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CARBOHYDRATE NUTRITION

Carbohydrate drinks – can fructose enhance endurance?

Despite the numerous claims to the contrary by the sports nutrition industry, real advances in sports nutrition are comparatively rare. But recent research into carbohydrate absorption and utilisation could herald a new breed of carbohydrate drink, which promises genuinely enhanced endurance performance. Andrew Hamilton explains

Before we go on to discuss carbohydrate formulations, it's worth recapping just why carbohydrate nutrition is so vital for athletes. Although the human body can use fat and carbohydrate as the principle fuels to provide energy, it's carbohydrate that is the preferred or 'premium grade' fuel for sporting activity.

There are two main reasons for this. Firstly, carbohydrate is more oxygen-efficient than fat; each molecule of oxygen yields six molecules of ATP (adenosine triphosphate – the energy liberating molecule used in muscle contraction) compared with only 5.7 ATPs per oxygen molecule when fat is oxidised. That's important because the amount of oxygen available to working muscles isn't unlimited – it's determined by your maximum oxygen uptake (VO_2max).

Secondly and more importantly, unlike fat (and protein), carbohydrate can be broken down very rapidly without oxygen to provide large amounts of extra ATP via a process known as **glycolysis** during intense (anaerobic) exercise. And since all but ultra-endurance athletes tend to work at or near their **anaerobic threshold**, this additional energy route provided by carbohydrate is vital for maximal performance. This explains why, when your muscle carbohydrate supplies (glycogen) run low, you sometimes feel as though you've hit a 'wall' and have to drop your pace significantly from that sustained when glycogen stores were higher.

Carbohydrate storage

Endurance training coupled with the right carbohydrate loading strategy can maximise glycogen concentrations, which can extend the duration of exercise by up to 20% before fatigue sets in[1]. Studies have shown that the onset of fatigue coincides closely with the depletion of glycogen in exercising muscles[2,3].

However, valuable as these glycogen stores are, and even though some extra carbohydrate (in the form of circulating blood glucose) can be made available to working muscles courtesy of glycogen stored in the liver, they are often insufficient to supply the energy needs during longer events.

For example, a trained marathon runner can oxidise carbohydrate at around 200-250g per hour at racing pace; even if he or she begins the race with fully loaded stores, muscle glycogen stores would become depleted long before the end of the race. Premature depletion can be an even bigger problem in longer events such as triathlon or

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In this issue

At a glance:

- The importance of consuming carbohydrate during endurance events is explained;
- The background to modern carbohydrate drink formulation is outlined;
- Recent research on the potential benefits of mixed carbohydrate drinks containing fructose is presented;
- Recommendations for endurance athletes are made.

endurance cycling and can even be a problem for athletes whose events last 90 minutes or less and who have not been able to fully load glycogen stores beforehand.

Given that stores of precious muscle glycogen are limited, can ingesting carbohydrate drinks during exercise help offset the effects of glycogen depletion by providing working muscles with another source of glucose? Back in the early 1980s, the prevailing consensus was that it made little positive contribution. This was because of the concern that carbohydrate drinks could impair fluid uptake, which might increase the risk of dehydration. It was also mistakenly believed that ingested carbohydrate in such drinks actually contributed little to energy production in the working muscles[4].

Later that decade, however, it became clear that carbohydrate ingested during exercise can indeed be oxidised at a rate of roughly 1g per minute[5-7] (supplying approximately 250kcals per hour) and a number of studies subsequently showed that this could be supplied and absorbed well by drinking 600-1,200mls of a solution of 4-8% (40-80g per litre of water) carbohydrate solution per hour[8-11]. More importantly, it was also demonstrated both that this ingested carbohydrate becomes the predominant source of carbohydrate energy late in a bout of prolonged exercise[10], and that it can delay the onset of fatigue during prolonged cycling and running as well as improving the power output that can be maintained[12,13].

Drink formulation

The research findings above have helped to shape the formulation of most of today's popular carbohydrate drinks. Most of these supply energy in the form of glucose or glucose polymers (*see box right for explanation*) at a concentration of around 6%, to be consumed at the rate of around 1,000mls per hour, so that around 60g per hour of carbohydrate is ingested. Higher concentrations or volumes than this are not recommended because not only does gastric distress become a problem, but also the extra carbohydrate ingested is simply not absorbed or utilised.

But as we've already mentioned, 60g per hour actually amounts to around 250kcals per hour, which provides only a modest replenishment of energy compared to that being expended during training or competition. Elite endurance athletes can burn over 1,200kcals per hour, of which perhaps 1,000kcals or more will be derived from carbohydrate, leaving a

Jargonbuster

Glycolysis
The partial but rapid breakdown of carbohydrate without oxygen

Anaerobic threshold
The exercise intensity at which the proportion of energy produced without oxygen rises significantly, resulting in an accumulation of lactate

shortfall of at least 750kcals per hour. It's hardly surprising, therefore, that one of the goals of sports nutrition has been to see whether it's possible to increase the rate of carbohydrate replenishment. And now a series of studies carried out by scientists at the University of Birmingham in the UK indicates that this may indeed be possible.

Carbohydrate type and performance

Many of the early studies on carbohydrate feeding during exercise used solutions of glucose, which produced demonstrable improvements in performance as discussed. In the mid-1990s, some researchers experimented by varying the type of carbohydrate used in drinks, for example by using glucose polymers or sucrose (table sugar). However, it seemed that there was little evidence that these other types of carbohydrate offered any advantage[3].

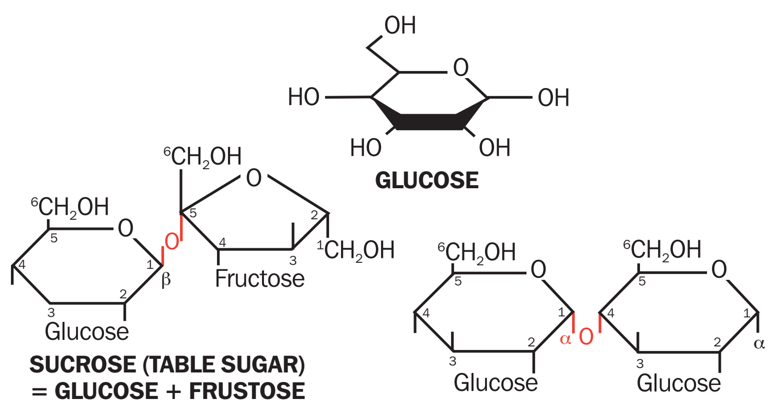
But, at about the same time, a Canadian research team were experimenting with giving mixtures of two different sugars (glucose and fructose) to cyclists. In one experiment cyclists pedalled for two hours at 60% of VO_2max while ingesting 500mls of one of five different drink mixtures[14]:

- 50g glucose;
- 100g glucose;
- 50g fructose;
- 100g fructose;
- 100g of 50g glucose + 50g fructose.

CARBOHYDRATE BUILDING BLOCKS

The fundamental building blocks of carbohydrates are molecules known as sugars. Although there are a number of sugars, the most important is glucose, which can be built into very long chains to form starch (found in bread, pasta, potatoes, rice *etc*). Fructose is also important, accounting for a significant proportion of the carbohydrate found in fruits. The disaccharide (*ie* two sugar unit) sucrose is composed of glucose and fructose linked together and is more commonly known as table sugar.

Sports drinks often contain glucose and fructose, but also other carbohydrates such as dextrins, maltodextrins and glucose polymers. These consist of chains of glucose units linked together, with varying amounts of chain length and branching. Because of their more complex structure, more digestion is required, which tends to slow the rate of absorption, resulting in a smoother, more sustained uptake into the bloodstream.



SUCROSE (TABLE SUGAR) = GLUCOSE + FRUSTOSE

MALTOSE ('BREWERS SUGAR') = GLUCOSE + GLUCOSE

These sugars were **radio-labelled** with **carbon-13** so the researchers could see how well they were absorbed and oxidised for energy by measuring the amount of carbon dioxide containing carbon-13 exhaled by the cyclists (as opposed to unlabelled carbon dioxide, which would indicate oxidation of stored carbohydrate). The key finding was that 100g of the 50/50 glucose fructose mix produced a 21% larger rate of oxidation than 100g of pure glucose alone and a 62% larger rate than 100g of pure fructose alone.

Although these findings provided experimental support for using mixtures of carbohydrates in the energy supplements for endurance athletes, it wasn't until 2003 that researchers from the University of Birmingham in the UK began looking more closely at the issue. In particular, they wanted to see whether combinations of different sugars could be absorbed and utilised more rapidly than the 1.0g per minute peak values that had been recorded with pure glucose drinks.

One of their early experiments compared the oxidation rates of ingested carbohydrate in nine cyclists during three-hour cycling sessions at 60% of VO_2max[15]. During the rides, the cyclists drank 1,950mls of radio-labelled carbohydrate solution, which supplied one of the following:

- 1.8g per min of pure glucose;
- 1.2g of glucose + 0.6g per minute of sucrose;
- 1.2g of glucose + 0.6g per minute of maltose;
- Water (control condition).

The results showed that while the pure glucose and glucose/maltose drinks produced an oxidation rate of 1.06g of carbohydrate per minute, the glucose/sucrose combination drink produced a significantly higher rate of 1.25g per minute. This was an important finding because while both maltose and sucrose are disaccharides (*see box opposite*), maltose is composed of just two chemically bonded glucose molecules, whereas sucrose combines a glucose with a fructose molecule. This suggested that it was the glucose/fructose combination that was being absorbed more rapidly and therefore producing higher rates of carbohydrate oxidation.

Fructose connection

The same team had also performed another carbohydrate ingestion study on eight cyclists pedalling at 63% of VO_2max for two hours[16]. In this study the cyclists performed four exercise trials in random order while drinking a radio-labelled solution supplying of one of the following:

- 1.2g per min of glucose (medium glucose);
- 1.8g per min of glucose (high glucose);
- 1.2g of glucose + 0.6g of fructose per minute (glucose/fructose blend);
- Water (control).

There were two key findings; firstly, the carbohydrate oxidation rate when drinking high glucose drink was no higher than when medium glucose was consumed; secondly, the peak and average oxidation rates of ingested glucose/fructose solution were around 50% higher than both of the glucose-only drinks.

These findings point strongly to the fact that the maximum rate of glucose absorption into the body is around 1.2g per minute because feeding more produces no more glucose oxidation – probably because the absorption mechanism is already saturated. But because giving extra fructose does increase overall carbohydrate oxidation rates, they also indicate that fructose in the glucose/fructose drink was absorbed from the intestine via a different mechanism than glucose (*see box above*).

The studies above and others[17] had shown that glucose/fructose mixtures do result in higher oxidation rates of ingested carbohydrate, especially in the later stages of exercise. But what the team wanted to find out was whether this extra carbohydrate uptake could help with water uptake from the intestine, and also whether the increased oxidation of ingested carbohydrate had a sparing effect on muscle glycogen, or other sources of stored carbohydrate (*eg* in the liver).

To do this, they set up another study using a similar protocol to that above (eight trained cyclists pedalling at around 60% VO_2max on three separate occasions, ingesting one of three drinks on each occasion[18]). However, in this study, the duration of the trial was extended to five hours during which the subjects drank one of the following:

- 1.5g per minute of glucose;
- 1.5g per minute of glucose/fructose mix (1.0g glucose/0.5g fructose);
- Water (control).

The water used in the drinks was also radio-labelled (to help determine uptake into the bloodstream) and the cycling trials were conducted in warm conditions (32°C) to add heat stress. Exercise in the heat results in a greater reliance on carbohydrate metabolism, which is thought to be due to increased

Intestinal absorption of glucose and fructose

Like many nutrients, sugars aren't absorbed passively – *ie* they don't just 'leak' across the intestinal wall into the bloodstream. They have to be actively transported across by special proteins called '**transporter proteins**'.

We now know that the intestinal transport of glucose occurs via a glucose transporter called SGLT1, which is located in the **brush-border membrane** of the intestine. It is likely that the SGLT1-transporters become saturated at a glucose ingestion rate of around 1g per minute (*ie* all the transport sites are occupied), which means at ingestion rates above 1g per minute, the surplus glucose molecules have to 'queue up' to await transportation.

In contrast to glucose, fructose is absorbed from the intestine by a completely different transporter called GLUT-5. So when carbohydrate is given at 1.8g per minute as 1.2g per min of glucose and 0.6g per min of fructose rather than 1.8g per min of pure glucose, the extra fructose molecules don't have to 'queue up' as they have their own route across the intestine independent of glucose transporters. The net effect is that more carbohydrate in total finds its way into the bloodstream, which means that more is available for oxidation to produce energy.

Jargonbuster

Radio-labelled
Where a normal atom in a compound (eg glucose) is replaced by a chemically identical atom, but one carrying a different number of neutrons (isotope) making it possible to track the fate of that compound using a technique known as spectrometry

Carbon-13
A carbon atom with an extra neutron in the nucleus

Transporter proteins
Large molecules that sit in cell walls and assist in the transport of substances in and out of the cell

Brush-border membrane
Densely packed protrusions (microvilli) on the intestinal wall, which help maximise nutrient absorption

muscle glycogen utilisation, and is associated with higher levels of fatiguing lactate concentrations.

There were a number of important findings from this study:

- During the last hour of exercise, the oxidation rate of ingested carbohydrate was 36% higher with glucose/fructose than with pure glucose (*figure 1*);
- During the same time period, the oxidation rate of endogenous (*ie* stored) carbohydrate was significantly less with glucose/fructose than with pure glucose (*figure 1*);
- The rate of water uptake from the gut into the bloodstream was significantly higher with glucose/fructose than with pure glucose (*figure 2*);
- The perception of stomach fullness was reduced with the glucose/fructose drink compared to pure glucose;
- Perceived rates of exertion in the later stages of the trial were lower with glucose/fructose than with pure glucose.

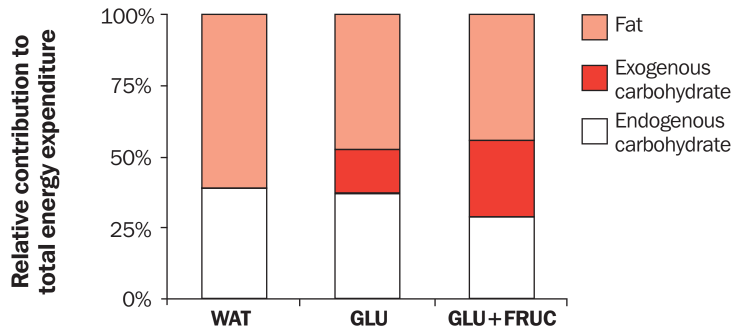
Although no direct muscle glycogen measurements were made, the kinetics of the rate of appearance and disappearance of glucose in the bloodstream from the drinks led the researchers to postulate that the extra carbohydrate oxidation observed could be as a result of increased liver oxidation, or the formation of non-glucose energy substrates during exercise, such as lactate, which is known to be an important fuel for exercising muscles. More research is needed to determine the exact mechanisms involved.

Implications for athletes

These research findings are very encouraging; higher rates of energy production from ingested carbohydrate, lower rates from stored carbohydrate and increased water uptake sounds like a dream combination for endurance athletes. But can a glucose/fructose drink actually enhance endurance performance in real athletes under real race conditions?

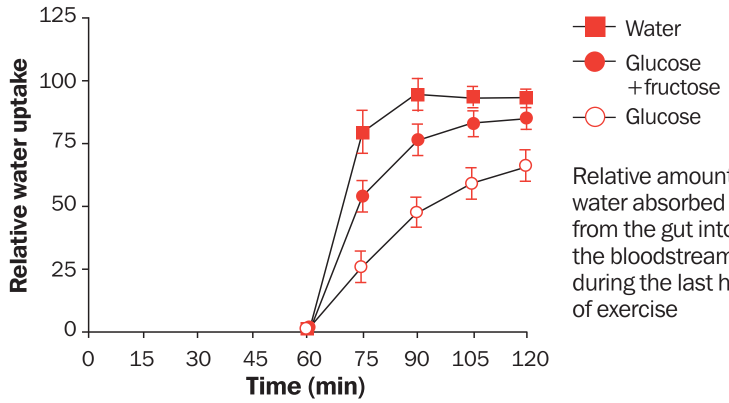
That's the question scientists at the University of Hertfordshire are currently trying to answer in a double-blind, placebo controlled study to test commercially available drinks, which was set up earlier this year. The main goal is to compare the effects on cycling performance of a popular glucose/glucose polymer (containing very low levels of fructose – ~3-4%) drink with a 2:1 glucose/fructose drink (trade name of 'Super Carbs' – 33% fructose) on cycling performance. The results of these trials are yet to be published, but according to the research team, the initial findings are 'very promising'.

Figure 1: Drink type and fuel usage



Relative contribution of fat, exogenous (ingested) and endogenous (stored) carbohydrate to energy expenditure during last hour of exercise

Figure 2: Drink type and water uptake



Relative amount of water absorbed from the gut into the bloodstream during the last hour of exercise

Recommendations for athletes

If you're an endurance athlete, is it worth rushing out and trying to get hold of a glucose/fructose drink to use during training/competition? Despite the promising initial research, the cautious approach would be to hold back until scientists have confirmed beyond doubt that these drinks really do confer a performance advantage.

However, fructose is cheap, which means these drinks are no more expensive than conventional glucose/glucose polymer drinks; as all the indications are that any performance differences produced by a glucose/fructose drink will be positive, there's certainly no harm in a 'try it and see approach', and possibly much to gain.

Having said that, it's important to remember that conventional glucose/glucose polymer drinks can still confer proven advantages for endurance athletes when taken during training or competition; both glucose/glucose polymer and glucose/fructose drinks can boost endurance performance over using nothing at all! But should the initial findings above be confirmed, the future for glucose/fructose carbohydrate drinks looks bright.

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References

1. *Sports Med 1997; 24:73-81*
2. *Acta Physiol Scand 1967; 71:129-139*
3. *Williams C, Harries M, Standish WD, Micheli LL (eds) (1998) Oxford Textbook of Sports Medicine, 2nd edn. New York: Oxford University Press*
4. *Int J Sports Med 1980; 1:2-14*
5. *Sports Med 1992; 14: 27-42*
6. *Metabolism 1996; 45:915-921*
7. *Am J Physiol Endocrinol Metab 1999; 276: E672-E683*
8. *Med Sci Sports Ex 1993; 25:42-51*
9. *Int J Sports Med 1994; 15:122-125*
10. *Med Sci Sports Ex 1996; 28: i-vii*
11. *J Athletic Training 2000; 35:212-214*
12. *Int J Sports Nutr 1997; 7:26-38*
13. *Nutrition Reviews 1996; 54:S136-S139*
14. *J Appl Physiol 1994; ss76(3):1014-9*
15. *J Appl Physiol 2004; 96:1285-1291*
16. *J Appl Physiol 2004; 96:1277-1284*
17. *Med Sci Sports Exerc 2004; 36(9):1551-1558*
18. *J Appl Physiol 2006; 100:807-816*