THE NUTRITION X-CHANGE

4 CARBOHYDRATE INTAKE DURING EXERCISE

A LOOK AT THE EFFECT OF CARBOHYDRATE INTAKE ON EXERCISE PERFORMANCE

BY PROFESSOR DON MACLAREN

Carbohydrate intake during exercise

PROFESSOR DON MACLAREN

Practical Implications

- Carbohydrate ingestion during exercise has a beneficial effect on prolonged performance possibly by preventing hypoglycemia or enhancing carbohydrate oxidation late in exercise or attenuating muscle glycogen use.

- Most forms of carbohydrate are suitable and give similar results with regard to performance and oxidation, although fructose may prove problematic.

- Factors that affect the availability of ingested carbohydrate during exercise include gastric emptying, intestinal absorption, primary liver use, as well as transport to and across muscle.

- The likely maximal rates of carbohydrate oxidation from ingested carbohydrate are 1.0g/min for single transportable carbohydrates and small polysaccharides, and 1.75g/min for multiple transportable carbohydrates (i.e. glucose combined with fructose).

- Carbohydrate ingestion is unlikely to be beneficial for bouts of exercise of about 60 minutes or less although some benefits have been seen with a carbohydrate mouth rinse.

- Skill, decision making, cognitive function, reaction time, and rating of perceived exertion benefit from carbohydrate ingestion during exercise – particularly in the later stages i.e. after 60 minutes.

- Since carbohydrate ingestion during exercise favours carbohydrate oxidation, any so-called fat burning is likely to be diminished.

Background

Carbohydrates and fats are the two major energy sources that fuel muscle during prolonged steady state and intermittent exercise. The fatigue associated with prolonged performance has been reported to coincide with the depletion of endogenous stores of carbohydrate, and of disturbances in the level of circulating plasma glucose (Cermak & van Loon, 2013). Significant improvements in endurance performance and capacity are well established when carbohydrates are ingested before and/or during activity (Stellingwerff & Cox, 2014). These improvements could be due to a number of factors such as stimulation of carbohydrate receptors in the oral cavity modulating neural drive and attenuating perceived exertion (Carter et al., 2004) and/or maintenance of plasma glucose concentration leading to an increase in carbohydrate oxidation late in exercise (Coggan & Coyle, 1989; Jeukendrup, 2004). In addition, it has been demonstrated that carbohydrate intake during exercise not only increases oxidation of carbohydrate but may spare use of muscle glycogen and thereby improve performance or time to fatigue (Stellingwerff et al., 2007; Tsintzas et al.,1995), although a number of studies have failed to show a sparing effect on muscle glycogen (Coyle et al., 1986; Mitchell et al., 1989).

Stellingwerff & Cox (2014) proposed a likelihood of performance benefits with carbohydrate ingestion when exercise was longer than 2-h but not necessarily if the bout was less than 1-h. They concluded that the primary mechanism by which carbohydrates enhance endurance performance was due to a high rate of carbohydrate delivery resulting in elevated rates of carbohydrate oxidation. Consequently, many investigations have explored the promotion of carbohydrate delivery to muscle by using high levels of a single source of carbohydrate or by ingesting multiple transportable carbohydrates such as glucose:fructose combinations (Newell et al., 2018). The issue with ingesting large amounts of carbohydrate during performance (particularly running) is that the gastrointestinal system is compromised and may lead to unwarranted symptoms such as gut pain, flatulence, diarrhea, and vomiting. Even so, it appears that the maximum rate of exogenous carbohydrate is achieved when ingesting around 90g/h. Amounts of ingested carbohydrate at these high levels results in a maximal rate of exogenous carbohydrate oxidation of ~1.0g/min for single sources of carbohydrates or ~1.75g/min using multiple transportable carbohydrates (Jeukendrup, 2010).

Carbohydrates and gastric emptying

Previous research has demonstrated that the energy content and osmolality of the ingested solution plays a key role in the rate of gastric emptying (Vist & Maughan, 1994). Solutions of low osmolality (effectively low concentration) empty from the stomach at a faster rate than those with a high osmolality. Beverages with as little as 2.5% carbohydrate have been shown to empty more slowly than water. Figure 1 illustrates the gastric emptying of fluid or glucose based on the concentration of an ingested glucose solution. The amount of carbohydrate delivery to the intestine and the rate of exogenous carbohydrate oxidation increases linearly with increasing carbohydrate concentration despite the decrease in gastric emptying. Only solutions with low or isotonic carbohydrate should be ingested during prolonged exercise as they are emptied rapidly and help hydrate. When the requirement is for greater amount of carbohydrate during strenuous exercise, this can be achieved with a more concentrated carbohydrate source irrespective of the reduced gastric emptying (Foster, 1990). The type of carbohydrate ingested appears immaterial for gastric emptying since osmolality is more important (El-Sayed & MacLaren, 1997).

Carbohydrate sources, absorption, and oxidation

The majority of carbohydrate drinks ingested during exercise are monosaccharides or so-called simple sugars such as glucose, fructose, and galactose, although disaccharides such as sucrose (table sugar) and polysaccharides such as maltodextrins and

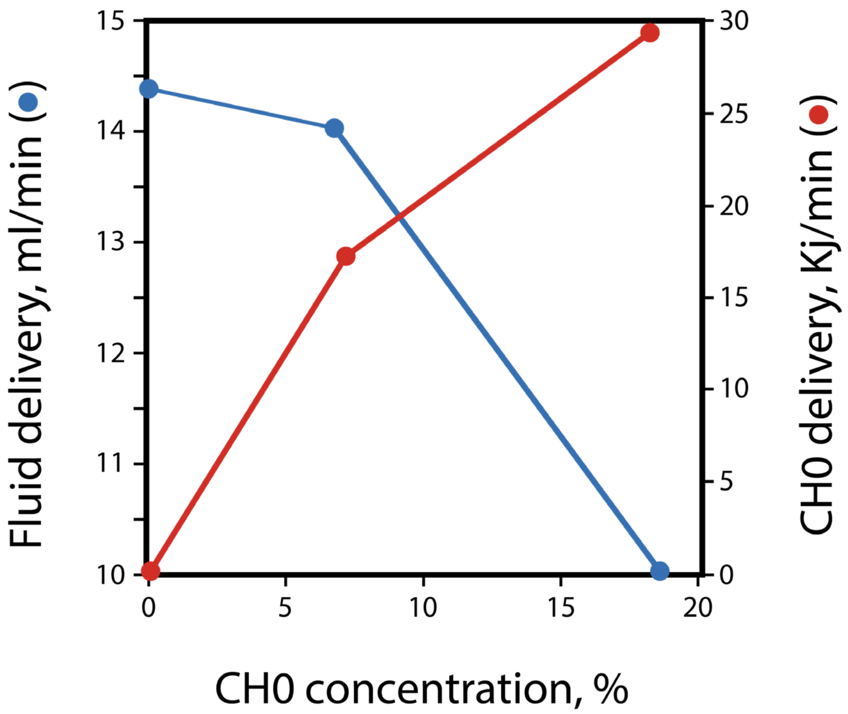

Figure 1. Fluid delivery and carbohydrate delivery across the gut in relation to increasing carbohydrate concentration ingested. Note that as the carbohydrate concentration is increased there is an initial gradual reduction in fluid delivery with a concomitant increase in carbohydrate delivery. After a concentration of about 8% carbohydrate the fluid delivery is markedly reduced whereas the carbohydrate delivery is enhanced significantly.

even starch have been employed. The disaccharides and polysaccharides have to be digested to their respective monosaccharides before being absorbed across the gut in the small intestine. Figure 2 highlights how glucose, fructose and galactose are absorbed. It is evident that a sodium-dependent glucose transporter (SGLT1) and a glucose transporter (GLUT 5) are required for glucose/galactose and fructose uptake respectively across the brush border, and that GLUT2 and a glucose transporter (GLUT5 or GLUT2) are required to transport the monosaccharides into the portal blood vessels. The fact that glucose and fructose employ different gut transporters is probably the reason why so-called multiple carbohydrate drinks result in a greater rate of carbohydrate oxidation. Evidence is available that the number of SGLT1 transporters are in abundance when compared with GLUT5 transporters, and is a factor as to why glucose uptake across the intestine is greater (and faster) than fructose. Indeed, high concentrations of fructose ingested during running-based activities in particular have been reported to contribute to increases in gastrointestinal problems – notably diarrhea, pain, and flatulence (Prado de Oliveira et al., 2014).

Once glucose is dispersed into the portal system most of it by-passes the liver and is transported to muscle for oxidation (at least during exercise) whereas fructose is taken up by liver and undergoes either oxidation or is converted to glucose and lactate, which are then transported out of the liver for muscle and other tissue to utilize. The consequence of carbohydrate ingestion during exercise is that plasma glucose and insulin levels increase and so drive carbohydrate and attenuate fat oxidation.

During exercise there is a reduction in splanchnic blood flow and so, in general, the availability of absorbed nutrient sources may be compromised. This is another possible factor to consider vis a vis utilisation of ingested carbohydrate. So once the glucose is in the general circulation, it can then be taken up into muscle for oxidation. Glucose does not freely diffuse into muscle, rather it is taken across the plasma membrane using a glucose transporter

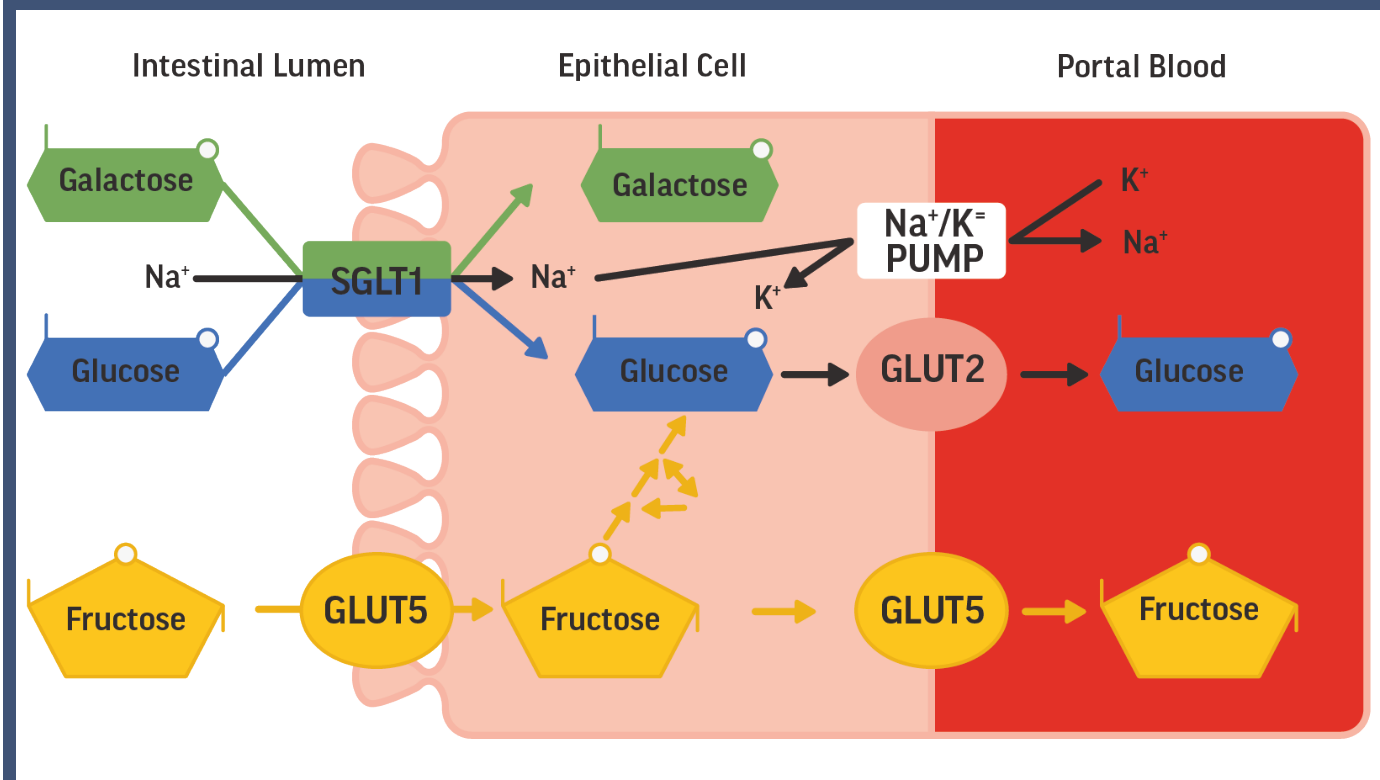

Figure 2. Transport of monosaccharides across the gut wall. SGLT1 is sodium dependent glucose transporter; GLUT5 and GLUT2 are glucose transporters.

(GLUT4). GLUT4 normally resides in intracellular vesicles and is translocated to the plasma membrane due to signaling mechanisms. Figure 3 illustrates that insulin provides one such mechanism in so far as plasma insulin levels are promoted due to increasing concentration of glucose, and that the insulin binds to its cell membrane receptor causing changes within the muscle cell. One of the molecules 'turned on' by insulin is Akt, which drives the translocation of GLUT4 to the surface of the cell membrane and promotes uptake of glucose. Incidentally, the other key 'driver' for GLUT4 translocation is AMPK, which is elevated due to an increase in calcium ions resulting from the muscle activity.

So, in summary, the carbohydrate ingested has to empty from the stomach rapidly, be digested if in a complex form, get absorbed across the gut wall, pass into the body circulatory system, and then get transported across the muscle membrane before oxidation is possible. This series of processes are potential limiting factors for carbohydrate use during exercise (Rosset et al., 2017)

Limitations of exogenous carbohydrate use

The maximal rates of exogenous glucose oxidation during exercise have consistently observed to be around 1.0g/min irrespective of the dose ingested (Jeukendrup, 2010). Ingestion of short-chain glucose polysaccharides such as maltose and maltodextrins result in similar maximal oxidation rates as glucose. Since such glucose polysaccharides are required to be digested before absorption and yet maximal rates of oxidation are similar to glucose would indicate that pre-absorptive factors are not limiting. Consequently, the limitation of carbohydrate oxidation maybe considered to be at the level of intestinal absorption, with the ≈1 g/min plateau being consistent with intestinal glucose absorption kinetics. This hypothesis was primarily based on multiple intestinal segmentation experiments showing limited absorption of concentrated glucose solutions (Shi et al., 1995). Another physiological effect of exercise, decreased splanchnic blood

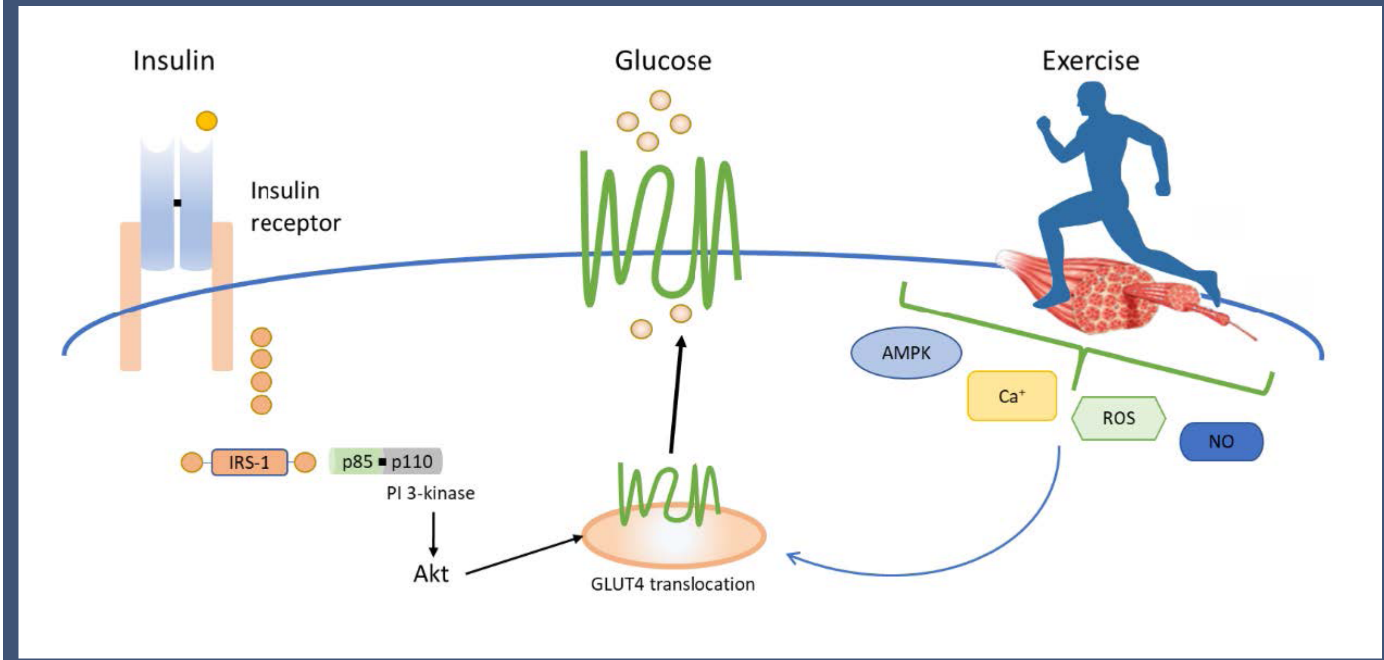

Figure 3. Insulin stimulation of GLUT4 translocation to the cell membrane via promotion of Akt.

flow, may also limit intestinal absorption capacity. Yet, in absence of invasive direct assessments of glucose flows across the intestinal barrier, the idea that intestinal absorption limits exogenous glucose oxidation during exercise remains a hypothesis.

The plateau in exogenous glucose oxidation may also result from hepatic limitations. The route for ingested carbohydrate is to follow portal circulation to the liver, where they can either be stored, metabolized or pass to the systemic circulation. The liver is also known to play a pivotal role in maintenance of euglycemia through releasing the precise amount of glucose required to match extra-hepatic use (Moore et al., 2012). Hence, the factors responsible for the limitation in exogenous glucose oxidation during exercise remain unclear, but probably not restricted to intestinal glucose absorption. For a more comprehensive treatise on the matter of the carbohydrate intake, the gastrointestinal tract and exercise it is worth reading Rosset et al. (2017).

Since the gut presents a 'barrier' not just in terms of carbohydrate delivery into the blood but also in relation to gastrointestinal problems, any question as to the maximal potential rates of exogenous carbohydrate utilization during exercise are thereby hindered by the gut. However, infusing glucose directly into a vein disposes of the need for gut transport and other inherent problems. Previous work in which I have been involved using the hyperglycemic glucose clamp technique to observe metabolic changes during intense bouts of exercise has clearly shown that maintained hyperglycemia (by glucose infusion) resulted in a maximal glucose utilisation rate (GUR) of 1.8g/min (i.e. 108g/h) and a maximal rate of total CHO oxidation of 2.65g/min (MacLaren et al., 1999). Therefore, ~70% of the exogenous carbohydrate was oxidized; the rest of the carbohydrate oxidation arising from endogenous sources (most probably muscle glycogen). In fact, two of our younger participants presented with a GUR of ~2.8g/min (168g/h) which is similar to data we reported more recently (Mohebbi et al., 2020). It would thus be reasonable to suggest that the ~1g/min higher rate of exogenous glucose use from infusion compared with ingestion studies is, in part, due to the gut as a 'barrier'.

Likely benefits of carbohydrate ingestion during exercise

Carbohydrate ingestion during exercise has been consistently shown to improve prolonged exercise performance, and typical guidelines recommend ingesting 30–60 g carbohydrate per hour (American Dietetic et al., 2009). While original recommendations essentially suggested glucose-based formulations more recent guidelines propose that with increased exercise duration, the optimal intake should not only be increased (up to 90 g h−1 carbohydrate during sessions lasting more than 2.5 h), but also that formulations comprising both glucose and fructose may optimize performance (Cermak & Van Loon, 2013; Jeukendrup, 2014). Combinations of both monosaccharides have been shown to increase performance (Currell & Jeukendrup, 2008). In this cross-over controlled study, simulated 40 km cycling time-trial performance was measured after an initial 2 h endurance bout. Repeated glucose ingestion significantly enhanced performance by +8% relative to non-caloric placebo, with a further +8% improvement observed with a glucose–fructose formulation. However, the effects of glucose-fructose formulations on football simulated exercise has not been proven (Clarke et al., 2012).

To undertake a comprehensive treatise on the reported benefits of carbohydrate ingestion during exercise on performance or capacity is beyond the scope of this article. It is unquestionable that carbohydrates of varying types and doses present a positive beneficial effect on performance or capacity as well as improvements in skill, attenuation of ratings of perceived exertion, and maintenance of blood glucose concentrations when compared with placebo. To this end, it would be useful to examine some more detailed review articles (Jeukendrup, 2014; Williams & Rollo, 2015) or to note the conclusions from a recent meta-analysis of the benefits of carbohydrate intake during exercise on performance (Pochmuller et al., 2016). In the latter review and meta-analysis, the authors concluded that (a) there was a performance benefit of carbohydrate ingestion during exercise, (b) that this benefit was greatest for exercise durations greater than 90 minutes and that there were no significant benefits when exercise was 60 minutes or less in duration, and (c) that doses in the range of 6-9% carbohydrate were most beneficial, although appropriate carbohydrate sources (glucose with fructose) of 10-12% were also beneficial.

It is worth considering that some recent findings have promulgated the concept that carbohydrate feeding during exercise is beneficial in prolonged intermittent sporting activities such as soccer, and not merely extended bouts of cycling or running. To this end the use of the Loughborough Intermittent Shuttle Test (LIST) has proved worthwhile. In one study, games players exhibited a 33% increase in part B of the test when ingesting a 6.5% carbohydrate-electrolyte drink than placebo (Nicolas et al., 1995). In a similar type of investigation using the LIST, professional rugby league referees were found to significantly increase distance covered in part B of the test by 280-m, to have a faster mean 20-m sprint speed of 3%, and a 5% lower rating of perceived exertion when ingesting a 6% maltodextrin drink compared with placebo (MacLaren & Close, 2000). More recently, use has been made of simulating soccer activity on a computerised-driven treadmill. Twelve soccer players underwent 90 minutes of intermittent running on the treadmill in the heat and ingested carbohydrate electrolyte drinks or placebo during the bouts. An uphill high intense bout of running to fatigue after the 90minute simulation resulted in a longer time to fatigue with carbohydrate (Clarke et al., 2011).

Carbohydrate gels provide a convenient means of carbohydrate during prolonged running and cycling. However, there are only a few studies on the benefits of ingesting carbohydrate gels during exercise. Two investigations which both employed the LIST observed the significant positive impact of ingesting gels (Patterson & Gray, 2007; Phillips et al., 2012). In both studies the improvements for gel ingestion were noted for endurance running capacity (6.1 vs 4.2 min; 4.6 vs 3.8 min respectively). Due to the higher osmolarities of the carbohydrate gels (normally hypertonic), there are concerns about the potential delay in gastric emptying. However, these concerns can be allayed by the likely performance benefits.

Most sporting activities require some element of skill and decision making: think of soccer, rugby, hockey, basketball, volleyball, netball and so on. It is evident that at some later stages in these sports there are elements of fatigue which manifest themselves in slower decision making, slower reaction times, and general impaired cognitive function. Ingesting carbohydrates during such sporting activities invariably results in an attenuation of the rating of perceived exertion (RPE) and of maintenance of skill compared with a placebo. Currell et al. (2009) observed a significant improvement in soccer dribbling, agility, and shooting during a 90minute protocol with 7.5% maltodextrin compared with placebo. In a further study, a modified LIST protocol to mimic basketball play was employed with participants undertaking 20-m sprints in each of the four 15minute blocks as well as tests of motor skills and mood state (Winnick et al., 2005). Six percent carbohydrate electrolyte drinks or placebo were ingested, with the result that significant improvements were noted for sprints, motor skill, and mood states in the fourth quarter.

Almost without exception, the ingestion of carbohydrates during exercise has a positive effect on cognitive function, motor skill, and RPE after a period of about 60 minutes of exercise. There are clear potential benefits to be gained from drinking carbohydrate products (as long as they are not too concentrated and cause gastric problems) in the second half of games and for exercise of durations longer than 60 minutes.

An interesting relatively new area of research into carbohydrate intake (note I refrain from using the terms ingestion or consumption since these imply intake, digestion and absorption across the gut) is that of using carbohydrate mouth rinsing. This is where a carbohydrate solution is taken into the mouth and swirled for a short period of time and then spat out – so no actual carbohydrate passes further into the gastrointestinal tract. The concept is that the mouth possesses glucose sensors that activate brain regions related to the sensation of reward and pleasure. These receptors appear to be especially responsive in metabolic conditions of reduced endogenous CHO stores of muscle and liver glycogen. The resultant effect is that mouth rinsing may have a positive impact on performance in terms of skill and perceived exertion. These studies have not shown any effect on metabolism since the effect is neural rather than metabolic. Such studies have shown that mouth rinsing may have a positive effect on exercise lasting up to 60 minutes (de Ataide e Silva et al., 2014).

Likely benefits of carbohydrate ingestion during exercise

Although there are undoubted benefits in consuming carbohydrate drinks during exercise in terms of performance, caution should be expressed in relation to two considerations:-

1. There are numerous reports of the likely adverse effects of carbohydrate consumption during exercise on the gastrointestinal tract (de Oliveira et al., 2014). It is estimated that somewhere between 30-90% of endurance athletes (particularly runners) have experienced a range of gastrointestinal problems. These include nausea, vomiting, abdominal cramps, and diarrhea. In some instances, these disturbances have resulted in impaired performance. From a carbohydrate perspective, it appears that higher carbohydrate intakes (i.e. more concentrated/ hypertonic drinks) or high fructose ingestion is more likely to result in gastrointestinal issues (de Oliveira et al., 2014). In order to reduce or eliminate such effects it is worthwhile ensuring that the carbohydrate intake is not too high, and/or that the gut is 'trained' to accommodate carbohydrate ingestion (Murray, 2006). More recently, there has been a focus on additional ingredients in carbohydrate-electrolyte drinks to further improve gastric emptying, minimize gastrointestinal problems, and enhance carbohydrate absorption and oxidation during exercise (Sutehall et al., 2018). Through the addition of alginate and pectin, solutions form a hydrogel structure in the low pH environment of the stomach, thereby "encapsulating" other constituents of the drink (such as carbohydrate), then returning to a liquid consistency in the higher pH environment of the duodenum. The research is still in its infancy although a very recent report has not provided positive answers (McCubbin et al., 2020). Recently, work from Professor Close's laboratory has shown that probiotics consumed before exercise has been able to reduce GI discomfort and potentially increase maximum exogenous carbohydrate oxidation. Although this work is in its infancy, probiotic supplementation may be an exciting strategy, especially for those who suffer with GI discomfort during exercise (see nutrition X Change article by Pugh and Close on Probiotics).

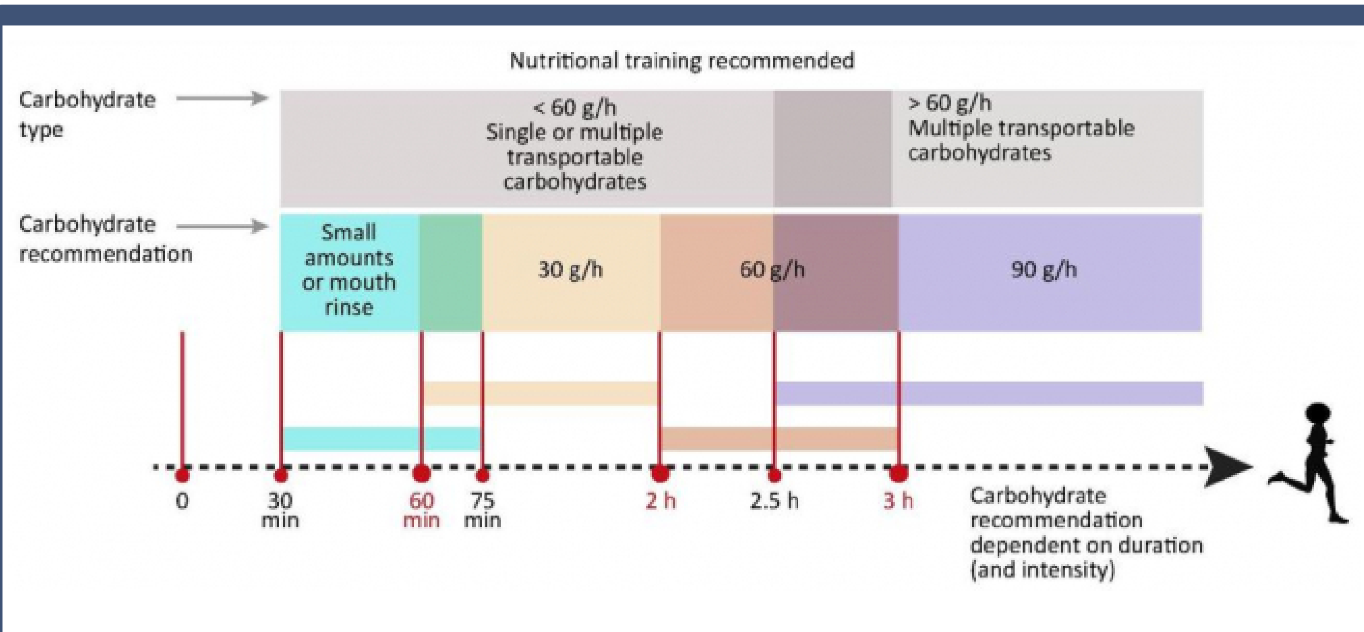

Figure 4. Illustration of amount and type of carbohydrate intake as a function of duration of the activity.

2. If carbohydrate ingestion favours carbohydrate oxidation then any athlete who wishes to engage in so-called 'fat burning' exercise, should ensure that no carbohydrate is consumed during such exercise. There is very clear evidence in carbohydrate ingestion and glucose infusion studies that carbohydrate intake attenuates fat oxidation (El-Sayed & MacLaren, 1997; MacLaren et al., 1999; Mohebbi et al., 2020). Having said that, the increase in fat oxidation during exercise due to no carbohydrate ingestion may not translate to greater fat loss overall unless appropriate dietary habits are taken into consideration. There is a place for training with no carbohydrates and a place for carbohydrate ingestion when high quality training is the key.

Conclusion

There is a wealth of research literature on the positive beneficial effects of carbohydrate ingestion during exercise as long as the exercise/performance period is longer than 60 minutes. These include enhanced capacity, maintenance of power and speed during the activity, as well as improved cognition and skill performance. Carbohydrate drink concentrations of up to 8% for single sugars and 12% for multiple carbohydrate sources (notably glucose:fructose mixes) are advisable, as is the use of carbohydrate gels. The amount of carbohydrate consumed within an hour in order to satisfy both the carbohydrate and fluid needs of the athlete as well as avoidance of gastrointestinal problems should be about 60g/h for activities lasting up to 2-h and above 60g/h (maybe up to 90g/h) for the ensuing period (see Figure 4).

Author bio

Professor Don MacLaren,
Cert.Ed., BSc., MSc., PhD., FBASES, FECSS

Don is an emeritus professor of Sports Nutrition at Liverpool John Moores University, which is a testimony to his many publications on the subject in journals and books as well as his presentations at scientific and coaching conferences. He has been research-active since 1980 in the fields of carbohydrate and fat metabolism, nutritional supplements, and applied aspects of sports nutrition. A consequence of the work undertaken has resulted in two fellowships being awarded i.e. FBASES and FECSS.

Don has been nutritional consultant with a number of Premiership and Championship football clubs as well as with Sale Sharks RUFC and Northampton Saints RUFC. His lecturing duties have resulted in many successful PhD, MSc and BSc students 'passing through his hands'. Although retired from full time duties at LJMU in 2010, Don has kept up his academic duties by lecturing to final year students and on the MSc programmes at LJMU, and the MSc programmes at the University of Chester and UCLAN.

References:

American Dietetic Association (2009). American college of sports medicine position stand: Nutrition and athletic performance. Medicine & Science in Sports & Exercise, 41, 709–731.

Cermack NM, van Loon LJC (2013). The use of carbohydrates during exercise as an ergogenic aid. Sports Med 43: 1139-1155.

Clarke ND., Campbell IT, Drust B, Evans L, Reilly T., & MacIaren DPM (2012). The ingestion of combined carbohydrates does not alter metabolic responses or performance capacity during soccer-specific exercise in the heat compared to ingestion of a single carbohydrate. Journal of Sports Sciences, 30: 699- 708

Clarke, ND, Maclaren, DPM, Reilly, T, and Drust, BD (2011) Carbohydrate ingestion and pre-cooling improves exercise capacity following soccer-specific intermittent exercise performed in the heat. European Journal of Applied Physiology, 111: 1447-1455.

Coyle EF, Coggan AR, Hemmert MK, Ivy JL (1986). Muscle glycogen utilization during exercise when fed carbohydrate. Journal of Applied Physiology 61: 165-172.

Coggan, AR, & Coyle, EF. (1989). Metabolism and performance following carbohydrate ingestion late in exercise. Medicine and Science in Sport and Exercise 21: 59-65.

Currell, K, Conway, S, & Jeukendrup, AE. (2009). Carbohydrate ingestion improves performance of a new reliable test of soccer performance. International Journal of Sports Nutrition and Exercise Metabolism 19; 34-46.

Currell, K., & Jeukendrup, A. E. (2008). Superior endurance performance with ingestion of multiple transportable carbohydrates. Medicine & Science in Sports & Exercise, 40: 275– 281.

de Oliveira, EP, Burini, RC, Jeukendrup, AE. (2014). Gastrointestinal complaints during exercise: Prevalence, etiology, and nutritional recommendations. Sports Medicine 44: S79-S85.

de Ataide e Silva T, Di Cavalcanti ME, de Souza A, de Amorim JF, Stathis CG, Leandro CG, & Lima-Silva AE (2014). Can Carbohydrate Mouth Rinse Improve Performance during Exercise? A Systematic Review. Nutrients, 6: 1-10.

Foster, C. (1990) Gastric emptying during exercise: Influence of carbohydrate concentration, carbohydrate source, and exercise intensity. In: Fluid Replacement and Heat Stress. National Academy of Sciences 39 :1-11..

Jeukendrup AE. (2004) Carbohydrate intake during exercise and performance. Nutrition 20: 669-677.

Jeukendrup AE. (2010) Carbohydrate and exercise performance: the role of multiple transportable carbohydrates. Current Opinion in Clinical Nutrition Metabolism Care 13: 452-457.

Jeukendrup, AE. (2014). A step towards personalized sports nutrition: Carbohydrate intake during exercise. Sports Medicine, 44: S25–S33.

El Sayed MS, MacLaren DPM, and Rattu AJ (1997). Influence of exogenous carbohydrate on muscle metabolism. Comparative Physiology and Biochemistry 118A, 789-803.

MacLaren, DPM, and Close, GL (2000). Effect of carbohydrate supplementation on simulated exercise of rugby league referees. Ergonomics 43: 1528-1537.

MacLaren DPM, Reilly T, Campbell IT, and Hopkin C (1999). Hormonal and metabolic responses to maintained hyperglycaemia during prolonged exercise. Journal of Applied Physiology 87, 124-131.

McCubbin AJ., Zhu A., Gaskell SK., and Costa RJS. (2020). Hydrogel Carbohydrate-Electrolyte Beverage Does Not Improve Glucose Availability, Substrate Oxidation, Gastrointestinal Symptoms or Exercise Performance, Compared With a Concentration and Nutrient-Matched Placebo. International Journal of Sport Nutrition and Exercise Metabolism, 30: 25-33.

Mitchell JB, Costill DL, Houmard JA, Fink WJ, Pascoe DD, and Pearson DR (1989) Influence of carbohydrate dosage on exercise performance and glycogen metabolism. Journal of Applied Physiology 67: 1843-1849.

Mohebbi, H, Campbell, IT, Keegan, MA, Malone, JJ, Hulton, AT, and MacLaren DPM. (2020).

Hyperinsulinemia and hyperglycemia promote glucose utilization and storage during low- and high-intensity exercise. European Journal of Applied Physiology, 120:

Moore, MC, Coate, KC, Winnick, JJ, An,Z, and Cherrington, AD. (2012). Regulation of hepatic glucose uptake and storage in vivo. Advances in Nutrition: An International Review Journal, 3: 286–294.

Murray R. (2006) Training the gut for competition. Current Sports Medicine Reports 5: 161–4.

Newell, ML, Wallis GA, Hunter AM, Tipton KD, Galloway SDR (2108) Metabolic responses to carbohydrate ingestion during exercise: associations between dose and endurance performance. Nutrients 10: 37.

Nicholas, C, Williams, C, and Lakomy, H. (1995). Influence of ingesting a carbohydrate-electrolyte solution on endurance capacity during intermittent high intensity shuttle running. Journal of Sports Science 13: 283-290.

Patterson S, and Gray S. (2007). Carbohydrate-gel supplementation and endurance performance during intermittent high-intensity shuttle running. International Journal of Sports Nutrition and Exercise Metabolism. 17: 445–455.

Phillips SM, Turner AP, and Sanderson MF, (2012). Carbohydrate gel ingestion significantly improves the intermittent endurance capacity, but not sprint performance, of adolescent team games players during a simulated team games protocol. European Journal of Applied Physiology. 112: 1133–1141.

Pöchmüller M., Schwingshackl L., Colombani PC., and Hoffmann G. (2018). A systematic review and meta-analysis of carbohydrate benefits associated with randomized controlled competition-based performance trials. Journal of the International Society of Sports Nutrition 13: 27-39.

Rosset, RR, Egli, L, and Lecoultre, V. (2017). Glucose–fructose ingestion and exercise performance: The gastrointestinal tract and beyond. European Journal of Sport Science 17: 874–884.

Shi, X., Summers, R. W., Schedl, H. P., Flanagan, S. W., Chang, R., and Gisolfi, C. V. (1995). Effects of carbohydrate type and concentration and solution osmolality on water absorption. Medicine & Science in Sports & Exercise, 27: 1607–1615.

Stellingwerff T, and Cox GR (2014) Systematic review: Carbohydrate supplementation on exercise performance or capacity of various durations. Applied Physiology Nutrition and Metabolism 39: 998 – 1011.

Stellingwerth T, Boon H, Gijsen AP, Stegen JHCH, Kuipers H, and van Loon LJC (2007) Carbohydrate supplementation during prolonged cycling exercise spares muscle glycogen but does not affect intramyocellular lipid use. Pflugers Archive 454: 635-647.

Sutehall, S., Muniz-Pardos, B., Bosch, A.N., Di Gianfrancesco, A., and Pitsiladis, Y.P. (2018). Sports drinks on the edge of a new era. Current Sports Medicine Reports, 17: 112–116.

Tsintzas OK, Williams C, Boobis L, and Greenhaff P. (1995) Carbohydrate ingestion and glycogen utilization in different muscle fibre types in man. Journal of Physiology 489: 243-250.

Vist GE., and Maughan RJ. (1994) Gastric emptying of ingested solutions in man: Effect of beverage glucose concentration. Medicine and Science in Sports and Exercise 26: 1269-1273.

Williams C., and Rollo I. (2015). Carbohydrate nutrition and team sport performance. Sports Medicine 45: S13-S22