Update on Carbohydrate: Solid Versus Liquid

Ellen Coleman

Athletes often train or compete in athletic events that significantly reduce muscle and liver glycogen reserves. Carbohydrate ingestion before or during endurance exercise enhances performance by maintaining blood glucose levels and carbohydrate utilization. Also, an adequate intake of carbohydrate following endurance exercise helps to restore muscle and liver glycogen. This paper reviews the physiologic and performance benefits of solid versus liquid carbohydrate feedings before, during, and following endurance exercise. Solid and liquid carbohydrates are equally effective in raising blood glucose and enhancing performance when consumed during endurance exercise. Also, both forms of carbohydrate are similarly beneficial in promoting muscle glycogen synthesis after exercise. It is unclear whether solid and liquid carbohydrate feedings have the same effect on serum glucose and performance when consumed before exercise. Although limited research suggests that a low glycemic solid carbohydrate may represent the best preexercise meal choice, further research is needed to support this hypothesis.

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The depletion of endogenous carbohydrate stores (muscle and liver glycogen and blood glucose) is a primary limiting factor in prolonged endurance exercise. Consuming carbohydrate prior to or during endurance exercise can improve endurance performance by maintaining blood glucose levels and carbohydrate oxidation when muscle glycogen levels are low (5, 23). Furthermore, consuming adequate carbohydrate following endurance exercise is necessary to replenish muscle and liver glycogen between daily exercise sessions or competitive events (4).

Considerable research has focused on the physiologic effects and performance benefits of carbohydrate ingestion before, during, and following endurance exercise. Although previous studies have demonstrated the effectiveness of various liquid (5, 6, 11, 22, 23) and solid (9, 18, 24) carbohydrate feedings, only a few studies (15, 17, 18, 20) have directly compared the physiologic and performance effects of liquid and solid carbohydrate feedings.

This review will evaluate the physiologic and performance effects of ingesting solid and liquid carbohydrates before, during, and after exercise to answer the following three questions: Do liquid and solid carbohydrates have the same effect on blood glucose and endurance performance when consumed before exercise? Do liquid and solid carbohydrates have the same effect on blood glucose
and endurance performance when consumed during exercise? And lastly, do liquid and solid carbohydrates have the same effect on glycogen synthesis when consumed following exercise?

**Proposed Differences Due to Carbohydrate Form**

Factors influencing blood glucose responses to ingested carbohydrate include gastric emptying, digestion, and intestinal absorption. Differences in gastric emptying between liquids and solids may be used to propose that a specific carbohydrate form be ingested at a specific time relative to exercise. At rest, solid food empties from the stomach more slowly than does liquid food (14). The slower gastric emptying rate of solid carbohydrate foods may provide a slow, sustained release of glucose. The faster gastric emptying rate of liquid carbohydrate foods may elevate blood glucose levels more quickly and to a greater extent.

If this is the case, then solid carbohydrates may represent a better preexercise food choice than liquid carbohydrates by providing a more continuous supply of glucose during exercise. However, liquid carbohydrates may be a better choice during and after exercise due to their ability to rapidly elevate blood glucose to high levels, thereby enhancing endurance and promoting glycogen repletion. If solid and liquid carbohydrates provide similar blood glucose responses, then no difference in performance or glycogen repletion would be expected.

**Glycemic Index**

The glycemic index classifies carbohydrate-rich foods according to the degree to which they increase blood glucose concentration. The glycemic index is based on the total area under the blood glucose response curve during the 2-hour period after the food is consumed, compared with the standard response of an equivalent carbohydrate amount (50 g) of white bread (13).

The glycemic index is determined by the rate at which the ingested carbohydrate is made accessible to intestinal enzymes for hydrolysis and absorption. This is a function of the gastric emptying rate (16) and the physical availability of the starch or sugar to hydrolytic enzymes (19). A number of factors are known to influence the digestion and absorption of starch in the intestine. These include cooking, which alters the integrity of the starch granule (26), the degree of gelatinization (19), and the amylose/amylopectin ratio (1).

In practical terms, the glycemic index is influenced by the form in which the food is eaten, its fiber content, the presence of protein and fat, and food processing and preparation methods. It is a misconception to believe that the glycemic index is a function of whether the carbohydrate is a starch or simple sugar. For example, a baked potato has a glycemic index of 135, which is almost identical to the glycemic index value of 138 for glucose (13). It is also misleading to think that the glycemic index is a function of whether the carbohydrate is in a liquid or solid form. An orange has a glycemic index of 66, which is similar to the glycemic index value of 67 for orange juice (13).

The glycemic index concept is not without limitations. The data now available are largely based on tests using single foods. Foods with high glycemic indexes do not affect the glycemic response when given in mixed meals. The glycemic index is based on a percentage change in blood glucose, whereas
changes in mg/dl have more clinical utility. Also, the glycemic index is based on equal grams of carbohydrate, not average portion sizes. In spite of these limitations, the glycemic index may be helpful for "fine tuning" food choices.

**Glycemic Index and Exercise Performance**

It may be speculated that low glycemic index foods confer an advantage when eaten before prolonged endurance exercise. Low glycemic foods may provide a slow-release source of glucose to the blood (without an accompanying insulin surge) that may not be available after a high glycemic food.

It may also be proposed that high glycemic foods confer an advantage when ingested before and following exercise. High glycemic foods may elevate blood glucose and delay fatigue by providing a fast carbohydrate source for the exercising muscles when muscle glycogen levels are low. Also, following exercise, high glycemic foods may maintain blood glucose at high levels, thereby promoting glycogen repletion better than low glycemic foods.

**Carbohydrate Feedings and Exercise**

**The Hour Before Exercise**

Early research by Costill et al. (3) indicated that consuming 75 g of liquid glucose 30 min prior to treadmill exercise (30 min at 70% of VO₂max) caused hypoglycemia and accelerated glycogen depletion. Following this, research by Foster et al. (8) suggested that consuming 75 g of liquid glucose 30 min prior to cycling at 80% of VO₂max reduced exercise time by 19% due to elevated carbohydrate oxidation and impaired free fatty acid mobilization.

The results of these studies led to the recommendation that athletes avoid consuming sugar (solid or liquid) prior to exercise. It was originally believed that performance would be impaired as a result of hypoglycemia or an accelerated rate of muscle glycogen utilization due to elevated insulin levels. However, a greater rate of muscle glycogenolysis following preexercise carbohydrate feeding and impaired performance have not been confirmed in subsequent experiments (10).

It appears that the hypoglycemia following preexercise carbohydrate feedings is transient and probably will not harm performance unless the individual is susceptible to a lowering of serum glucose. Hargreaves et al. (10) compared the ingestion of liquid glucose (high glycemic) and liquid fructose (low glycemic) 45 min before exercise. The subjects cycled at 75% of VO₂max to exhaustion. Even though blood glucose and serum insulin levels were more stable in the fructose and placebo trial, there were no differences in exercise time to exhaustion or muscle glycogen utilization between the trials.

In fact, preexercise carbohydrate feedings may actually enhance endurance performance. Sherman et al. (23) compared the ingestion of 1.1 g/kg and 2.2 g/kg of liquid carbohydrate one hour prior to exercise. The subjects cycled at 70% VO₂max for 90 min, and then underwent a performance trial. The performance trial required the subjects to complete the number of revolutions equivalent to another 45 minutes of cycling at 70% of VO₂max as quickly as possible. Serum insulin was elevated both at the start of and during exercise, and blood glucose
initially decreased. However, time-trial performance was significantly improved
12.5% by the carbohydrate feedings, presumably via increased carbohydrate
oxidation.

Although the research findings are equivocal regarding carbohydrate inges-
tion 30–60 min before exercise, only one study has reported a negative effect
(8) and several studies have shown a positive effect (23, 25). Thus, preexercise
carbohydrate feedings consumed in the hour before exercise may improve endur-
ance performance via an enhanced carbohydrate availability.

Does the glycemic index of the preexercise carbohydrate feeding make a
difference? Only one study has evaluated the affect of glycemic index on exercise
performance. Thomas et al. (24) compared the consumption of 1 g of car-
bohydrate/kg of lentils (low glycemic), potato (high glycemic), and glucose one
hour prior to exercise. The subjects cycled to exhaustion at 65–70% of VO₂max.
Compared to the potato and glucose, the lentil feeding provided a more gradual
rise and fall in blood glucose. Endurance time was 20 min longer for the low
glycemic lentils than for all other trials, which were not different from each
other. A low glycemic preexercise meal may improve endurance by producing
less postprandial hyperglycemia and hyperinsulinemia and by maintaining plasma
glucose at higher levels during critical periods of exercise.

Does the form of the preexercise carbohydrate feeding make a difference?
Neuffer et al. (18) compared the consumption of 45 g of solid carbohydrate and
45 g of liquid carbohydrate 5 min before exercise. The subjects cycled for 45
min at 77% of VO₂max, followed by a performance ride. For the performance
ride, the subjects were transferred to an isokinetic cycle ergometer and asked to
produce as much work as possible in 15 min. The liquid and solid carbohydrate
feedings improved performance and elevated serum glucose compared to the
placebo but were not significantly different from each other.

However, carbohydrate feedings several minutes before exercise cannot be
compared to carbohydrate feedings 30–60 min prior to exercise (2). Since plasma
glucose and insulin levels typically peak 30–60 min after carbohydrate consump-
tion, the serum glucose response and performance effects of consuming carbohy-
drate a few minutes before exercise are very similar to consuming carbohydrate
during exercise. To date, no study has directly compared solid and liquid carbohy-
drate ingestion 30–60 min before exercise.

The study by Thomas et al. (24) suggests that a low glycemic solid carbohy-
drate feeding may be a better preexercise food choice than a high glycemic solid
or liquid carbohydrate because a low glycemic solid feeding provides a more
continuous supply of glucose during exercise. Additional, well-controlled research
studies are needed to confirm this hypothesis. In addition, if the goal is to provide
a continuous supply of glucose during exercise, the athlete should consume
carbohydrate during exercise (25).

4 Hours Before Exercise

In contrast to the equivocal effect on performance of ingesting carbohydrate in
the hour before exercise, several studies (18, 22) have reported that consuming
carbohydrate 4 hours before exercise enhances performance. This improvement,
however, is less than when smaller quantities of carbohydrate are consumed
during exercise itself (25).
Neuffer et al. (18) evaluated the effect of a 200 g carbohydrate mixed meal consumed 4 hours before cycling exercise, combined with a 45 g solid carbohydrate feeding 5 min before exercise. This trial was in addition to the two 45 g solid and liquid carbohydrate feedings provided 5 min prior to exercise. The subjects cycled for 45 min at 77% of VO$_{2\text{max}}$, followed by the 15 min performance ride on an isokinetic bike, as previously described. Total work produced during the performance trial was significantly greater for the meal plus the solid carbohydrate feeding compared to all other trials.

Sherman (22) evaluated the effect of a 312 g, 156 g, and 45 g liquid carbohydrate feeding 4 hours prior to exercise. Interval cycling was undertaken for 95 min, followed by a performance trial after a 5 min rest. The performance trial required the subjects to complete the number of revolutions equal to another 45 min at 70% of VO$_{2\text{max}}$ as quickly as possible. The 312 g feeding provided 4.5 g of carbohydrate/kg, the 156 g feeding provided 2 g of carbohydrate/kg, and the 45 g feeding provided .6 g of carbohydrate/kg. The 312 g carbohydrate feeding improved performance by 15%, despite elevated insulin levels at the start of and during exercise.

The reason for improvement following carbohydrate feedings 4 hours before exercise is not well established but may be related to the "topping off" of muscle and liver glycogen stores. Also, because the carbohydrate is absorbed over a longer period of time, a large carbohydrate load consumed 4 hours before exercise may continue to provide glucose into the bloodstream during exercise. The performance benefits of a preexercise carbohydrate feeding appear to be additive to those of consuming carbohydrate during exercise (25). This implies that these two nutritional strategies operate by different mechanisms (2).

Does the form of carbohydrate consumed 4 hours before exercise make a difference? To date, no study has directly compared liquid and solid carbohydrate feedings 4 hours before exercise, though a 200 g carbohydrate mixed meal (18) and 312 g carbohydrate liquid meal (22) both improved exercise performance. Further research is needed to determine whether a specific carbohydrate form is more beneficial when consumed 4 hours before exercise.

How much carbohydrate should be consumed prior to exercise? Research by Sherman and colleagues (22, 23) suggests that 1.0 to 4.5 g of carbohydrate/kg be consumed 1 to 4 hours before exercise. To avoid potential gastrointestinal distress, the carbohydrate content of the meal should be reduced the closer to exercise it is consumed. For example, a carbohydrate feeding of 1 g/kg is appropriate an hour before exercise, whereas 4.5 g/kg may be consumed 4 hours before exercise.

**During Exercise**

During prolonged (≥2 hours) high intensity exercise (≥70% of VO$_{2\text{max}}$), there is a progressive shift from muscle glycogen to blood glucose oxidation. It is clear that consuming carbohydrate during such exercise improves endurance (5, 6). This improvement in performance is not due to a sparing of muscle glycogen use during exercise (5). Instead, carbohydrate feedings maintain blood glucose levels at a time when muscle glycogen levels are low (5). This allows carbohydrate oxidation and energy production to continue at high rates.
Is the form of carbohydrate important? Coyle et al. (6) evaluated whether liquid carbohydrate feedings during exercise could delay the development of fatigue during prolonged cycling. The carbohydrate feedings were 1 g/kg at 20 min and .25 g/kg at 60, 90, and 120 min. The point of fatigue was defined as the time at which the subject’s exercise intensity dropped from 74% of VO₂max to 64% of VO₂max. The subjects who were fed carbohydrate exercised 33 min longer before reaching the point of fatigue.

Coyle et al. (5) also evaluated the effect of carbohydrate feedings upon muscle glycogen utilization during prolonged cycling to fatigue at 71% of VO₂max. The liquid carbohydrate feedings were 2 g/kg at 20 min and .4 g/kg every 20 min thereafter. When fed carbohydrate, which maintained plasma glucose concentration, the subjects were able to exercise an hour longer. The carbohydrate feedings did not affect muscle glycogen utilization.

Hargreaves et al. (9) evaluated the effect of solid carbohydrate feedings during 4 hours of interval cycling exercise. The subjects consumed 43 g of carbohydrate, 9 g of fat, and 3 g of protein with water at 0, 1, 2, and 3 hours of exercise. During a sprint (100% of VO₂max) at the end of each hour trial, the subjects exercised 45% longer when fed carbohydrate.

Recently, Mason et al. (15) compared liquid and solid carbohydrate feedings during 2 hours of continuous cycling exercise at 65% of VO₂max. The carbohydrate feedings were ingested at 30, 60, and 90 min of exercise and provided 25 g of carbohydrate/kg. No differences were observed between the liquid or solid carbohydrate feedings. This study indicated that liquid and solid carbohydrate feedings with equal carbohydrate content produce similar blood glucose and insulin responses during exercise.

At this time, it appears that liquid and solid carbohydrate feedings consumed during exercise are equally effective in increasing blood glucose and improving endurance. Each carbohydrate form holds certain advantages for the athlete. Liquid carbohydrate feedings encourage the consumption of water needed to maintain hydration during exercise. Also, ingested carbohydrate must be in a liquid or semiliquid state before leaving the stomach. However, compared to liquids, solid carbohydrate feedings can be easily carried by the athlete during exercise and provide both variety and satiety.

How much carbohydrate should be consumed during endurance exercise? Research by Coyle and colleagues (5, 6, 7) suggests that 30 to 60 g of carbohydrate be consumed per hour in the form of glucose, sucrose, or starch.

Following Exercise

Replenishment of muscle and liver glycogen between daily training sessions or competitive events is essential for peak performance. To optimize muscle glycogen repletion, carbohydrate should be consumed immediately after, and at frequent intervals following, exercise (11).

Does the form of carbohydrate influence glycogen repletion? Ivy et al. (11) provided 2 g of liquid carbohydrate/kg either immediately following 2 hours of cycling or at 2 hours after cycling. During the first 2 hours after exercise, muscle glycogen storage was 7.7 μmol/kg-hr for the immediate carbohydrate feeding and only 2.5 μmol/kg-hr for the delayed feeding. During the second 2 hours of recovery, glycogen storage slowed to 4.3 μmol/kg-hr for the immediate carbohy-
drate feeding, but increased to 4.1 μmol/kg·hr for the delayed feeding. Even with
the increase, the rate of glycogen storage was still 45% slower overall.

Reed et al. (20) provided 3 g of carbohydrate/kg in liquid or solid form
or by intravenous infusion following 2 hours of cycling at 60 to 75% of VO₂max.
The subjects received half of the carbohydrate immediately after exercise and
after 2 hours of exercise. The glucose infusion was continuous throughout 4
hours of recovery. The increase in blood glucose was three times greater than
that for the carbohydrate feedings, but was not different between liquid or solid
form. There was no difference in muscle glycogen storage rates between the
treatments after the first 2 hours or second 2 hours. This study indicated that
providing liquid or solid carbohydrate feedings with equal carbohydrate content
postexercise produces similar glycogen repletion rates.

Murdoch et al. (17) provided 1.1 g carbohydrate/kg of either solid or
slurried bananas immediately following prolonged exhaustive endurance exercise
(90 min of running, followed by 90 min of cycling—both at 70% of VO₂max).
Following a 20 min rest, the subjects cycled at 70% of VO₂max until exhausted.
Serum glucose was significantly higher for the carbohydrate feedings than the
placebo, but was not different for banana form. Cycling performance time was also
significantly longer when fed carbohydrate, but was not different for carbohydrate
form.

These studies suggest that both liquid and solid carbohydrate feedings are
equally effective in promoting glycogen storage following exercise. Since many
athletes are not hungry immediately after strenuous exercise, a high carbohydrate
beverage may be the preferred carbohydrate choice for glycogen repletion. This
will also encourage rehydration. A high carbohydrate meal can then be consumed
several hours after exercise.

How much carbohydrate should be consumed following exercise? Research
by Ivy et al. (12) suggests that 1.5 g of carbohydrate/kg be consumed immediately
after exercise and at 2-hour intervals thereafter. Sherman (21) recommends a
daily intake of 8–11 g of carbohydrate/kg for athletes who train intensely for 2
hours or longer in order to optimize repletion of muscle and liver glycogen stores.

Conclusion

Liquid and solid carbohydrate feedings consumed during exercise are equally
effective in increasing blood glucose and improving endurance. In addition, liquid
and solid carbohydrate feedings are similarly beneficial in promoting glycogen
repletion following exercise.

One question raised at the beginning of this review remains unanswered.
Do liquid and solid carbohydrates have the same effect on serum glucose and
performance when consumed before exercise? Although the study by Neuffer et
al. (18) suggests that liquid and solid feedings are equally suitable, the serum
glucose response and performance effects of consuming carbohydrate a few
minutes before exercise are very similar to consuming carbohydrate during exer-
cise. At this time, no study has compared solid and liquid carbohydrates 30–60
min before exercise, or 4 hours before exercise.

The research by Thomas et al. (24) proposes that a low glycemic solid
carbohydrate feeding an hour before exercise is a better choice than a high
glycemic liquid or solid carbohydrate feeding because the solid feeding will
provide a more continuous supply of serum glucose during exercise. Further well-controlled experimental studies are required to support this hypothesis. Additional research is also needed to determine whether the carbohydrate form matters when the preexercise meal is consumed 4 hours before exercise.

References


