchange ratio (Coyle et al., 1983; Ivy et al., 1979). This could mean that insulin levels are not elevated enough to stimulate increased glucose uptake by muscle and increased carbohydrate oxidation. On the other hand, if glucose uptake is increased and total carbohydrate oxidation remains unchanged, muscle glycogen utilisation would be reduced. Based upon the findings of Bergström and Hultman (1967), who found 25% less muscle glycogen depletion during exercise with glucose infusion, it would appear that blood glucose uptake is increased above fasting levels during some period. It is not certain, however, whether glucose supplementation increases glucose uptake above fasting levels throughout the

exercise period or if greater uptake occurs during the latter stages of exercise. This information would dictate when during prolonged intense exercise it is most beneficial to elevate blood glucose and insulin.

There are data in humans which suggest that leg glucose uptake is accelerated when glycogen stores become depleted and that glucose uptake is higher when feedings are provided. Gollnick et al. (1981) reported that the extraction of glucose by the exercising leg, and estimated leg glucose uptake, are related to the percentage of muscle fibres which are empty of glycogen. Estimated leg glucose uptake increased 2-fold towards the end of exercise when glycogen stores were almost depleted. When glycogen-depleted subjects exercise intensely, blood lactate levels are 2-fold higher and carbohydrate oxidation increases dramatically when glucose feedings are provided compared with when fasted (Bonen et al., 1981). This suggests that blood glucose uptake might be capable of increasing to relatively high levels when glycogen-depleted subjects exercise at moderate to high intensities. If increased leg glucose uptake does occur during the latter stages of exercise, although it does not appear capable of providing for the total carbohydrate requirements of intense exercise, it may slow the depletion of the remaining muscle glycogen. This theory would agree with the observations that fatigue due to glycogen depletion can be delayed somewhat by carbohydrate feeding but cannot be prevented.

7. Practical Implications for Endurance Performance

Individuals who are exercising at a moderate intensity (i.e. 60-80% $\dot{V}O_{2max}$) for more than 2 hours, and who are fatigued due to muscle glycogen depletion, are likely to benefit from carbohydrate supplementation during exercise. This is especially true of individuals who normally display a lowering of blood glucose concentration during prolonged exercise. However, carbohydrate feedings should not be taken until exercise has begun. Since carbohydrate feedings can also compromise fluid

replacement, due to a slowing of gastric emptying, carbohydrate supplementation should not take precedence over fluid replacement during exercise in a hot environment. When fluid replacement is not a concern, we recommend that feeding take place every 20 to 30 minutes during prolonged exercise.

In a recent study (Coyle et al., 1983), we fed cyclists approximately 140ml of a concentrated carbohydrate solution (i.e. 50% by weight solution of glucose polymers) after 20 minutes of exercise. We then provided them with approximately 300ml of a 6% polymer solution every 30 minutes throughout the exercise bout. This feeding schedule was effective in maintaining an elevated blood glucose concentration and delaying the development of fatigue.

8. Conclusions

Prolonged exercise (i.e. > 2h) results in a failure of hepatic glucose output to keep pace with muscle glucose uptake. As a result, blood glucose concentration frequently declines below 2.5 mmol/L. Despite this hypoglycaemia, fewer than 25% of subjects display symptoms suggestive of central nervous system dysfunction. Since fatigue rarely results from hypoglycaemia by itself, the effectiveness of carbohydrate feeding should be judged by its potential for muscle glycogen sparing.

Carbohydrate feeding during moderate intensity exercise postpones the development of fatigue by approximately 15 to 30 minutes, yet it does not prevent fatigue. This observation agrees with data suggesting that carbohydrate supplementation reduces muscle glycogen depletion. It is not certain whether carbohydrate feeding increases muscle glucose uptake throughout moderate exercise or if glucose uptake is higher only during the latter stages of exercise.

In contrast to moderate intensity exercise, carbohydrate feeding during low intensity exercise (i.e. < 45% of $\dot{V}O_{2max}$) results in hyperinsulinaemia. Consequently, muscle glucose uptake and total carbohydrate oxidation are increased by approximately the same amount. The amount of ingested

glucose which is oxidised is greater than the increase in total carbohydrate oxidation and therefore endogenous carbohydrate is spared. The majority of sparing appears to occur in the liver, which is reasonable since muscle glycogen is not utilised to a large extent during mild exercise.

In summary, although carbohydrate feedings prevent hypoglycaemia and are readily used for energy during mild exercise, there is little data indicating that feedings improve endurance during low intensity exercise. When the reliance on carbohydrate for fuel is greater, as during moderate intensity exercise, carbohydrate feedings delay fatigue by apparently slowing the depletion of muscle glycogen.

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