

Module 1. The role of carbohydrate in the players' diet

Unit 1.1 An Introduction to Carbohydrate

The aim of this course is to build on your understanding of macronutrients in players' diet. The first unit in each module will introduce the macronutrient of interest, followed by Unit 2, which will discuss the macronutrients relevant to football. Knowing each macronutrient will provide the basis on how to compose meals and manipulate the players' diet to achieve health, performance and body composition goals. Carbohydrate is one of the most studied macronutrients in the disciplines of sports nutrition and football science. This is because, for nearly 100 years, carbohydrate ingestion has been associated with improved exercise/football performance. Specifically, the availability of carbohydrate has long been known to be important to provide fuel for the players' muscles and central nervous system. Thus, carbohydrate availability is vital in the maintenance of high intensity running and the skills required for football activity. The digestion and absorption of carbohydrate will be summarized, so that the factors that speed or inhibit the delivery of carbohydrates to the players' body can be understood. Common dietary sources of carbohydrate will be identified and, finally, the mechanisms by which carbohydrate may influence performance will be discussed.

Carbohydrate

Carbohydrates are composed of carbon, hydrogen, and oxygen. The general formula for carbohydrates is: CH_2O . The chemical formula for glucose is $\text{C}_6\text{H}_{12}\text{O}_6$.

KEY POINT

Carbohydrates include all the sugars, starches and fibres in a player's diet.

In general, carbohydrates can be classified by the number of monosaccharides (single sugars) they contain. The single sugars are joined by glycosidic bonds to form two or more sugars in sequence. A disaccharide is the term used to refer to two sugars joined together, which is very common. A polysaccharide is a chain of three to thousands of sugars (Figure 1). Carbohydrates with a large number of glucose sugars are called starches. Amylose is a

straight chain starch and is more resistant to digestion in comparison to amylopectin, which is a branched chain starch.

Figure 1: Carbohydrates classification by structure

Monosaccharides:

Single sugars



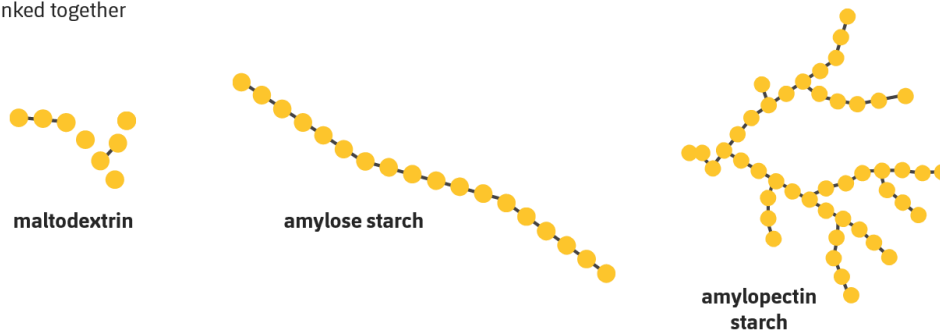
Oligosaccharides:

2-10 sugars bonded chemically:
disaccharides – very common



Polysaccharides:

Three to thousands of sugars
linked together



Source: Prepared by author-

DID YOU KNOW

Saccharide is another word for sugar.

Carbohydrate digestion and absorption

The players' body stores of carbohydrate are finite. Therefore, to maintain the supply of energy for muscle (and brain) metabolism, carbohydrates must be replenished. Thus, in football, the most prevalent interventions used to impact on a player's performance involve the ingestion of dietary sources of carbohydrate. Correspondingly, the effectiveness of nutritional interventions is dependent upon the regulation and absorption of carbohydrates by the gastrointestinal (GI) tract.

The GI tract is a tube approximately nine meters long that extends from the player's mouth to the anus. When players ingest food, it is moved along the GI tract by strong peristaltic contractions. As the food is moved through the GI tract, it is mixed with extensive secretions of fluid containing various enzymes which aid in the digestion and absorption of nutrients.

DID YOU KNOW

When food is ingested, it gets chewed and mixed into a small round mass, and when swallowed is referred to as a "bolus".

The digestion of carbohydrates begins in the player's mouth. Food is broken down mechanically by mastication and mixed with saliva secreted by the salivary glands. The salivary amylase begins the breakdown of starch into smaller oligosaccharides. It is in the mouth where the tongue begins the analysis of food, determining whether it is nutritive (i.e. sugar) and should be ingested or is potentially harmful and, therefore, should be expectorated (Katz, Nicoletis et al. 2000).

The palatability of solutions is an important consideration when providing drinks to players. Several studies have reported that flavouring or sweetening beverages can substantially increase the voluntary intake of fluid both during exercise and recovery from exercise (Passe, Horn et al. 2000). Nevertheless, it is advised to understand and provide several different flavours of beverage which the player "prefers". This will allow the flavour of drinks to be changed either during the week or during the season to avoid flavour fatigue.

DID YOU KNOW

Mastication is another word for chewing

Food and beverages move from the player's mouth to the stomach. In the stomach, the food is moved vigorously to mix with gastric juices, secreted from the stomach glands, and form chyme. The stomach acts as a reservoir to receive food whilst intermittently delivering the chyme to the intestine. Ingested food stays in the stomach between 1 and 4 hours.

The absorption of nutrients occurs almost entirely along the walls of the small intestine. Therefore, the benefits of ingesting carbohydrates and fluids at rest or during football exercise are only obtained following the movement of chyme from the stomach into the duodenum (gastric emptying). Numerous factors, such as temperature (Costill and Saltin 1974), osmolality (Brouns, Senden et al. 1995) and pH (Hunt and Knox 1968) have been investigated as possible regulating factors of gastric emptying. However, none appear to be of greater importance than the volume or energy content of the ingested food.

KEY POINT

The metabolic benefits of ingesting carbohydrates and fluids at rest or during exercise are only obtained following the movement of chyme (food) from the stomach into the intestines.

Energy density



Water empties rapidly from the stomach. As carbohydrate is added to the solution, typical in sports drinks, the energy content of the solution is increased and the rate of gastric emptying is slowed. Studies investigating the ingestion of equivalent volumes of solutions have reported that drinks containing a carbohydrate content of 2.5% or less empty at approximately the same rate as water. Increasing the concentration of carbohydrate in the solution to 4-5% has been shown to result in a small but significant slowing of gastric emptying (Costill and Saltin 1974). More recently, it was suggested that gastric emptying could be increased by including a mixture of carbohydrates within the ingested solution. For example, adding fructose to a glucose solution has been shown to increase fluid delivery compared to a glucose only solution (Jeukendrup and Moseley 2008). The fact that most sports drinks have a carbohydrate concentration of 5 - 8% is reflective of the balance between maintaining a high rate of gastric emptying whilst delivering adequate concentrations of carbohydrate to the intestine. It is for this reason that 6% carbohydrate beverages would be recommended for players to ingest "during" the match or breaks in play.

Gastric volume

The stomach is highly distensible with the ability to change its capacity from approximately 50 ml when empty to 1000 ml when full, with only minimal changes in gastric pressure (Maughan and Murray 2001). The gastric volume is an important determinant of the rate of gastric emptying. For example, the ingestion of different volumes of a dilute glucose solution (200, 400, 600, 800 and 1000 ml) was shown to influence the rate of gastric emptying, recorded 15-minutes following ingestion (Costill and Saltin 1974). The ingestion of 600 ml resulted in a greater rate of emptying in comparison to 400 ml, which emptied faster than 200 ml. However, when volumes above 600 ml were ingested, there was no further benefit regarding the gastric emptying rate. This suggests that there is a limit at which additional fluid ingestion results in no further benefit to gastric emptying. Of course, advising the ingestion of volumes of 600 ml or greater is not practical and would not be recommended for players prior to training or matches. Studies which have employed a repeated drinking design suggest that the gastric volume and, therefore, the pattern of drinking during exercise have a significant influence on the rate of both carbohydrate and water delivery from any solution (Noakes, Rehrer et al. 1991). Thereby, refilling the stomach at regular intervals ensures the volume of the stomach is kept high and faster rates of gastric emptying can be maintained. However, unfortunately, this pattern of drinking is not possible during football match play. Instead, carbohydrate intakes can be achieved by ingesting more concentrated carbohydrate beverages (12%) before and at half time, with *ad-libitum* water intake to allow for individual fluid needs (Funnell, Dykes et al. 2017, Harper, Stevenson et al. 2017).

Carbohydrate absorption

After leaving the stomach, the chyme enters the duodenum, which is the first part of the small intestine that links the stomach with the jejunum. The duodenum receives bile from the gall bladder and pancreatic secretions, important to facilitate the absorption of fats and the digestion of proteins.

The jejunum (approximately 2.5 m in length) is a long, convoluted tube, characterised by strong, rapid, peristaltic contractions that sweep along its length. Most of the absorption of nutrients (carbohydrate, electrolyte and water) occurs in the jejunum region. Carbohydrates entering the small intestine must first be hydrolysed to its constituent monosaccharides before their absorption and utilization (Holdsworth and Dawson 1964). Water is absorbed passively as a result of an osmotic gradient created between the intestinal lumen and the interstitial space by the movement of glucose, sodium (Na⁺) and other nutrients.

The terminal digestion of carbohydrate occurs at or on the surface of the intestinal epithelium (Holmes 1971). Disaccharides are located on the brush border and microvillous membrane. "The brush border contains several disaccharidases which hydrolyse the end products of pancreatic α -amylase digestion... Thus, maltase acts on maltose-liberating glucose, sucrase on sucrose-releasing glucose and fructose, and lactase hydrolyses lactose to glucose and galactose" (Holmes 1971).

The transport mechanisms involved in the absorption of monosaccharides from the intestinal lumen are located in the brush border of the epithelial cells. The absorption of glucose occurs mainly in conjunction with the active transport of Na⁺. Dietary monosaccharides are transported across the brush-border membrane of enterocytes (intestinal absorptive cells) by the Na⁺/glucose cotransporter SGLT1 (Dyer, Vayro et al. 2003). Glucose and galactose compete for the same transport. Fructose is absorbed by a separate transport system (Holdsworth and Dawson 1964). Fructose is transported by a different protein-carrier, GLUT-5 (Kristiansen, Darakhshan et al. 1997), which is not Na⁺ dependent and is less rapidly absorbed than glucose (Fordtran 1975). The hepatic portal system is a system of blood vessels consisting of hepatic portal veins which carry nutrients absorbed from the intestine to the player's liver for processing.

The final section of the small intestine is the ileum (approximately 3.6 m long), which provides a reserve of absorptive capacity. The ileum terminates at the ileocecal valve, where the large intestine begins. The large intestine (approximately 1.6 m in length) consists of the cecum, appendix, colon and anal canal. The colon is the main part consisting of three relatively straight sections: the ascending colon, the transverse colon

and the descending colon – and sigmoid colon that leads to the rectum and, in turn, to the anal canal. The large intestine receives the liquid by-product of digestion. The absorption of most water and electrolytes along its tract forms the solid consistency of faeces. Peristalsis is slower and less propulsive in the large intestine if compared to the small intestine. Food can remain in the large intestine from approximately 10 h to several days.

DID YOU KNOW

Flavour fatigue refers to players becoming “bored” with the taste of a drink or food. If this happens, it can make it more difficult to encourage voluntary fluid intake. Being able to provide a variety of flavours reduces the risk of flavour fatigue over a season.

Glycogen

Carbohydrate is available to the working muscles from blood glucose and muscle glycogen. Stores of glycogen are found in the liver (80 – 100 g) and muscles (250-500 g) and there is also a small energy reservoir of glycogen in the brain (3-4 mol/g).

The structure of glycogen granule consists of type A and type B chains. Both chains are uniform in length with a mean value of thirteen glucose residues. The A chains are not branched (1-4 glycosidic bonds), whereas the B chains are branched, each with two branching points (1-6 glycosidic bonds) that create either A or B chains. There are 4 glucose residues between branches and a tail after the second branch in the B chains. Glycogen phosphorylase can only work on A chains, as the tail of the B chain is too short (~4 glucose residues, the limit of phosphorylase action). As a consequence of the degree of branching ($r=2$), the number of chains on any tier is twice that of the previous one. Therefore, the glycogen molecule is organised into a spherical shape and arranged into concentric tiers, with every A chain in the most external tier. The arrangement of glucose into the glycogen polymer is a very efficient way of amassing large quantities of glucose, without causing a significant change in cell osmolality (Melendez-Hevia, Waddell et al. 1993). In the liver, glycogen can be formed directly by ingested glucose or through gluconeogenic precursors such as lactate, alanine and pyruvate (Katz and McGarry 1984).

Figure 2: Glycogen structure

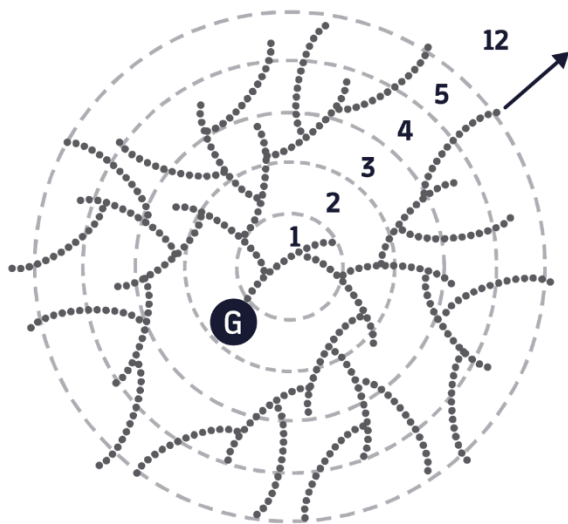


Figure 2: The molecule has a spherical shape with 12 concentric tiers in the full molecule (only 5 are shown in the diagram). Glycogenin (G) the protein primer for glycogen synthesis is located at the core of the granule.

Source: Adapted from Melendez-Hevia et al., 1993.

DID YOU KNOW

Glycogen phosphorylase is the enzyme that breaks down the glycogen molecule into the single sugar (glucose) units.

KEY POINT

Storing carbohydrate as glycogen allows the accumulation of a large quantity of cytoplasmic glucose, without causing a significant change in cell osmolality.

Central recognition

There is emerging evidence of a “central” response to ingesting carbohydrates. This has been investigated by using functional magnetic resonance imaging (fMRI, a method which can measure the activity of the brain). In one study, some participants ingested 300 ml of water (control), others glucose solution, others an aspartame (sweet taste) solution, and others a maltodextrin (non-sweet carbohydrate) solution. It was reported that both sweet taste and energy content are required for a hypothalamic response (Smeets, de Graaf et al. 2005).

In addition, the activation of the hypothalamus was reported to be dose dependant to carbohydrate, i.e. the greater concentration of carbohydrate the greater the response. Thus, a relationship was observed between the hypothalamic response and changes in the blood insulin concentration (Smeets, de Graaf et al. 2005).

Both glucose (sweet) and maltodextrin (non-sweet) in the mouth have been reported to activate regions in the brain associated with reward. These findings suggest that there may be a class of, so far unidentified, oral receptors that can detect and respond to carbohydrates independently of sweetness (Chambers, Bridge et al. 2009). Regions of the brain associated with reward are also believed to mediate behavioural responses to rewarding stimuli, such as taste (Rolls 2007).

Type of carbohydrates

Different types of carbohydrates elicit different physiological responses following ingestion. This is because carbohydrates are digested at different rates, which influences the players' blood glucose concentrations. Carbohydrate foods are commonly classified as either 'simple' or 'complex'. The classification is largely based on the quantity of fibre the carbohydrate food source contains, which influences its digestion and absorption, and subsequently, its impact on the player's blood glucose concentrations.

The Glycaemic Index is a method used to rank how carbohydrate foods impact on blood glucose concentrations after eating them (Stevenson, Williams et al. 2005). Thus, a more accurate classification of carbohydrates is based on the glycaemic response two hours after the ingestion of a standard amount of food. The reference food is usually glucose or white bread, which has a glycaemic index of 100. Those carbohydrates that result in a slow rise and a low peak in blood glucose concentrations are termed "low glycaemic" carbohydrates. Those carbohydrates that produce a rapid rise and high peak in blood glucose concentrations are termed 'high glycaemic' carbohydrates. The glycaemic index of carbohydrate can be calculated as follows:

$$\text{Glycaemic index} = \frac{\text{Area under the curve of the test food}}{\text{areas under the curve for reference food}} \times 100.$$

The value of high-glycaemic index carbohydrates is between 71 and 100; moderate-glycaemic index foods are between 56 and 70; and low-glycaemic index carbohydrates have a score equal to or less than 55. Examples of high, moderate and low glycaemic-index foods are shown in Figure 3.

Figure 3: Examples of high-, moderate- and low-glycaemic index carbohydrate foods

High	Moderate	Low
<ul style="list-style-type: none">• glucose• sucrose• cane• maple syrup• corn syrup• honey• corn flakes• raisins• white rice• white bread	<ul style="list-style-type: none">• whole grain bread• spaghetti (pasta)• corn• oatmeal• orange• grapes	<ul style="list-style-type: none">• lentils• yogurt• peanuts• peas• beans• apple• peach• pear• figs• milk

Source: Prepared by Author.

It is important to note that the glycaemic index of any given food may vary considerably among players. The overall quantity of carbohydrates a player eats is also important. In addition, the principle of glycaemic index is limited, as players will typically ingest “foods” and “meals” which contain a variety of carbohydrate sources as well as other nutrients. It is rare for players to ingest carbohydrates in isolation, with the exception of acutely before and during exercise, which will be discussed in the next section. The foods listed in Figure 3 aim to provide a guide. Knowledge of high-glycaemic foods, for example, may be useful when attempting to reduce the amount of energy-dense foods in a players’ diet while managing body composition. In general, replacing high-glycaemic index foods with foods with a lower glycaemic index, such as beans, lentils, fruits and vegetables, improves the satiety of the player, constitutes a good carbohydrate choice and can help the player manage their body weight. When translating this piece of advice to the player, using more common terms such as “simple” and “complex” and applying them to different foods may be more relatable and may help them make better carbohydrate choices depending on the requirement.

KEY POINT

The energy yield of carbohydrate is 4 kcal/g of carbohydrate.

Carbohydrates ingestion during exercise

Ingesting carbohydrates during exercise has several key effects, which may potentially influence football performance. Ingesting carbohydrate, especially during prolonged (>60 minutes), intense (>60% maximal oxygen uptake) football exercise helps delay the onset of fatigue by:

- preserving blood glucose concentrations;
- maintaining the required rate of carbohydrate oxidation;
- reducing liver glycogen breakdown;
- reducing muscle glycogen breakdown.

Research studies have investigated the effect and efficacy of ingesting different types of carbohydrates during exercise. Special techniques are used to determine the quantity of carbohydrates that has been taken up from the blood and used for energy metabolism. This method captures when and how much of the ingested carbohydrate is used and a comparison between the different types of carbohydrates can be made.

Much of our understanding on carbohydrate used during exercise is based on the studies of Professor Asker Jeukendrup, Professor Louise Burke and their respective research groups (Burke, Hawley et al. 2011). During exercise, the majority of carbohydrate oxidation takes place inside the muscle. When carbohydrate is ingested during exercise and appears in the circulation, it will be used by muscles (Jeukendrup, Wagenmakers et al. 1999). Increasing the quantity of carbohydrate ingested during exercise from 1 g/min to 3g/min has been shown to have no influence on the rate at which carbohydrate is used by the body (Jentjens, Cale et al. 2003). Instead, ingesting different types of carbohydrates may improve the use of carbohydrate during exercise. The rate of ingested (exogenous) carbohydrate use typically peaks at 60 minutes and beyond the following ingestion.

The ingestion of carbohydrates during exercise, including glucose, fructose, galactose, sucrose, maltose and glucose polymers, have been investigated (Figure 1). In summary, glucose is used by the muscle at a rate of 0.8 g/min. Fructose is oxidized at lower rates than glucose and galactose oxidation rates are half that of glucose (Burrelle, Lamoureux et al. 2006). These differences are due to the aforementioned absorption of the different carbohydrates and to the fact that fructose and galactose must be delivered to the liver and converted to glucose first, before they can be used for metabolism in the muscle. The disaccharide maltose and glucose polymers are used at the same rate as glucose. This suggests that the digestion of these sources of carbohydrate is not a limiting factor for their use. Interestingly, sucrose (glucose + fructose) ingestion has been shown to result in high rates of carbohydrate use. Less common carbohydrate sources, such as isomaltulose and trehalose, are oxidized at lower rates. The different types of carbohydrates can, in general, be divided into two categories: (a) fast carbohydrates, which are those used rapidly during exercise (up to ~60 g/h or 1 g/min); (b) slow carbohydrates, which are those that are oxidized relatively slowly during exercise (up to ~30 g/h or 0.5 g/min). Rapidly oxidized carbohydrates include glucose, maltose, sucrose, maltodextrin and amylopectin starch. Slower oxidized carbohydrates include fructose, galactose, isomaltulose, trehalose and amylose (Jentjens and Jeukendrup 2005).

The use of ingested carbohydrate during football exercise is dependent upon the speed at which it can be digested and absorbed to enter the blood stream. Thus, the digestion and absorption of carbohydrates is the major limiting factor to their use. With respect to the digestion of the different carbohydrate sources discussed earlier, the ingestion of a combination of carbohydrates that use different intestinal transporters for absorption has been shown to increase carbohydrate delivery and use by the muscle. An increase in carbohydrate oxidation is observed when the transport of glucose in the intestine is saturated (SGLT1) and a different transport system (GLUT-5) is used to transport carbohydrate simultaneously, i.e. glucose and fructose (Jentjens, Achten et al. 2004).

Achieving high exogenous rates of carbohydrate may be more relevant to endurance sports (≥ 90 minutes in duration), as it is unlikely the glucose transporters will become saturated during football with current ingestion recommendations (Unit 2). Nevertheless, the ingestion of multiple transportable carbohydrates (glucose, sucrose/fructose) may be relevant to players, as they have also been shown to increase fluid delivery and reduce the risk of gastrointestinal distress (Baker and Jeukendrup 2014).

Dietary fibre

Dietary fibre is the parts of plants that can be eaten but are not digested or absorbed in the small intestine. Dietary fibre is completely or partially broken down by the bacteria in the large intestine. Sufficient fibre in the players' diet is associated with a number of health benefits, including lowering the risk of heart disease, reduced risk of constipation and softening of stools (making them easier to pass). In general, adult players aged 16 years and older should aim to ingest approximately 30 g of fibre daily. However, high fibre foods are discouraged in the pre-match meal where the delivery of carbohydrate and increase in the body glycogen stores is the priority. Examples of dietary sources of fibre for the player to consume include:

- Breakfast cereals (high fibre): porridge oats, oat bran. Sweet potato, potato skin, wholemeal or wholegrain bread and pasta
- Pulses as baked beans and hummus
- Vegetables: broccoli, carrot, peas, frozen mixed vegetables, green beans.
- Fruits: All; apple, pear, cherries, strawberries, Kiwis, raspberries, blackberries, plums, bananas and oranges
- Nuts: almonds, hazelnuts and peanut

DID YOU KNOW

Fibre in the players' diet is resistant to digestion and absorption in the intestine.



Summary

- Carbohydrates can be classified by the number of monosaccharides (single sugars) they contain and can be broadly categorized as “simple” or “complex”, depending on their digestion and absorption profile.
- Carbohydrates with a “fast” digestion and absorption rate are recommended during exercise.
- Carbohydrate digestion begins in the mouth and is transported into players’ body by the small intestine.
- Carbohydrate is stored as glycogen, which constitutes an efficient way to store large quantities of carbohydrate in the body.
- Fibre is a carbohydrate that cannot be absorbed by the body but which is important for players’ general and gastrointestinal health.

Unit 1.2 Carbohydrate and Football

The aim of this unit is to build your understanding of the role that carbohydrates play on football performance. A brief historical of the literature will be done to provide a background on how we have arrived at the current recommendations. Importantly, this unit will address how carbohydrates influence football performance and the potential mechanisms which underpin the efficacy of carbohydrate feeding for football-specific performance.

Historical perspective

The benefits of carbohydrate can be traced back to the early 1900s. The early observations made by the Boston marathon in 1925 was notorious (Gordon, Kohn et al. 1925). In this study, it was reported that ingestion of sweets (sugar/confectionery) by runners during the run prevented hypoglycemia. Importantly, ingesting sweets also improved race times in comparison to races when no sweets were consumed.

For intermittent sports, similar work was initiated at the University of Florida, United States, in the 1970's. In 1971, Dr Cade and colleagues reported the effects of exercise on blood glucose changes in four players of the University of American football team during a vigorous two-hour training session, with no food or fluid intake (Cade, Free et al. 1971). The American football players' blood glucose concentration decreased progressively throughout the practice. This observation was followed by a study in 1972 to determine whether carbohydrate ingestion could prevent the disturbances in blood glucose concentration (Cade, Spooner et al. 1972). Cade and colleagues found that performance during a standardized walk-run test (7-mile course) was significantly improved when 1 L of a 3% glucose-electrolyte solution was consumed compared with when the players drank the same volume of water. Blood glucose concentration decreased during the water trials (by 1.3 mmol/L), whereas it increased (by 1.0 mmol/L) when the players were drinking the 3% glucose-electrolyte solution.

At a similar time, the importance of muscle glycogen to football performance was also being investigated in Europe. By using the muscle biopsy technique, Agnevik (1970) reported that male football players glycogen stores were nearly empty of muscle glycogen after a 90-minute football match (Agnevik 1970). The greatest rate of glycogen depletion occurred in the first half of the match. In a similar study, muscle samples were biopsied from the quadriceps femoris of recreational players at the beginning, halftime, and end of a football match (Saltin 1972).

Professor Bengt Saltin (1973) reported that muscle glycogen concentrations were significantly lower on completion of the match (pre: 96 mmol/kg wet weight (w.w.); halftime: 32 mmol/kg w.w.; end: 9 mmol/kg w.w.). Significantly, those players who began the match with low muscle glycogen (45 mmol/kg w.w.) had almost depleted stores by halftime. This was the first study to report the performance implication associated with muscle glycogen concentrations. Specifically, players who began the match with high muscle glycogen covered a greater distance and spent more of the total time completing high-intensity runs compared with those players who began the game with low muscle glycogen (24% vs. 15% of the match time in high vs. low muscle glycogen players, respectively). These findings corresponded with studies analysing the activity profile of professional football players in the UK. In these studies Professor Thomas Reilly reported that players covered less distance in the second half compared with the first half of a match. Since these seminal carbohydrate studies there has been continued research exploring carbohydrate ingestion and intermittent sports performance (Baker, Rollo et al. 2015). Key to our understanding on carbohydrate ingestion for sports performance has been the contribution of Professor Clyde Williams OBE and his research team at Loughborough University in the UK.

DID YOU KNOW

Hypoglycemia refers to low levels of blood glucose concentrations. Blood glucose concentrations of ≤ 3 mmol/L.

Match preparation

Carbohydrate is a key macronutrient for players during match preparations. On the day before to the match (match day -1), players are advised to ingest between 6-8 g of carbohydrate/kg body mass (BM) to increase muscle glycogen stores. Due to the invasive procedures required, to date it has not been possible to establish the glycogen use of male or female players during an elite match. Nevertheless, data from research studies where football activity has been simulated or “friendly” games played demonstrates that approximately 50% of muscle fibres are classified as empty or partially empty after match play (Krustrup, Mohr et al. 2006). When there are multiple matches in a week, for example, domestic fixtures, European competition, international games, carbohydrate intake should be maintained or increased up to 10 g/kg BM for the 48-72 hours between games. This elevated carbohydrate intake has been shown to promote adequate glycogen storage and maintain running capacity between games (Nicholas, Green et al. 1997). Studies on professional players suggest that carbohydrate consumption is less than recommendations and are in fact closer to an intake approximately 4 g/kg body mass (Anderson, Orme et al. 2017). To this end, practitioners should focus on the availability of

rich carbohydrate foods (Unit 1), when carbohydrate intake needs to be elevated. The intake of carbohydrate should be prioritized at the expense of fat intake (and possibly protein intake) to ensure adequate glycogen restoration.

Pre-match carbohydrate

On match day, the ingestion of carbohydrates before, during and after exercise is one of the most important considerations. Within the guideline of 6–8 g/kg body mass carbohydrate (Table 1), it is recommended that players consume a carbohydrate-rich meal (2–3 g/kg body mass) 3–4 hours before kick-off in order for players to begin the match with adequate glycogen stores (Williams 1993).

The pre-match meal is important to “top-up” liver glycogen stores, which can be reduced by about 50% following an overnight fast. This is particularly important for players when the kick-off time is scheduled for a lunchtime or early kick-off. In these circumstances, the intake of carbohydrates on the day prior to the match also takes on greater importance.

The benefits of pre-match meals may also extend to players technical abilities. Briggs and colleagues showed that Academy football players dribbling speed was enhanced when a larger breakfast (500 kcal versus 250 kcal, with 60% carbohydrate) was ingested 135 minutes before a match (Briggs, Harper et al. 2017). Indeed, data from many studies suggest that higher carbohydrate intakes before as well as during a match can delay fatigue (Holway and Spriet 2011) and enhance the capacity for intermittent high-intensity exercise (Russell and Kingsley 2014).

DID YOU KNOW

Professor Bengt Saltin was a world leading human physiologist. As a medical doctor he devoted his life to researching the effects of physical exercise on health and performance. His studies continue to inspire scientists to study sports nutrition and the nature of human physiology (3 June 1935 — 12 September 2014)
(http://www.exercisephysiology.net/Bengt_Saltin.asp).

Carbohydrate during match play

The available research shows performance benefits in protocols simulating football matches when carbohydrate is consumed during exercise at rates of ~30–60 g/h (Baker, Rollo et al. 2015). In general, it is recommended that 30–60 g of carbohydrate be split between post warm-up and half time to meet these guidelines (Funnell, Dykes et al. 2017, Harper, Stevenson et al. 2017).



Current practices of elite players have been reported to be in the lower end of recommended carbohydrate intakes. For example, one study reported that players in the English Premier League reported carbohydrate intakes of 32 g per hour during a match (Anderson, Orme et al. 2017). This may be attributed to match scheduled breaks in play which lends ingestion opportunities to the warm-up and half time. Low carbohydrate intake may also be due to the players fear or actual experience of gastrointestinal problems during matches. This may be alleviated through practicing carbohydrate intake on training days. Stoppages during the match may provide valuable opportunities for players to ingest carbohydrates and fluids. In these situations, the ingestion of well-formulated sports drinks is advised to optimise the delivery of fluid and carbohydrate to the player.

Despite the prevalence of extra time during major international football tournaments, there has been little research in this area of nutrition. It is intuitive that carbohydrate intake may require special attention in matches where extra time (2 x 15 minutes) is played. Studies that have shown improved endurance capacity (running time to fatigue) with carbohydrate ingestion following 90 minutes of simulated match play are relevant to extra time. However, there has been only one study to directly investigate the impact of carbohydrates on extra time performance (Harper, Briggs et al. 2016). In this study, carbohydrate-electrolyte gel ingestion raised blood glucose concentrations and improved dribbling performance during the extra-time period of simulated football match play.

HOW IMPORTANT EXTRA TIME IS?

Prevalence of extra time and penalties in three major competitions since 2010:

European Championships

2012 Euros: 2 games went to extra time (2/2 to penalties)

2016 Euros: 5 games went to extra time (including the final)

World Cup

2014 Brazil World Cup: 8 games went to extra time (including the final)

2018 Russia World Cup: 5 games went to extra time (4/5 to penalties)

Champions League

Champions League final 2016: extra time and penalties

Champions League final 2014: extra time

Champions League Final 2012: extra time and penalties

Carbohydrate and football skill



Carbohydrate ingestion during intermittent exercise is associated with improved shooting performance (Currell, Conway et al. 2009, Russell and Kingsley 2014), dribbling speed (Harper, Stevenson et al. 2017) and passing (Ali and Williams 2009), although the effects on sprinting, jumping, change of direction speed, and cognition are less consistent (Baker, Rollo et al. 2015). It is likely that inconsistencies in research findings are the result of small sample sizes, variability in carbohydrate intake protocols (e.g. amounts consumed) and poor measurement precision. It is important to note that “skill” *per se* is extremely difficult to assess. This is because of the typical day-to-day variation in players’ ability to apply a skill. In addition, the execution (accuracy/speed) of the skill needs to be quantified. Match-specific conditions, such as the crowd, opposing player pressure, speed to play, are almost impossible to replicate in laboratory conditions.

Recovery from match play

After a competitive match, the aggressiveness of the nutrition recovery strategy will depend on when the player is next required to train or perform. Nevertheless, the general principle is to speed up the time required for the player to fully recover (Nedelec, McCall et al. 2012). This is particularly important during periods of fixture congestion (2-3 matches per week) and pre-season. To speed the players’ recovery, players should rapidly replenish their carbohydrate stores. Post-match meals should target a carbohydrate intake of ~1 g/kg/h in the first 2 hours after exercise and continue for 4 hours (Burke, Collier et al. 1996). This recommendation is based on the observation that the rate of muscle glycogen restoration can be increased when carbohydrate is fed immediately after exercise in comparison to when carbohydrate feedings are delayed two hours post exercise (Ivy 1998). The carbohydrate intakes can be met by providing carbohydrate beverages and snacks in the changing rooms followed by post-match meals. The post-match meal can be provided whilst travelling and/or upon returning home.

When assessed 24 hours post exercise, the timing of carbohydrate feedings has little impact on glycogen concentrations, as long as a sufficient carbohydrate has been ingested (Parkin, Carey et al. 1997). Nevertheless, football activity involves a significant eccentric component. Eccentric muscle contractions are associated with muscle damage, which may interrupt the uptake of glucose into the muscle. Consequently, muscle glycogen resynthesis may be impaired following football matches or training with a large eccentric component (Asp, Daugaard et al. 1995). To this, end it is important to combine carbohydrate with other nutrition recovery strategies to speed the muscle remodelling and glycogen resynthesis (Module 2).

DID YOU KNOW

The autonomic nervous system regulates actions that occur in the player's body without their voluntary control, for example, heart rate or blood pressure. It consists of both the sympathetic and parasympathetic nervous systems.

The sympathetic nervous system prepares the player's body for stress (football competition), also known as the fight or flight response, for example increasing heart rate and increasing blood flow to the muscles.

The parasympathetic nervous system works in opposition and helps maintain the player's normal bodily functions when stimulated, such as reducing the heart rate and increase digestive functions.

Training

Carbohydrate requirements for training were discussed in later courses. Please see Table 1 for a summary of different training occasions and corresponding recommended carbohydrate intakes (Modified from UEFA consensus document, 2019).

Table 1: Carbohydrate requirements for training

Training occasion	Training objectives	Desired training adaptations	Typical daily external training load parameters (quantified during pitch-based training: GPS; HSR, denotes high speed running => 19,8 km.h⁻¹)	Suggested daily CHO range	Comments
Pre-season training	<ul style="list-style-type: none"> • Player health (avoid illness/injury) • Improve player physical / mental / tactical qualities • Prepare players for a full playing season 	<ul style="list-style-type: none"> • Increase aerobic and anaerobic fitness • Increase/maximise strength, speed, power for performance and injury prevention • Increase lean mass / reduce fat mass 	Duration (min): 60-180 Total distance (km): 3-12 HSR (m): >400	4-8 g.kg ⁻¹ body mass	Carbohydrate ingestion range accommodates likely variations in training in loads as well as individual training goals (e.g. manipulation of body composition to accommodate weight loss and fat loss or weight gain and lean mass gain)
In-season training (1 game per week)	<ul style="list-style-type: none"> • Maintain / improve player physical qualities • Player health (avoid injury / illness) 	<ul style="list-style-type: none"> • To maintain aerobic and anaerobic fitness, strength and lean mass 	Duration (min): 45-90 Total distance (km): 2-7 HSR (m): >400	3-8 g.kg ⁻¹ body mass	Carbohydrate ingestion range accommodates likely variations in loads across the micro-cycle (e.g. low load days and MD-1 CHO loading protocols) as well as individual training goals
In-season training (congested fixture periods)	<ul style="list-style-type: none"> • To avoid injury and illness • To accelerate recovery 	<ul style="list-style-type: none"> • Restore muscle function as quickly as possible • Promote glycogen resynthesis • Fluid replacement: rehydration • Alleviate mental fatigue 	Duration (min): <60 Total distance (km): <3 HSR (m): <50	6-8 g.kg ⁻¹ body mass	Carbohydrate ingestion range is to accommodate the requirement to replenish muscle glycogen stores in the 48-72 h period between games

Source: Modified from UEFA consensus document, 2019.



MECHANISMS

Metabolic Effects of Carbohydrate

Fundamentally, the deterioration of running and skill performance during football is a consequence of fatigue. Due to the physiological demands of football fatigue manifests at different times during training and matches and can be a consequence of distinctly different mechanisms. For example, players experience temporary fatigue following the most intense periods throughout a game and more permanent fatigue in the final phases of a game (Baker, Rollo et al. 2015).

The precise mechanisms underpinning transient fatigue are beyond the scope of this module but are unlikely to be influenced by carbohydrate provision as long as glycogen concentrations remain above a certain critical level (~200 mmol/kg dry weight (d.w) in active muscle (Baker, Rollo et al. 2015).

It is well established that carbohydrate and fat are the two primary fuel sources oxidized by skeletal muscle tissue during prolonged (endurance-type) exercise. The relative contribution of these fuel sources largely depends on the exercise intensity and duration, with a greater absolute and relative contribution from carbohydrate as exercise intensity increases above 60% $\dot{V}O_{2\max}$ (Cermak and van Loon 2013). Muscle glycogen provides a rapidly available substrate for energy production when completing high intensity efforts during intermittent activity (Baker, Rollo et al. 2015).

For example, in a single 6-sec sprint muscle glycogen contributes ~50% to adenosine triphosphate (ATP) turnover within the muscle (Gaitanos, Williams et al. 1993). Thus, the consequence of repeated sprint activity is a net reduction in muscle glycogen concentrations (Bendiksen, Bischoff et al. 2012). Although glycogen is depleted in type I and II muscle fiber types, it may be the specific depletion of glycogen in type II muscle fibers that results in the significant loss in power output during repetitive sprints. It may be that the decrease in muscle glycogen below a critical level in response to variable intensity running contributes to the more permanent fatigue experienced towards the end of a game (Mohr, Krstrup et al. 2005). Furthermore, the impact of low muscle glycogen is likely to have a greater consequence in football where the endogenous store of glycogen is insufficient to meet the energy demands over the duration of the exercise (e.g., extra time) (Baker, Rollo et al. 2015).

In one study (employing the Loughborough intermittent shuttle running test (LIST); the protocol mimicking the demands of football, muscle biopsy analysis revealed a significant reduction in muscle glycogen concentration in type I and II muscle fibers

from before to after exercise (Nicholas, Tsintzas et al. 1999). However, muscle glycogen use was reduced by 22% when players ingested a 6.9% carbohydrate solution throughout exercise compared with placebo. The preservation of muscle glycogen is a viable mechanism to explain why players consuming carbohydrate are able to sustain high-intensity running in the second half of live football matches. For example, the performances of ten football players were video-recorded on two separate occasions: when players drank either 400 mL of a concentrated carbohydrate solution (16% maltodextrin) or placebo before and during halftime of the match. The players who drank the carbohydrate solution ran ~40% greater distance during the second half of the game, in comparison with when the placebo beverage was consumed (Kirkendall, Foster et al. 1988) (Baker, Rollo et al. 2015).

An important consideration when interpreting performance data during any team sport is the high variability observed between games, as the tactical formation and level of competition have been reported to influence the distance a player covers at high speed. Thus, although an interesting measure, assessing the impact that carbohydrate ingestion has on team sport performance in live matches is challenging due to the complex interaction between physical and technical components (Rollo 2019).

A study using the Copenhagen football Test (CST) obtained frequent and rapid measurements of muscle and blood metabolites allowing in sight regarding the anaerobic energy turnover and rates of muscle glycogen use in various phases of a 90-min simulated football match (Bendixsen, Bischoff et al. 2012). Both type I and type II muscle fibers exhibited significant glycogen depletion, with ~80% of fibers being depleted or almost depleted (<200 mmol/kg d.w) of glycogen after 90 minutes of intermittent activity. Muscle glycogen concentrations <~200 mmol/kg d.w have been shown to significantly decrease the glycolytic rate. In addition, the depletion of muscle glycogen in sub-cellular glycogen compartments (i.e., sarcoplasmic reticulum) results in concomitant reductions in muscle calcium handling. A reduced rate of sarcoplasmic reticulum vesicle calcium release has been reported to reduce peak power output (Gejl, Hvid et al. 2014). Thus, low muscle glycogen influences the flux of calcium and impairs the contractile property of the muscle (Baker, Rollo et al. 2015).

DID YOU KNOW

Sarcoplasmic reticulum is structure found within muscle cells which stores and releases calcium in the muscle required for muscle contractions.

The rate of muscle glycogen utilization has been found to decrease from the first to second half of a simulated football match. Specifically, in a study employing the Copenhagen football Test, the rate of muscle glycogen use was reported to be

highest during the warm-up and the first 15 min of simulated play (Baker, Rollo et al. 2015). By comparison, muscle glycogen use was significantly lower from 15 to 60 minutes and lower still from 60 to 90 minutes.

In a study utilizing the LIST protocol, participants ingested either a 6.4% carbohydrate-electrolyte solution (~90 g/h) or a placebo immediately before and at 15-min intervals during exercise. A similar rate of muscle glycogen use from before exercise to 90 minutes was reported in the carbohydrate and placebo trials (Foskett, Williams et al. 2008). In this study participants continued to complete blocks of the LIST after 90 minutes to volitional fatigue. All participants ran longer during the carbohydrate trial (158.0 ± 28.4 minutes) compared with the placebo trial (131.0 ± 19.7 minutes), representing a 21% increase in intermittent running capacity. Fatigue occurred at similar muscle glycogen concentrations in both trials (~200 mmol/kg d.w). Concentrations of plasma glucose and serum insulin were higher in the carbohydrate trial than the placebo trial at the point of fatigue, suggesting a role of greater glucose availability in the superior performance (Baker, Rollo et al. 2015).

The role of blood glucose

The metabolic response to carbohydrate ingestion differs depending whether the player is at rest or exercising. At rest the response to elevated blood glucose is an upregulation in the synthesis and secretion of insulin within the pancreas (beta cells of the islets of Langerhans). Insulin causes decreased lipolysis and increased glucose uptake in liver, skeletal muscle, and fat cells (Baker, Rollo et al. 2015).

The role of liver glycogen is the regulation of blood glucose concentration (euglycemia: 4.0–5.5 mmol/L). At the onset of exercise, muscular contraction causes an increased uptake of glucose from the blood. In opposition to the effect of insulin, liver glycogenolysis is activated by the actions of glucagon and epinephrine. Russell, Benton, and Kingsley (2014) reported that the insulin response to carbohydrate ingestion during the warm-up period prior to team sport activity is inhibited by the actions of epinephrine, which accounts for the elevated blood glucose concentrations typically observed during this stage of exercise. It has long been established that, as exercise duration increases, blood glucose has an increasing contribution to carbohydrate oxidation in the muscle (Coyle, Coggan et al. 1986, Russell, Benton et al. 2014). Blood glucose concentration can increase in response to intermittent sport activity due to an increase in circulating catecholamines (Bangsbo 1994)). Although glucagon is reported to be relatively unchanged during a match, concentrations of epinephrine and norepinephrine increase through the stimulation of the sympathetic nervous system. Epinephrine stimulates glycogenolysis in the liver, which results in an increase in blood glucose concentration above resting values (Bangsbo 1994). Although transient decreases in blood glucose concentration

have been reported following half time of a match (Russell, Benton et al. 2014), hypoglycemia is relatively rare in players during football specific exercise lasting 90 minutes in fed individuals (Ekblom 1986), suggesting that liver glycogen is sufficient to maintain or even increase blood glucose concentration during a match (Krustrup, Mohr et al. 2006) (Baker, Rollo et al. 2015).

Nevertheless, team sport players are advised to ingest carbohydrate during exercise for the benefits to preserving endogenous glycogen and ability to maintain high intensity running performance late in exercise (Williams and Rollo 2015). An effect of ingesting carbohydrate-electrolyte beverages during intermittent exercise is an increase in blood glucose concentrations during exercise, compared with the ingestion of non-caloric beverages. Although mechanisms remain unclear, authors have suggested that that decision-making and successful skill execution during a match may be influenced by blood glucose concentrations. Elevated blood glucose has been associated with an overall improvement in skill performance in football (Russell and Kingsley 2014, Baker, Rollo et al. 2015).

In addition, Bandelow and colleagues showed that high plasma glucose concentration from sports drink ingestion during a football match was related to faster response speeds during several cognitive/motor skill tests, including fine motor skill, complex visual discrimination, working memory, following a 90 minute match (Bandelow, Maughan et al. 2010). However, it is important to note that in this study the faster response speed in working memory came at the expense of reduced accuracy, so this may have simply been an artifact of a speed/accuracy "trade off". Blood glucose concentration may influence skill performance since the brain is almost entirely dependent on a continuous supply of glucose from the circulation for optimal functioning (Duelli and Kuschinsky 2001). Elevations in blood glucose have been reported to increase the supply of glucose to the brain and preserve the integrity of the central nervous system. Furthermore, elevated blood glucose concentrations have also been associated with muscle glycogen sparing (Tsintzas, Williams et al. 1995), improved neuromuscular function (Nybo, Pedersen et al. 2009) and reduced central fatigue (Nybo 2003) (Baker, Rollo et al. 2015).

Both a 9.6% carbohydrate solution (plus carbohydrate gel, 142 g carbohydrate/h) and a 5.6% carbohydrate solution (plus placebo gel, 54 g carbohydrate/h) before and at half time increased blood glucose concentrations compared with the ingestion of a placebo during a protocol which simulates match play (Kingsley, Penas-Ruiz et al. 2014). Mean sprint speed was consistently faster in both the carbohydrate trials (9.6% solution: 5.73m/s; 5.6% solution: 5.66m/s) in comparison with placebo (5.58 m/s) from the start to end of 90 minutes. It is important to note, that it is not possible to distinguish if the improved performance was due to a dose dependent effect of carbohydrate ingestion on blood glucose concentration, as the participants also

ingested caffeine (6 mg/kg body mass) with the 9.6% carbohydrate solution. A study by the same research group investigated the impact of carbohydrate (0.7 g/kg body mass) or placebo ingestion on physical and skill performance in the extra time-period of a simulated football protocol. In this study, carbohydrate was provided in the form of glucose and maltodextrin gels before exercise, half time, and at 90 minutes. The carbohydrate trial increased blood glucose concentrations and was associated with improved dribbling precision in the extra time period (90–120 min). However, the elevated blood glucose was not able to attenuate the reduction in sprinting and jumping performance observed in this time (Baker, Rollo et al. 2015, Harper, Briggs et al. 2016).

When carbohydrate stores are severely reduced during the latter stages of prolonged exercise, the threat to brain metabolism may be prevented by discontinuing exercise (Foskett, Williams et al. 2008). It is likely that during exhaustive, high-intensity, intermittent exercise, decreased performance and ultimately volitional fatigue is a multifaceted consequence of peripheral as well as central mechanisms. Nybo and colleagues demonstrated that, when endurance-trained cyclists developed hypoglycemia, neuromuscular performance (sustained maximal voluntary contraction) was impaired. The lower force production was reported to be a consequence of central fatigue (i.e., a diminished activation drive from the central nervous system) (Nybo 2003). When glucose was fed to cyclists to preserve blood glucose concentrations throughout exercise, neuromuscular performance was maintained. The mechanism underlying the hypoglycemia-induced central fatigue has been speculated to be directly related to a reduced delivery of glucose as a substrate to the brain.

With regard to intermittent sports, large regions of the brain, such as the motor cortex, will be activated, as well as regions involved in cardiorespiratory regulation. Endothelial glucose transport may become rate limiting for the cerebral metabolic rate of glucose when the concentrations of arterial glucose fall to hypoglycemic levels (Nybo 2003). Interestingly, transient changes in blood glucose concentrations have been reported during intermittent high-intensity exercise. Specifically, elevated blood glucose concentrations observed during the first half of football-specific exercise are negated in the early stages of the second half, when replicating carbohydrate ingestion and passive half-time practices typical of football. This observation is of relevance because physical performance has been reported to be reduced in the early stages of the second half compared with the opening stages of a match (Mohr, Krstrup et al. 2005). Russell and colleagues reported that blood glucose values recorded at the beginning of the half time period dropped 30% by the beginning of the second half period (Russell, Benton et al. 2014). In this and other studies which have observed a transient fall in blood glucose over the half time period in response to carbohydrate feedings, blood glucose concentrations are

typically similar to those observed in the placebo trials. Importantly, consistent with reports from endurance exercise the transient drop in blood glucose following half time has not been associated with decrements in football performance (Jeukendrup and Killer 2010, Baker, Rollo et al. 2015). In general, elevated blood glucose is associated with superior skill performance, whilst the maintenance of blood glucose concentrations would improve skill and running performance under circumstances of fatigue and/or hypoglycemia.

Non-metabolic effects of carbohydrates

In addition to providing the muscle with substrate, carbohydrate ingested during exercise may exert a “non-metabolic” central effect. Studies in running and cycling have reported a benefit of routinely mouth-rinsing and expectorating a carbohydrate solution on high intensity endurance performance lasting „30–70 min (Rollo, Williams et al. 2011). Thus, the ergogenic effect of carbohydrate ingestion when the exercise is of high intensity (>75% VO₂max) and relatively short duration may be mediated via the activation of brain pathways associated with reward and motivation, in response to carbohydrate recognition in the mouth (Rollo and Williams 2011).

To date, the benefits of mouth-rinsing carbohydrate on repeated sprint (football) performance remain unclear. Dorling and Earnest (2013) found no effect of mouth rinsing a 6.4 % maltodextrin solution on the average or fastest time to complete 3 repeated sprint ability tests during the LIST protocol (Dorling and Earnest 2013). However, this performance measure during the LIST protocol, in which the subjects were not able to self-pace, may not have been sufficiently sensitive to detect a potential influence of carbohydrate mouth rinse. By contrast, Rollo and colleagues (Rollo, Homewood, Williams, Carter, & Goosey-Tolfrey, 2015) utilized a validated self-selected pacing LIST protocol (Ali, Foskett et al. 2014). In this study, mouth rinsing a 10% maltodextrin solution was associated with increased self-selected jogging speed and also an 86% likelihood of benefiting 15-meter sprint performance during the final stages (75–90 minutes) of exercise, in comparison with mouth rinsing a placebo (Baker, Rollo et al. 2015).

Whether mouth rinsing carbohydrate is sufficient to improve skill performance is an interesting question. Although specific research examining the effect of carbohydrate mouth rinse on skill performance is currently lacking, the relevance of the results would be questionable due to the aforementioned benefits of carbohydrate ingestion on endogenous glycogen and blood glucose. Nevertheless, practically the use of mouth-rinsing carbohydrate during match-play could potentially be advantageous for those players seeking to enhance performance but carbohydrate consumption is limited by gastrointestinal concerns (Rollo,

Homewood et al. 2015). Finally, there is no evidence of a dose-response performance effect to increasing the concentration of the carbohydrate beverage rinsed in the mouth (James, Ritchie et al. 2017).

In summary, the mechanisms by which carbohydrate ingestion before and during football are complex. The importance of carbohydrate availability for football is evident by studies which have reported severe reduction in endogenous stores of carbohydrate during exercise. The associated fatigue observed with low muscle glycogen translates directly to reduced performance, which may manifest in less high intensity running and reduced skill. Carbohydrate ingestion prior to exercise blunts the hepatic release of glucose and thus preserves the limited endogenous glycogen stores. The magnitude of the impact that carbohydrate ingestion has on football performance is likely to be dependent on the carbohydrate status of the player; that is, carbohydrate ingestion has the greatest impact on performance under circumstances eliciting permanent fatigue and/or hypoglycemia. When ingesting carbohydrate-electrolyte beverages during exercise, players may gain an “additional” benefit by simply mouth-rinsing the solution prior to ingestion (Rollo, Williams et al. 2011).

Practical considerations

It is important to note that, in general, it is not difficult to encourage players to ingest enough carbohydrate around matches. This is because carbohydrate is “sweet” and, therefore, a “favourite” option. The challenge is to provide carbohydrate to players who need it. For example, on a match day, when carbohydrate options are readily available or provided “buffet” style, the entire squad has access. Thus, despite not needing additional carbohydrate, substitutes (and staff) are known to “raid” the carbohydrate options provided. This may result in unfavourable energy balance for those players, which, if left unaddressed, may negatively affect body composition. Several options may be used to resolve this, including; removing the buffet and providing individual player options; providing alternative foods/beverages for the substitutes, in concert with an education program. Finally, as with all food and daily dietary intakes, excess ingestion of sugars may negatively impact on players’ dental health (Venables, Shaw et al. 2005). Thus, it is simply advised that players brush their teeth following training and matches when carbohydrate is ingested.

Summary

- A carbohydrate-rich meal (2-3 g/kg body mass) should be ingested 3-4 hours before kick-off in order for players to begin the match with adequate glycogen stores.

- Ingestion of carbohydrate (30-60 g/hour) is associated with improved running and skill performance, especially under circumstances of fatigue and/or hypoglycemia.
- Elevated blood glucose during football exercise is associated with superior football skill performance.
- After a match, the ingestion of carbohydrate (~1 g/kg/h) will speed up the rate of muscle glycogen resynthesis.
- The ingestion of carbohydrate post exercise should be achieved in concert with other nutrition goals to speed up players' recovery (fluid and protein).

Disclaimer: Ian Rollo is an employee of the Gatorade Sports Science Institute, a division of PepsiCo, Inc. The views expressed in this course are those of the authors and do not necessarily reflect the position or policy of PepsiCo, Inc.



References

- Agnevik, G.** (1970). "Fotboll: ." Indrottsfysiologi; Trygg-Hansa: Stockholm, Sweeden.
- Ali, A., A. Foskett and N. Gant (2014). "Measuring intermittent exercise performance using shuttle running." J Sports Sci **32**(7): 601-609.
- Ali, A. and C. Williams** (2009). "Carbohydrate ingestion and soccer skill performance during prolonged intermittent exercise." J Sports Sci: 1-10.
- Anderson, L., P. Orme, R. Naughton, G. Close, J. Milsom, D. Rydings, A. O'Boyle, R. Di Michele, J. Louis, C. Hambley, J. Speakman, R. Morgans, B. Drust and J. Morton** (2017). "Energy intake and expenditure of professional soccer players of the English Premier League: evidence of carbohydrate periodization." International Journal of Sport Nutrition and Exercise Metabolism **4**: 1-25.
- Asp, S., J. R. Dugaard and E. A. Richter** (1995). "Eccentric exercise decreases glucose transporter GLUT4 protein in human skeletal muscle." J Physiol **482 (Pt 3)**: 705-712.
- Baker, L. B. and A. E. Jeukendrup (2014). "Optimal composition of fluid-replacement beverages." Compr Physiol **4**(2): 575-620.
- Baker, L. B., I. Rollo, K. W. Stein and A. E. Jeukendrup** (2015). "Acute Effects of Carbohydrate Supplementation on Intermittent Sports Performance." Nutrients **7**(7): 5733-5763.
- Bandelow, S., R. Maughan, S. Shirreffs, K. Ozgunen, S. Kurdak, G. Ersoz, M. Binnet and J. Dvorak** (2010). "The effects of exercise, heat, cooling and rehydration strategies on cognitive function in football players." Scand J Med Sci Sports **20 Suppl 3**: 148-160.
- Bangsbo, J.** (1994). "The physiology of soccer--with special reference to intense intermittent exercise." Acta Physiol Scand Suppl **619**: 1-155.
- Bendiksen, M., R. Bischoff, M. B. Randers, M. Mohr, I. Rollo, C. Suetta, J. Bangsbo and P. Krstrup** (2012). "The Copenhagen Soccer Test: physiological response and fatigue development." Med Sci Sports Exerc **44**(8): 1595-1603.
- Briggs, M. A., L. D. Harper, G. McNamee, E. Cockburn, P. L. S. Rumbold, E. J. Stevenson and M. Russell** (2017). "The effects of an increased calorie breakfast consumed prior to simulated match-play in Academy soccer players." Eur J Sport Sci **17**(7): 858-866.
- Brouns, F., J. Senden, E. J. Beckers and W. H. Saris** (1995). "Osmolarity does not affect the gastric emptying rate of oral rehydration solutions." JPEN J Parenter Enteral Nutr **19**(5): 403-406.



Burelle, Y., M. C. Lamoureux, F. Peronnet, D. Massicotte and C. Lavoie (2006). "Comparison of exogenous glucose, fructose and galactose oxidation during exercise using ¹³C-labelling." Br J Nutr **96**(1): 56-61.

Burke, L. M., G. R. Collier, P. G. Davis, P. A. Fricker, A. J. Sanigorski and M. Hargreaves (1996). "Muscle glycogen storage after prolonged exercise: effect of the frequency of carbohydrate feedings." Am J Clin Nutr **64**(1): 115-119.

Burke, L. M., J. A. Hawley, S. H. Wong and A. E. Jeukendrup (2011). "Carbohydrates for training and competition." J Sports Sci **29 Suppl 1**: S17-27.

Cade, J. R., H. J. Free, A. M. De Quesada, D. L. Shires and L. Roby (1971). "Changes in body fluid composition and volume during vigorous exercise by athletes." J Sports Med Phys Fitness **11**(3): 172-178.

Cade, R., G. Spooner, E. Schlein, M. Pickering and R. Dean (1972). "Effect of fluid, electrolyte, and glucose replacement during exercise on performance, body temperature, rate of sweat loss, and compositional changes of extracellular fluid." Journal Sports Medicine and Physical Fitness. **12**: 150-156.

Cermak, N. M. and L. J. van Loon (2013). "The use of carbohydrates during exercise as an ergogenic aid." Sports Med **43**(11): 1139-1155.

Chambers, E. S., M. W. Bridge and D. A. Jones (2009). "Carbohydrate sensing in the human mouth: effects on exercise performance and brain activity." J Physiol **587**(Pt 8): 1779-1794.

Costill, D. L. and B. Saltin (1974). "Factors limiting gastric emptying during rest and exercise." Journal of Applied Physiology **37**(5): 679-683.

Coyle, E. F., A. R. Coggan, M. K. Hemmert and J. L. Ivy (1986). "Muscle glycogen utilization during prolonged strenuous exercise when fed carbohydrate." Journal of Applied Physiology **61**(1): 165-172.

Currell, K., S. Conway and A. E. Jeukendrup (2009). "Carbohydrate ingestion improves performance of a new reliable test of soccer performance." Int J Sport Nutr Exerc Metab **19**(1): 34-46.

Dorling, J. L. and C. P. Earnest (2013). "Effect of carbohydrate mouth rinsing on multiple sprint performance." J Int Soc Sports Nutr **10**(1): 41.

Duelli, R. and W. Kuschinsky (2001). "Brain glucose transporters: relationship to local energy demand." News Physiol Sci **16**: 71-76.

Dyer, J., S. Vayro, T. P. King and S. P. Shirazi-Beechey (2003). "Glucose sensing in the intestinal epithelium." Eur J Biochem **270**(16): 3377-3388.

Ekblom, B. (1986). "Applied physiology of soccer." Sports Med **3**(1): 50-60.



Fordtran, J. S. (1975). "Stimulation of active and passive sodium absorption by sugars in the human jejunum." Journal of Clinical Investigation **55**(4): 728-737.

Foskett, A., C. Williams, L. Boobis and K. Tsintzas (2008). "Carbohydrate availability and muscle energy metabolism during intermittent running." Med Sci Sports Exerc **40**(1): 96-103.

Funnell, M. P., N. R. Dykes, E. J. Owen, S. A. Mears, I. Rollo and L. J. James (2017). "Ecologically Valid Carbohydrate Intake during Soccer-Specific Exercise Does Not Affect Running Performance in a Fed State." Nutrients **9**(1).

Gaitanos, G. C., C. Williams, L. H. Boobis and S. Brooks (1993). "Human muscle metabolism during intermittent maximal exercise." J Appl Physiol (1985) **75**(2): 712-719.

Gejl, K. D., L. G. Hvid, U. Frandsen, K. Jensen, K. Sahlin and N. Ortenblad (2014). "Muscle Glycogen Content Modifies SR Ca²⁺ Release Rate in Elite Endurance Athletes." Med Sci Sports Exerc **46**(3): 496-505.

Gordon, B., L. A. Kohn, S. A. Levine, M. Matton, S. M. and B. Whiting (1925). "SUGAR CONTENT OF THE BLOOD IN RUNNERS FOLLOWING A MARATHON RACE WITH ESPECIAL REFERENCE TO THE PREVENTION OF HYPOGLYCEMIA: FURTHER OBSERVATIONS." JAMA **85**(7): 508-509.

Harper, L. D., M. A. Briggs, G. McNamee, D. J. West, L. P. Kilduff, E. Stevenson and M. Russell (2016). "Physiological and performance effects of carbohydrate gels consumed prior to the extra-time period of prolonged simulated soccer match-play." J Sci Med Sport **19**(6): 509-514.

Harper, L. D., E. J. Stevenson, I. Rollo and M. Russell (2017). "The influence of a 12% carbohydrate-electrolyte beverage on self-paced soccer-specific exercise performance." J Sci Med Sport.

Holdsworth, C. D. and A. M. Dawson (1964). "The Absorption of Monosaccharides in Man." Clin Sci **27**: 371-379.

Holdsworth, C. D. and A. M. Dawson (1964). "The Absorption of Monosaccharides in Man." Clinical Science **27**: 371-379.

Holmes, R. (1971). "Carbohydrate digestion and absorption." Journal of Clinical Pathology: Supplement(5): 10-13.

Holway, F. E. and L. L. Spriet (2011). "Sport-specific nutrition: practical strategies for team sports." J Sports Sci **29 Suppl 1**: S115-125.

Hunt, J. N. and M. T. Knox (1968). "Control of gastric emptying." Am J Dig Dis **13**(4): 372-375.



Ivy, J. L. (1998). "Glycogen resynthesis after exercise: effect of carbohydrate intake." Int J Sports Med **19 Suppl 2**: S142-145.

James, R. M., S. Ritchie, I. Rollo and L. J. James (2017). "No Dose Response Effect of Carbohydrate Mouth Rinse on Cycling Time-Trial Performance." Int J Sport Nutr Exerc Metab **27**(1): 25-31.

Jentjens, R. L., J. Achten and A. E. Jeukendrup (2004). "High oxidation rates from combined carbohydrates ingested during exercise." Med Sci Sports Exerc **36**(9): 1551-1558.

Jentjens, R. L., C. Cale, C. Gutch and A. E. Jeukendrup (2003). "Effects of pre-exercise ingestion of differing amounts of carbohydrate on subsequent metabolism and cycling performance." Eur J Appl Physiol **88**(4-5): 444-452.

Jentjens, R. L. and A. E. Jeukendrup (2005). "High rates of exogenous carbohydrate oxidation from a mixture of glucose and fructose ingested during prolonged cycling exercise." Br J Nutr **93**(4): 485-492.

Jeukendrup, A. E. and S. C. Killer (2010). "The myths surrounding pre-exercise carbohydrate feeding." Ann Nutr Metab **57 Suppl 2**: 18-25.

Jeukendrup, A. E. and L. Moseley (2008). "Multiple transportable carbohydrates enhance gastric emptying and fluid delivery." Scand J Med Sci Sports.

Jeukendrup, A. E., A. J. Wagenmakers, J. H. Stegen, A. P. Gijsen, F. Brouns and W. H. Saris (1999). "Carbohydrate ingestion can completely suppress endogenous glucose production during exercise." Am J Physiol **276**(4 Pt 1): E672-683.

Katz, D. B., M. A. Nicoletis and S. A. Simon (2000). "Nutrient tasting and signaling mechanisms in the gut. IV. There is more to taste than meets the tongue." Am J Physiol Gastrointest Liver Physiol **278**(1): G6-9.

Katz, J. and J. D. McGarry (1984). "The glucose paradox. Is glucose a substrate for liver metabolism?" J Clin Invest **74**(6): 1901-1909.

Kingsley, M., C. Penas-Ruiz, C. Terry and M. Russell (2014). "Effects of carbohydrate-hydration strategies on glucose metabolism, sprint performance and hydration during a soccer match simulation in recreational players." J Sci Med Sport **17**(2): 239-243.

Kirkendall, D., C. Foster, J. Dean, J. Grogan and N. Thompson (1988). "Effect of glucose polymer supplementation on performance of soccer players." In: T. Reilly, A. Lees, K. Davids, and W. Murphy, eds. **Science and Football**.(London: E & FN Spon.): 33-41.



Kristiansen, S., F. Darakhshan, E. A. Richter and H. S. Hundal (1997). "Fructose transport and GLUT-5 protein in human sarcolemmal vesicles." Am J Physiol **273**(3 Pt 1): E543-548.

Krustrup, P., M. Mohr, A. Steensberg, J. Bencke, M. Kjaer and J. Bangsbo (2006). "Muscle and blood metabolites during a soccer game: implications for sprint performance." Med Sci Sports Exerc **38**(6): 1165-1174.

Maughan, R. J. and R. Murray (2001). "Nutrition in Exercise and Sports Sciences: Sports drinks. Basic sciences and practical aspects."

Melendez-Hevia, E., T. G. Waddell and E. D. Shelton (1993). "Optimization of molecular design in the evolution of metabolism: the glycogen molecule." Biochem J **295** (Pt 2): 477-483.

Mohr, M., P. Krustrup and J. Bangsbo (2005). "Fatigue in soccer: a brief review." J Sports Sci **23**(6): 593-599.

Nedelec, M., A. McCall, C. Carling, F. Legall, S. Berthoin and G. Dupont (2012). "Recovery in soccer: part I - post-match fatigue and time course of recovery." Sports Med **42**(12): 997-1015.

Nicholas, C. W., P. A. Green, R. D. Hawkins and C. Williams (1997). "Carbohydrate intake and recovery of intermittent running capacity." Int J Sport Nutr **7**(4): 251-260.

Nicholas, C. W., K. Tsintzas, L. Boobis and C. Williams (1999). "Carbohydrate-electrolyte ingestion during intermittent high-intensity running." Med Sci Sports Exerc **31**(9): 1280-1286.

Noakes, T. D., N. J. Rehrer and R. J. Maughan (1991). "The importance of volume in regulating gastric emptying." Med Sci Sports Exerc **23**(3): 307-313.

Nybo, L. (2003). "CNS fatigue and prolonged exercise: effect of glucose supplementation." Med Sci Sports Exerc **35**(4): 589-594.

Nybo, L., K. Pedersen, B. Christensen, P. Aagaard, N. Brandt and B. Kiens (2009). "Impact of carbohydrate supplementation during endurance training on glycogen storage and performance." Acta Physiol (Oxf) **197**(2): 117-127.

Parkin, J. A., M. F. Carey, I. K. Martin, L. Stojanovska and M. A. Febbraio (1997). "Muscle glycogen storage following prolonged exercise: effect of timing of ingestion of high glycemic index food." Med Sci Sports Exerc **29**(2): 220-224.

Passe, D. H., M. Horn and R. Murray (2000). "Impact of beverage acceptability on fluid intake during exercise." Appetite **35**(3): 219-229.

Rollo, I. (2019). "Carbohydrate: The Football Fuel."

Rollo, I., G. Homewood, C. Williams, J. Carter and V. L. Goosey-Tolfrey (2015). "The Influence of Carbohydrate Mouth Rinse on Self-Selected Intermittent Running Performance." Int J Sport Nutr Exerc Metab **25**(6): 550-558.

Rollo, I. and C. Williams (2011). "Effect of Mouth-Rinsing Carbohydrate Solutions on Endurance Performance." Sports Medicine **41**(6): 449-461.

Rollo, I., C. Williams and M. Nevill (2011). "Influence of ingesting versus mouth rinsing a carbohydrate solution during a 1-h run." Med Sci Sports Exerc **43**(3): 468-475.

Rolls, E. T. (2007). "Sensory processing in the brain related to the control of food intake." Proc Nutr Soc **66**(1): 96-112.

Russell, M., D. Benton and M. Kingsley (2014). "Carbohydrate ingestion before and during soccer match play and blood glucose and lactate concentrations." J Athl Train **49**(4): 447-453.

Russell, M. and M. Kingsley (2014). "The efficacy of acute nutritional interventions on soccer skill performance." Sports Med **44**(7): 957-970.

Saltin, B. (1972). "[Substrate metabolism of the skeletal musculature during exercise. 5. Muscle glycogen]." Lakartidningen **69**(14): 1637-1640.

Smeets, P. A., C. de Graaf, A. Stafleu, M. J. van Osch and J. van der Grond (2005). "Functional MRI of human hypothalamic responses following glucose ingestion." Neuroimage **24**(2): 363-368.

Stevenson, E., C. Williams and M. Nute (2005). "The influence of the glycaemic index of breakfast and lunch on substrate utilisation during the postprandial periods and subsequent exercise." Br J Nutr **93**(6): 885-893.

Tsintzas, O. K., C. Williams, L. Boobis and P. Greenhaff (1995). "Carbohydrate ingestion and glycogen utilization in different muscle fibre types in man." The Journal of Physiology **489 (Pt 1)**: 243-250.

Venables, M. C., L. Shaw, A. E. Jeukendrup, A. Roedig-Penman, M. Finke, R. G. Newcombe, J. Parry and A. J. Smith (2005). "Erosive effect of a new sports drink on dental enamel during exercise." Med Sci Sports Exerc **37**(1): 39-44.

Williams, C. (1993). "Carbohydrate needs of elite athletes." World Rev Nutr Diet **71**: 34-60.

Williams, C. and I. Rollo (2015). "Carbohydrate Nutrition and Team Sport Performance." Sports Med **45 Suppl 1**: S13-22.

