Journal of Sports Sciences, 2011; 29(S1): S91–S99

Routledge
Taylor & Francis Group

Nutrition for endurance sports: Marathon, triathlon, and road cycling

ASKER E. JEUKENDRUP

School of Sport and Exercise Sciences, University of Birmingham, Birmingham, UK

(Accepted 1 August 2011)

Abstract

Endurance sports are increasing in popularity and athletes at all levels are looking for ways to optimize their performance by training and nutrition. For endurance exercise lasting 30 min or more, the most likely contributors to fatigue are dehydration and carbohydrate depletion, whereas gastrointestinal problems, hyperthermia, and hyponatraemia can reduce endurance exercise performance and are potentially health threatening, especially in longer events (>4 h). Although high muscle glycogen concentrations at the start may be beneficial for endurance exercise, this does not necessarily have to be achieved by the traditional supercompensation protocol. An individualized nutritional strategy can be developed that aims to deliver carbohydrate to the working muscle at a rate that is dependent on the absolute exercise intensity as well as the duration of the event. Endurance athletes should attempt to minimize dehydration and limit body mass losses through sweating to 2–3% of body mass. Gastrointestinal problems occur frequently, especially in long-distance races. Problems seem to be highly individual and perhaps genetically determined but may also be related to the intake of highly concentrated carbohydrate solutions, hyperosmotic drinks, as well as the intake of fibre, fat, and protein. Hyponatraemia has occasionally been reported, especially among slower competitors with very high intakes of water or other low sodium drinks. Here I provide a comprehensive overview of recent research findings and suggest several new guidelines for the endurance athlete on the basis of this. These guidelines are more detailed and allow a more individualized approach.

Keywords: *Carbohydrate, endurance, performance*

Introduction

Endurance sports are becoming increasingly popular and more people are running half marathons, marathons, ultramarathons, half Ironmans, and even Ironman competitions, lasting anywhere between 2 h and 17 h. Many events are organized to encourage people to take up endurance sports and events of 30 min to 2 h, which are more manageable for the novice athlete, are also rapidly increasing in popularity. For the purpose of this review, endurance exercise will therefore refer to events lasting 30 min or more as defined in the PASSCLAIM document (Saris et al., 2003). PASSCLAIM was an initiative of the European Commission with the aim to develop a set of methods and procedures for assessing the scientific support for function-enhancing and health-related claims for foods and food components.

This review focuses on areas of sports nutrition that have developed significantly in the last 5 years. Other areas, where developments have been relatively slow, will be reviewed and summarized and the reader will be referred to recent review articles.

Physiological demands and nutritional demands of endurance sports

Muscle glycogen and blood glucose are the most important substrates for the contracting muscle (Romijn et al., 1993). Fatigue during prolonged exercise is often associated with muscle glycogen depletion and reduced blood glucose concentrations (Jeukendrup, 2004) and, therefore, high pre-exercise muscle and liver glycogen concentrations are believed to be essential for optimal performance, although it is unlikely that any of these factors *alone* limits prolonged exercise performance.

In addition to glycogen depletion, dehydration can also impair endurance performance (for a review, see Sawka et al., 2007). Sweat losses occur because there is the need to dissipate the heat that is generated during exercise. Therefore, the nutritional challenge is to prevent major dehydration (>2–3%) and thus contribute to the prevention of fatigue (Shirreffs, 2011). This recommendation is in line with the most recent guidelines by the American College of Sports Medicine stating that dehydration of more than

Correspondence: A. Jeukendrup, School of Sport and Exercise Sciences, University of Birmingham, Edgbaston, Birmingham B15 2TT, UK.
E-mail: a.e.jeukendrup@bham.ac.uk

ISSN 0264-0414 print/ISSN 1466-447X online © 2011 Taylor & Francis
http://dx.doi.org/10.1080/02640414.2011.610348

2–3% of body weight should be prevented but also warns against drinking in excess of sweating rate (Sawka et al., 2007) to prevent hyponatraemia.

Pre-competition

Carbohydrate loading. The effect of high-carbohydrate diets and elevated muscle glycogen on exercise performance has been summarized in a review by Hawley and colleagues (Hawley, Schabort, Noakes, & Dennis, 1997), and despite this review being published in 1997, it is still up to date. It was suggested that supercompensated muscle glycogen levels can improve performance (i.e. time to complete a predetermined distance) compared with low to normal glycogen (non-supercompensated) by 2–3% in events lasting more than 90 min. There seems to be little or no performance benefit of supercompensated muscle glycogen when the exercise duration is less than 90 min.

Well-trained endurance athletes can achieve glycogen supercompensation without the need for the depletion phase prior to loading (Burke, Hawley, Wong, & Jeukendrup, 2011). Furthermore, the amount of dietary carbohydrate needed to provide the high carbohydrate availability needed to recover glycogen stores on a daily basis or promote glycogen loading depends on the duration and intensity of the athlete's exercise programme. Such requirements can vary from around 5 to 12 $g \cdot kg^{-1} \cdot day^{-1}$ depending on the athlete and their activity. It should be noted that even if a higher carbohydrate intake can achieve higher glycogen stores, this might not always result in better performance. For example, in one study (Coyle, Jeukendrup, Oseto, Hodgkinson, & Zderic, 2001) increasing the carbohydrate intake from 10 $g \cdot kg^{-1}$ to almost 13 $g \cdot kg^{-1}$ resulted in an increase of muscle glycogen but had no effect on endurance performance. Another consideration for some athletes is that glycogen storage is associated with weight gain as a result of water retention (approximately 3 g per gram of glycogen) and this may not be desirable in some cases.

Carbohydrate ingestion <60 min before exercise. Although the consumption of a high-carbohydrate diet in the days before exercise as well as ingestion of carbohydrate meals 3–4 h before exercise (Hargreaves, Hawley, & Jeukendrup, 2004) can have positive effects on exercise performance, it has been suggested that the intake of carbohydrate 30–60 min before exercise may adversely affect performance (Foster, Costill, & Fink, 1979). Glucose ingestion in the hour before exercise can result in hyperglycaemia and hyperinsulinaemia, which is often followed by a rapid decline in blood glucose 15–30 min after the onset of exercise (Foster et al., 1979; Koivisto, Karonen, & Nikkila, 1981), referred to as reactive or rebound hypoglycaemia. The fall in blood glucose is most likely the result of an increased muscle glucose uptake as well as a reduced liver glucose output. In addition, hyperinsulinaemia following carbohydrate ingestion inhibits lipolysis and fat oxidation (Foster et al., 1979; Koivisto et al., 1981) and this may lead to more rapid muscle glycogen depletion. Therefore, pre-exercise carbohydrate feedings in the hour before exercise may have the potential to impair performance. However, only two studies have found reduced performance capacity, while the majority of studies have reported no change or an improvement in performance following pre-exercise carbohydrate ingestion (Jeukendrup & Killer, 2011). Furthermore, a rebound hypoglycaemia in the early stage of exercise seems to be of little functional significance, as it does not affect exercise performance (Jeukendrup & Killer, 2011). This suggests that there is no need to avoid carbohydrate intake in the hour before exercise.

It is interesting to note that rebound hypoglycaemia occurs in some triathletes but not in others (Jentjens & Jeukendrup, 2002). Kuipers and colleagues (Kuipers, Fransen, & Keizer, 1999) suggested that rebound hypoglycaemia in trained triathletes is related to a high insulin sensitivity. However, we have shown that trained individuals who developed rebound hypoglycaemia did not have better glucose tolerance compared with individuals who did not show rebound hypoglycaemia (Jentjens & Jeukendrup, 2002). It is therefore unlikely that insulin sensitivity plays an important role in the prevalence of rebound hypoglycaemia in trained athletes. It may be argued that there are some athletes who are very "sensitive" to low blood glucose levels and for them exercise-induced hypoglycaemia may be a major contributor to fatigue. These metabolic disturbances may be attenuated by choosing pre-exercise carbohydrate sources with a low glycaemic index because these result in more stable blood glucose and insulin responses during subsequent exercise (Jentjens & Jeukendrup, 2003; Wee, Williams, Gray, & Horabin, 1999). Another approach to minimize the glycaemic and insulinaemic responses during exercise is to delay carbohydrate feeding until 5–15 min before the start of the activity (Moseley, Lancaster, & Jeukendrup, 2003). Of note, the metabolic and performance effects of carbohydrate ingestion shortly before exercise (<15 min) are very similar to those observed when carbohydrate is fed during activity.

An intriguing observation is that there is no clear relation between hypoglycaemia (blood glucose <3.5 $mmol \cdot L^{-1}$) and symptoms of hypoglycaemia (Jeukendrup & Killer, 2011). Symptoms are often reported in the absence of true hypoglycaemia and low plasma glucose concentrations are not always associated with symptoms. This finding is not new, however. In 1979, Foster and colleagues noted that reported symptoms did not match serum glucose concentrations in a cohort of individuals who consumed glucose before exercise. Further attention to this issue is warranted.

In conclusion, the advice to avoid carbohydrate feeding in the hour before exercise is unfounded. Some athletes may develop symptoms similar to those of hypoglycaemia, even though they are not always linked to low glucose concentrations. Most importantly, rebound hypoglycaemia does not appear to affect performance. To minimize symptoms of hypoglycaemia, an individual approach may be desirable, which could include ingesting carbohydrate just before exercise or during warm-up and selection of low-to-moderate glycaemic index carbohydrates. The effects of pre-exercise carbohydrate feeding are discussed in more detail in a recent review (Jeukendrup & Killer, 2011).

Fluid ingestion before exercise. As discussed earlier, dehydration can compromise exercise performance and it is therefore important to start exercise in a euhydrated state. When hydrating prior to exercise ''the individual should slowly drink beverages (for example, ~5–7 mL/kg BW [body weight]) at least 4 h before the exercise task. If the individual does not produce urine, or the urine is dark or highly concentrated, s/he should slowly drink more beverage (for example, another ~3–5 mL/kg) about 2 h before the event'' (Sawka et al., 2007).

It is believed that athletes who have difficulty drinking sufficient amounts of fluid during exercise or who lose body water at high rates (i.e. during exercise in hot conditions) may benefit from hyperhydration. Hyperhydration has been suggested to improve thermoregulation and exercise performance, especially in the heat (for a review, see van Rosendal, Osborne, Fassett, & Coombes, 2010). However, attempting to hyperhydrate with fluids that expand the extra- and intracellular spaces (e.g. water and glycerol solutions) will greatly increase the risk of having to void during competition (Latzka et al., 1998). There is also a risk that hyperhydration can substantially dilute and lower plasma sodium prior to exercise, thereby increasing the risk of dilutional hyponatraemia, if fluids are replaced aggressively during exercise (Montain, Cheuvront, & Sawka, 2006). Finally, it must be noted that plasma expanders or hyper-hydrating agents like glycerol are banned by the World Anti-Doping Agency.

During competition

Carbohydrate ingestion during exercise and performance. Although the exact mechanisms are still not completely understood, it has been known for some time that carbohydrate ingestion during exercise can increase exercise capacity and improve exercise performance (for reviews, see Jeukendrup, 2008, 2010). In general, during exercise longer than 2 h, the effects of carbohydrate are mainly metabolic.

However, carbohydrate ingestion during exercise has also been demonstrated to improve exercise performance even when the exercise is of high intensity ($>75\%$ $\dot{V}O_{2max}$) and relatively short duration (~1 h), and it has become clear that the underlying mechanisms for the ergogenic effect during this type of activity is not metabolic but may reside in the central nervous system. Carbohydrate mouth rinses have been shown to result in similar performance improvements (Jeukendrup & Chambers, 2010). This would suggest that the beneficial effects of carbohydrate feeding during exercise are not confined to its conventional metabolic advantage but may also serve as a positive afferent signal capable of modifying motor output (Gant, Stinear, & Byblow, 2010). These effects are specific to carbohydrate and are independent of taste (Chambers, Bridge, & Jones, 2009). The receptors in the oral cavity have not yet been identified and the exact role of various brain areas is not clearly understood. Further research is warranted to fully understand the separate taste transduction pathways for simple and complex carbohydrates and how these differ between mammalian species, particularly in humans. However, it has been convincingly demonstrated that carbohydrate is detected in the oral cavity by unidentified receptors and this can be linked to improvements in exercise performance (for a review, see Jeukendrup & Chambers, 2010). New guidelines suggested here take these findings into account (Table I).

These results suggest that it is not necessary to ingest large amounts of carbohydrate during exercise lasting approximately 30–60 min and a mouth rinse with carbohydrate may be sufficient to obtain a performance benefit (Table I). In most conditions, the performance effects with the mouth rinse have been similar to ingesting the drink, so there does not seem to be a disadvantage of taking the drink, although occasionally athletes may complain of gastrointestinal distress when taking on board too much fluid. Of course when the exercise is more prolonged (2 h or more), carbohydrate becomes a very important fuel and it is essential to ingest carbohydrate. As will be discussed below, larger amounts of carbohydrate may be required for more prolonged exercise.

Different carbohydrates ingested during exercise may be utilized at different rates (Jeukendrup, 2010) but until a landmark publication in 2004 (Jentjens, Moseley, Waring, Harding, & Jeukendrup, 2004), it was believed that carbohydrate ingested during

Table I. Recommendations for carbohydrate (CHO) intake during different endurance events.

Event	CHO required for optimal performance and minimizing negative energy balance	Recommended intake	CHO type	Single carbohydrate (e.g. glucose)	Multiple transportable carbohydrates (e.g. glucose : fructose)
<30 min	None required	–	–	–	–
30–75 min	Very small amounts	Mouth rinse	Most forms of CHO	●	●
1–2 h	Small amounts	Up to 30 g · h^{-1}	Most forms of CHO	●	●
2–3 h	Moderate amounts	Up to 60 g · h^{-1}	Forms of CHO that are rapidly oxidized (glucose, maltodextrin)	○	●
>2.5 h	Large amounts	Up to 90 g · h^{-1}	Only multiple transportable CHO		●

Note: ●, optimal; ○, OK, but perhaps not optimal. These guidelines are intended for serious athletes, exercising at a reasonable intensity (>4 kcal · min^{-1}). If the (absolute) exercise intensity is below this, the figures for carbohydrate intake should be adjusted downwards.

exercise could only be oxidized at a rate no higher than 1 g · min^{-1} (60 g · h^{-1}) independent of the type of carbohydrate. This is reflected in guidelines published by the ACSM, which recommends that athletes should take between 30 and 60 g of carbohydrate during endurance exercise (>1 h) (Sawka et al., 2007) or 0.7 g ·kg^{-1} · h^{-1} (Rodriguez, Di Marco, & Langley, 2009).

It appears that exogenous carbohydrate oxidation is limited by the intestinal absorption of carbohydrates. It is believed that glucose uses a sodium dependent transporter SGLT1 for absorption that becomes saturated at a carbohydrate intake around 60 g · h^{-1}. When glucose is ingested at this rate and another carbohydrate (fructose) that uses a different transporter is ingested simultaneously, oxidation rates that were well above 1 g · min^{-1} (1.26 g · min^{-1}) (Jentjens et al., 2004) can be observed. A series of studies followed in an attempt to work out the maximal rate of exogenous carbohydrate oxidation. In these studies, the rate of carbohydrate ingestion was varied and the types and combinations of carbohydrates varied. All studies confirmed that multiple transportable carbohydrates resulted in (up to 75%) higher oxidation rates than carbohydrates that use the SGLT1 transporter only (for reviews, see Jeukendrup, 2008, 2010). Interestingly, such high oxidation rates could not only be achieved with carbohydrate ingested in a beverage but also as a gel (Pfeiffer, Stellingwerff, Zaltas, & Jeukendrup, 2010a) or a low-fat, low-protein, low-fibre energy bar (Pfeiffer, Stellingwerff, Zaltas, & Jeukendrup, 2010b).

Carbohydrate during exercise and performance: dose–response. Very few well-controlled dose–response studies on carbohydrate ingestion during exercise and exercise performance have been published. Most of the older studies had serious methodological issues that made it difficult to establish a true dose–response relationship between the amount of carbohydrate ingested and performance. The conclusion seemed to be that you needed a minimum amount of carbohydrate (probably about 20 g · h^{-1} based on one study) but it was assumed that there was no dose–response relationship (Rodriguez et al., 2009).

Evidence is accumulating for a dose–response relationship between carbohydrate ingestion rates, exogenous carbohydrate oxidation rates, and performance. In one recent carefully conducted study, endurance performance and fuel selection were assessed during prolonged exercise while ingesting glucose (15, 30, and 60 g · h^{-1}) (Smith et al., 2010b). Twelve participants cycled for 2 h at 77% $\dot{V}O_{2peak}$ followed by a 20-km time-trial. The results suggest a relationship between the dose of glucose ingested and improvements in endurance performance. The exogenous glucose oxidation increased with ingestion rate and it is possible that an increase in exogenous carbohydrate oxidation is directly linked with, or responsible for, exercise performance.

In a large-scale multi-centre study, Smith et al. (2010a) also investigated the relationship between carbohydrate ingestion rate and cycling time-trial performance to identify a range of carbohydrate ingestion rates that would enhance performance. In their study, across four research sites, 51 cyclists and triathletes completed four exercise sessions consisting of a 2-h constant-load ride at a moderate to high intensity. Twelve different beverages (consisting of glucose:fructose in a 2:1 ratio) were compared, providing participants with 12 different carbohydrate doses raging from 10 to 120 g carbohydrate per hour during the constant-load ride. At all four sites, a common placebo that was artificially sweetened, coloured, and flavoured and did not contain carbohydrate was provided. The order of the beverage treatments was randomized at each site (three at each site). Immediately after the constant-load ride, participants completed a computer-simulated 20-km time-trial as quickly as possible. The ingestion of carbohydrate significantly improved performance in a dose-dependent manner and the authors concluded that the greatest performance enhancement was seen at an ingestion rate between

60 and 80 g carbohydrate per hour. Based on the studies above, carbohydrate intake recommendation for more prolonged exercise can be formulated and are listed in newly proposed guidelines in Table I. Please note that these guidelines for carbohydrate intake during exercise are expressed in grams per hour of exercise and that these figures are not corrected for body mass.

Effect of body weight. In the most recent position statement by the American Dietetics Association (ADA) and ACSM (Rodriguez et al., 2009), advice with respect to carbohydrate intake during exercise is expressed in $g \cdot kg\ BW^{-1}$. The rationale for this was unclear, as there appears to be no correlation between body mass and exogenous carbohydrate oxidation (Jeukendrup, 2010). The reason for this lack of correlation between body weight and exogenous carbohydrate oxidation is probably that the limiting factor is carbohydrate absorption and absorption is largely independent of body mass. It is likely, however, that the absorptive capacity of the intestine is modified by carbohydrate content of the diet, as it has been shown in animal studies that intestinal transporters can be upregulated with increased carbohydrate intake. Since exogenous carbohydrate is independent of body mass or muscle mass, but dependent on absorption and to some degree the absolute exercise intensity (at very low absolute intensities, low carbohydrate rates may also restrict exogenous carbohydrate oxidation), the advice given to athletes should be in absolute amounts. These results clearly show that there is no rationale for expressing carbohydrate recommendations for athletes per kilogram body mass (Table I).

In summary, individual differences in exogenous carbohydrate oxidation exist, although they are generally small. These differences are not related to body mass but more likely to a capacity to absorb carbohydrates. This in turn could be diet related.

Carbohydrate intake in real-life events. In a study by Kimber and colleagues (Kimber, Ross, Mason, & Speedy, 2002), the average carbohydrate intake during an Ironman distance triathlon was $1.0\ g \cdot kg\ BW^{-1} \cdot h^{-1}$ in female triathletes and $1.1\ g \cdot kg\ BW^{-1} \cdot h^{-1}$ in male triathletes. They achieved these carbohydrate intakes by ingesting very large amounts of carbohydrate during cycling (approximately $1.5\ g \cdot kg\ BW^{-1} \cdot h^{-1}$). Most of the intake occurred during the cycling leg, where intake was almost three times as high as during the running leg. In male athletes, carbohydrate intake was positively correlated with finish time but this relationship could not be confirmed in females. In a large study of endurance events, Pfeiffer et al. (2011a) demonstrated wide variation in carbohydrate intake reported by athletes between and within events, with the highest intakes in cycling and triathlon events and the lowest in marathons. Pfeiffer et al. also found that in Ironman races carbohydrate intake was related to finish time, with greater carbohydrate intake correlating with better performance.

Different advice for different endurance sports. With carbohydrate feeding during cycling, it has repeatedly been shown that muscle glycogen breakdown is unaffected. During running, however, there are suggestions that muscle glycogen breakdown is reduced in particular in type I muscle fibres (Tsintzas, Williams, Boobis, & Greenhaff, 1995). Therefore, carbohydrate feeding results in improved performance in cycling and running, although the mechanism by which this occurs may not necessarily be the same. This issue is discussed in more detail in an excellent review by Tsintzas and Williams (1998). Exogenous carbohydrate oxidation appears to be similar in cycling and running (Pfeiffer, Stellingwerff, Zaltas, Hodgson, & Jeukendrup, 2011b), suggesting that the advice for cyclists and runners should not be different.

Training the gut. Since the absorption of carbohydrate limits exogenous carbohydrate oxidation, and exogenous carbohydrate oxidation seems to be linked with exercise performance, an obvious potential strategy would be to increase the absorptive capacity of the gut. Anecdotal evidence in athletes would suggest that the gut is trainable and that individuals who regularly consume carbohydrate or have a high daily carbohydrate intake may also have an increased capacity to absorb it. Intestinal carbohydrate transporters can indeed be upregulated by exposing an animal to a high carbohydrate diet (Ferraris, 2001). To date, there is limited evidence in humans. In a recent study, Cox et al. (2010) investigated whether altering daily carbohydrate intake affects substrate oxidation and in particular exogenous carbohydrate oxidation. It was demonstrated that exogenous carbohydrate oxidation rates were higher after the high carbohydrate diet ($6.5\ g \cdot kg\ BW^{-1} \cdot day^{-1}$; $1.5\ g \cdot kg\ BW^{-1}$ provided mainly as a carbohydrate supplement during training) for 28 days compared with a control diet ($5\ g \cdot kg\ BW^{-1} \cdot day^{-1}$). This study provided evidence that the gut is indeed adaptable and this can be used as a practical method to increase exogenous carbohydrate oxidation. We recently suggested that this may be highly relevant to the endurance athlete and may be a prerequisite for the first person to break the 2-h marathon barrier (Stellingwerff & Jeukendrup, 2011).

Maintaining fluid balance during exercise. To prevent large fluid losses, perhaps the best advice is for endurance athletes to weigh themselves to assess fluid losses during training and racing and limit weight losses to 2–3% during exercise lasting more than 90 min. In the absence of such planning, concrete advice is difficult since differences between individuals, race distances, course profiles, and environmental conditions will confound any suggestions. The addition of sodium and carbohydrate to sports drinks is widely recommended to enhance the absorption of water.

Although hypertonic solutions tend to delay water absorption in the intestine (Rehrer, Brouns, Beckers, & Saris, 1994) and energy density is perhaps the most important factor dictating gastric emptying rates (Brouns, Senden, Beckers, & Saris, 1995; Noakes, Rehrer, & Maughan, 1991), the use of multiple transportable carbohydrates can help to maintain high rates of gastric emptying and improve the delivery of fluid (Jeukendrup & Moseley, 2010). Although difficult to draw firm conclusions in almost every study, we have also seen better tolerance of the drinks with multiple transportable carbohydrates compared with a single carbohydrate at these high intake rates ($>1\ g \cdot min^{-1}$).

In summary, a balance must be struck between the goals of maintaining hydration status and providing carbohydrate to the working muscle. The rate of fluid absorption is closely related to the carbohydrate content of the drink with high carbohydrate concentrations compromising fluid delivery, although multiple transportable carbohydrates can remove some of this impaired fluid delivery. In all cases, a drink should contain sodium ($10–30\ mmol \cdot L^{-1}$) (Maughan, 1998) for optimal fluid absorption and prevention of hyponatraemia.

Caffeine

Caffeine is one of the most common supplements used in endurance sports. It is an alkaloid xanthine derivative (1, 3, 7-trimethylxanthine) found in, and added to, a wide variety of foods, beverages, and sports nutrition products. Caffeine has been consumed in various foods and beverages for centuries due to its perceived work-enhancing (ergogenic) and alertness effects. A large number of studies have reported improvements in endurance performance (for reviews, see Graham, 2001; Tarnopolsky, 1994) and the ergogenic properties of caffeine are generally accepted. The International Olympic Committee (IOC) previously had caffeine on the banned substance list with urinary concentrations greater than $12\ mg \cdot L^{-1}$ considered a doping infraction; however, the Word Anti-Doping Agency removed caffeine from the banned substance list in 2004 and placed it on the monitoring list.

Although habitual consumption of caffeine may down-regulate many of the physiological effects (tachyphylaxis; attenuated acute ingestion induced rise in heart rate or blood pressure; attenuation of lipolytic effects), the ergogenic effects of caffeine are similar in both non-habitual and habitual caffeine consumers (Van Soeren, Sathasivam, Spriet, & Graham, 1993). In line with these findings, a recent study showed that 4 days of caffeine withdrawal had no effect on the ergogenic effect of caffeine during a time-trial lasting approximately 1 h (Irwin et al., 2011).

The vast majority of the studies that reported ergogenic effects used caffeine doses in the range 3–6 $mg \cdot kg^{-1}$ taken approximately 1 h before exercise. More recently, studies have reported that much lower doses of caffeine ($1.0–2.0\ mg \cdot kg^{-1}$), especially when taken later during an endurance exercise task, have also enhanced performance (Cox et al., 2002).

Caffeine is absorbed with a time to peak plasma concentration of 30–90 min and half-life of about 5 h. Therefore, an effective strategy might be to ingest a dose close to $3\ mg \cdot kg^{-1}$ 60 min before the start of exercise followed by $1\ mg \cdot kg^{-1}$ every 2 h after that. However, even when only taken late in exercise, caffeine can still be effective (Cox et al., 2002).

Gastrointestinal problems

There is a very high prevalence of gastrointestinal complaints during exercise among long-distance runners, triathletes, and athletes involved in other types of strenuous long lasting exercise (Rehrer et al., 1992), with studies reporting a prevalence of between 10% and 95% depending on the event, the environmental conditions, and methodology used to assess gastrointestinal distress. Pfeiffer et al. (2011a) reported severe gastrointestinal distress ranging from 4% in marathon running and cycling up to 32% in Ironman races. In a recent study, Pfeiffer and colleagues (Pfeiffer, Cotterill, Grathwohl, Stellingwerff, & Jeukendrup, 2009) demonstrated that there was a strong correlation between gastrointestinal symptoms and having a history of gastrointestinal symptoms, perhaps suggesting that some people are more prone to develop gastrointestinal distress and there might be a genetic component to these problems.

The most frequently reported symptoms include dizziness, nausea, stomach or intestinal cramps, vomiting, and diarrhoea. Rehrer et al. (1992) reported a link between nutritional practices and gastrointestinal complaints during a half Ironman distance triathlon. It was found that gastrointestinal problems were more likely to occur with the ingestion of fibre, fat, protein, and concentrated carbohydrate solutions during the triathlon. In particular, beverages with a very high osmolality seemed to be responsible for some of the reported complaints.

Symptoms are often mild and may not even affect performance. Some of the symptoms, however, can be very serious and will not only affect performance but are health threatening. For example, marathon runners and long-distance triathletes occasionally have blood loss in faeces in the hours following a marathon. Schaub and colleagues (Schaub, Spichtin, & Stalder, 1985) observed epithelial surface changes known to occur during ischaemia upon colonoscopic inspection of one such triathlete following a marathon and suggested that ischaemia of the lower gastrointestinal tract induced the problems. Øktedalen et al. (1992) reported increased intestinal permeability after a marathon, indicating damage to the gut and impaired gut function. Despite the high prevalence of symptoms, mild or severe, the aetiology of these gastrointestinal complaints in endurance athletes is still incompletely understood.

Hyponatraemia

Hyponatraemia has occasionally been reported in long-distance triathletes (Speedy et al., 1999). This appears to be most common among slow competitors in triathlons and ultra-marathon races and probably arises due to loss of sodium in sweat coupled with very high intakes of water or other low sodium drinks (Noakes, Goodwin, Rayner, Branken, & Taylor, 1985). The symptoms of hyponatraemia are similar to those associated with dehydration and include mental confusion, weakness, and fainting. Such symptoms are usually seen at serum sodium concentrations of 126–130 mmol $\cdot$ L^{-1}. Below 126 mmol $\cdot$ L^{-1}, seizures, coma, and death may occur.

Endurance athletes may develop hyponatraemia without displaying the symptoms. Hyponatraemia may occur in a state of euhydration or even dehydration but is generally associated with fluid overload (Speedy et al., 1999). To prevent hyponatraemia, athletes need to be informed about the potential dangers of drinking too much water or sodium-free beverages. One study showed no evidence that sodium ingestion significantly influenced changes in plasma sodium concentration or plasma volume more than fluid replacement alone (Speedy, Thompson, Rodgers, Collins, & Sharwood, 2002). The authors therefore suggested that sodium supplementation was not necessary to prevent the development of hyponatraemia in these athletes. In a modelling paper, Montain et al. (2006) suggested that electrolyte replacement should be considered only as part of the preventive process; most important is the avoidance of excessive fluid intake.

Conclusion

To optimize endurance exercise, carbohydrates and fluids play an important role, both before and during exercise. Starting with high muscle glycogen concentrations and being euhydrated is important, which can be achieved by high carbohydrate consumption and adequate drinking. An individualized nutritional strategy can be developed that aims to deliver carbohydrate to the working muscle at a rate that is dependent on the absolute exercise intensity as well as the duration of the event. Higher carbohydrate intakes may result in better performance and the ingestion of multiple transportable carbohydrates will allow very high carbohydrate oxidation rates and superior performance. Endurance athletes should attempt to minimize dehydration and limit body mass losses through sweating to 2–3% of body mass. Other issues in endurance sports include gastrointestinal problems, which are highly individual but can be minimized by talking certain nutritional precautions. Hyponatraemia has occasionally been reported but can be avoided in almost all cases by avoiding overdrinking.

References

Brouns, F., Senden, J., Beckers, E. J., & Saris, W. H. (1995). Osmolarity does not affect the gastric emptying rate of oral rehydration solutions. *Journal of Parenteral and Enteral Nutrition*, *19*, 403–406.

Burke, L. M., Hawley, J. A., Wong, S. H. S., & Jeukendrup, A. (2011). Carbohydrates for training and competition. *Journal of Sports Sciences*.

Chambers, E. S., Bridge, M. W., & Jones, D. A. (2009). Carbohydrate sensing in the human mouth: Effects on exercise performance and brain activity. *Journal of Physiology*, *587*, 1779–1794.

Cox, G. R., Clark, S. A., Cox, A. J., Halson, S. L., Hargreaves, M., Hawley, J. A. et al. (2010). Daily training with high carbohydrate availability increases exogenous carbohydrate oxidation during endurance cycling. *Journal of Applied Physiology*, *109*, 126–134.

Cox, G. R., Desbrow, B., Montgomery, P. G., Anderson, M. E., Bruce, C. R., Macrides, T. A. et al. (2002). Effect of different protocols of caffeine intake on metabolism and endurance performance. *Journal of Applied Physiology*, *93*, 990–999.

Coyle, E. F., Jeukendrup, A. E., Oseto, M. C., Hodgkinson, B. J., & Zderic, T. W. (2001). Low-fat diet alters intramuscular substrates and reduces lipolysis and fat oxidation during exercise. *Amerian Journal of Physiology: Endocrinology and Metabolism*, *280*, E391–E398.

Ferraris, R. P. (2001). Dietary and developmental regulation of intestinal sugar transport. *Biochemistry Journal*, *360*, 265–276.

Foster, C., Costill, D. L., & Fink, W. J. (1979). Effects of preexercise feedings on endurance performance. *Medicine and Science and Sports*, *11*, 1–5.

Gant, N., Stinear, C. M., & Byblow, W. D. (2010). Carbohydrate in the mouth immediately facilitates motor output. *Brain Research*, *1350*, 151–158.

Graham, T. E. (2001). Caffeine, coffee and ephedrine: Impact on exercise performance and metabolism. *Canadian Journal of Applied Physiology*, *26* (suppl.), S103–S119.

Hargreaves, M., Hawley, J. A., & Jeukendrup, A. (2004). Pre-exercise carbohydrate and fat ingestion: Effects on metabolism and performance. *Journal of Sports Sciences*, *22*, 31–38.

Hawley, J. A., Schabort, E. J., Noakes, T. D., & Dennis, S. C. (1997). Carbohydrate loading and exercise performance: An update. *Sports Medicine*, *24*, 73–81.

Irwin, C., Desbrow, B., Ellis, A., O'Keeffe, B., Grant, B., & Leveritt, M. (2011). Caffeine withdrawal and high intensity endurance cycling performance. *Journal of Sports Sciences*, *29*, 509–515.

Jentjens, R. L., & Jeukendrup, A. E. (2002). Prevalence of hypoglycemia following pre-exercise carbohydrate ingestion is not accompanied by higher insulin sensitivity. *International Journal of Sport Nutrition and Exercise Metabolism*, *12*, 398–413.

Jentjens, R. L., & Jeukendrup, A. E. (2003). Effects of pre-exercise ingestion of trehalose, galactose and glucose on subsequent metabolism and cycling performance. *European Journal of Applied Physiology*, *88*, 459–465.

Jentjens, R. L., Moseley, L., Waring, R. H., Harding, L. K., & Jeukendrup, A. E. (2004). Oxidation of combined ingestion of glucose and fructose during exercise. *Journal of Applied Physiology*, *96*, 1277–1284.

Jeukendrup, A. E. (2004). Carbohydrate intake during exercise and performance. *Nutrition*, *20*, 669–677.

Jeukendrup, A. (2008). Carbohydrate feeding during exercise. *European Journal of Sport Science*, *8*, 77–86.

Jeukendrup, A. E. (2010). Carbohydrate and exercise performance: The role of multiple transportable carbohydrates. *Current Opinion in Clinical Nutrition and Metabolic Care*, *13*, 452–457.

Jeukendrup, A. E., & Chambers, E. S. (2010). Oral carbohydrate sensing and exercise performance. *Current Opinion in Clinical Nutrition and Metabolic Care*, *13*, 447–451.

Jeukendrup, A. E., & Killer, S. (2011). The myths surrounding pre-exercise carbohydrate feeding. *Annals of Nutrition and Metabolism*, *57* (suppl. 2), 18–25.

Jeukendrup, A. E., & Moseley, L. (2010). Multiple transportable carbohydrates enhance gastric emptying and fluid delivery. *Scandinavian Journal of Medicine and Science in Sports*, *20*, 112–121.

Kimber, N. E., Ross, J. J., Mason, S. L., & Speedy, D. B. (2002). Energy balance during an ironman triathlon in male and female triathletes. *International Journal of Sport Nutrition and Exercise Metabolism*, *12*, 47–62.

Koivisto, V. A., Karonen, S. L., & Nikkila, E. A. (1981). Carbohydrate ingestion before exercise: Comparison of glucose, fructose, and sweet placebo. *Journal of Appllied Physiology*, *51*, 783–787.

Kuipers, H., Fransen, E. J., & Keizer, H. A. (1999). Pre-exercise ingestion of carbohydrate and transient hypoglycemia during exercise. *International Journal of Sports Medicine*, *20*, 227–231.

Latzka, W. A., Sawka, M. N., Montain, S. J., Skrinar, G. S., Fielding, R. A., Matott, R. P. et al. (1998). Hyperhydration: Tolerance and cardiovascular effects during uncompensable exercise-heat stress. *Journal of Applied Physiology*, *84*, 1858–1864.

Maughan, R. J. (1998). The sports drink as a functional food: Formulations for succesful performance. *Proceedings of the Nutrition Society*, *57*, 15–23.

Montain, S. J., Cheuvront, S. N., & Sawka, M. N. (2006). Exercise associated hyponatraemia: Quantitative analysis to understand the aetiology. *British Journal of Sports Medicine*, *40*, 98–105; discussion 198–105.

Moseley, L., Lancaster, G. I., & Jeukendrup, A. E. (2003). Effects of timing of pre-exercise ingestion of carbohydrate on subsequent metabolism and cycling performance. *European Journal of Applied Physiology*, *88*, 453–458.

Noakes, T. D., Goodwin, N., Rayner, B. L., Branken, T., & Taylor, R. K. N. (1985). Water intoxication: A possible complication during endurance exercise. *Medicine and Science in Sports and Exercise*, *17*, 370–375.

Noakes, T. D., Rehrer, N. J., & Maughan, R. J. (1991). The importance of volume in regulating gastric emptying. *Medicine and Science in Sports and Exercise*, *23*, 307–313.

Øktedalen, O., Lunde, O. C., Opstad, P. K., Aabakken, L., & Kvernebo, K. (1992). Changes in gastro-intestinal mucose after long-distance running. *Scandinavian Journal of Gastroenterology*, *27*, 270–274.

Pfeiffer, B., Cotterill, A., Grathwohl, D., Stellingwerff, T., & Jeukendrup, A. E. (2009). The effect of carbohydrate gels on gastrointestinal tolerance during a 16-km run. *International Journal of Sport Nutrition and Exercise Metabolism*, *19*(5), 485–503.

Pfeiffer, B., Stellingwerff, T., Hodgson, A. B., Randell, R., Poettgen, K., Res, P. et al. (2011a). Nutritional intake and gastrointestinal problems during competitive endurance events. *Medicine and Science in Sports and Exercise* (DOI: 10.1249/MSS.0b013e31822dc809).

Pfeiffer, B., Stellingwerff, T., Zaltas, E., Hodgson, A. B., & Jeukendrup, A. E. (2011b). Carbohydrate oxidation from a drink during running compared with cycling exercise. *Medicine and Science in Sports and Exercise*, *43*, 327–334.

Pfeiffer, B., Stellingwerff, T., Zaltas, E., & Jeukendrup, A. E. (2010a). CHO oxidation from a CHO gel compared with a drink during exercise. *Medicine and Science in Sports and Exercise*, *42*, 2038–2045.

Pfeiffer, B., Stellingwerff, T., Zaltas, E., & Jeukendrup, A. E. (2010b). Oxidation of solid versus liquid CHO sources during exercise. *Medicine and Science in Sports and Exercise*, *42*, 2030–2037.

Rehrer, N. J., Brouns, F., Beckers, E. J., Frey, W. O., Villiger, B., Riddoch, C. J. et al. (1992). Physiological changes and gastro-intestinal symptoms as a result of ultra-endurance running. *European Journal of Applied Physiology*, *64*, 1–8.

Rehrer, N. J., Brouns, F., Beckers, E. J., & Saris, W. H. M. (1994). The influence of beverage composition and gastrointestinal function on fluid and nutrient availability during exercise. *Scandinavian Journal of Medicine and Science in Sports*, *4*, 159–172.

Rodriguez, N. R., Di Marco, N. M., & Langley, S. (2009). American College of Sports Medicine position stand: Nutrition and athletic performance. *Medicine and Science in Sports and Exercise*, *41*, 709–731.

Romijn, J. A., Coyle, E. F., Sidossis, L. S., Gastaldelli, A., Horowitz, J. F., Endert, E. et al. (1993). Regulation of endogenous fat and carbohydrate metabolism in relation to exercise intensity. *American Journal of Physiology: Endocrinology and Metabolism*, *265*, E380–E391.

Saris, W. H., Antoine, J. M., Brouns, F., Fogelholm, M., Gleeson, M., Hespel, P., & Stich, V. (2003). PASSCLAIM – physical performance and fitness. *European Journal of Nutrition*, *42* (suppl. 1), I50–I95.

Sawka, M. N., Burke, L. M., Eichner, E. R., Maughan, R. J., Montain, S. J., & Stachenfeld, N. S. (2007). American College of Sports Medicine position stand: Exercise and fluid replacement. *Medicine and Science in Sports and Exercise*, *39*, 377–390.

Schaub, N., Spichtin, H. P., & Stalder, G. A. (1985). Ischämische Kolitis als Ursache einer Darmblutung bei Marathonlauf? *Schweizerische Medicin Wochenschrift*, *115*, 454–457.

Shirreffs, S. (2011). Fluid and electrolyte needs for training, competition and recovery. *Journal of Sports Sciences*.

Smith, J. W., Zachwieja, J. J., Horswill, C. A., Pascoe, D. D., Passe, D., Ruby, B. C. et al. (2010a). Evidence of a carbohydrate dose and prolonged exercise performance relationship. *Medicine and Science in Sports and Exercise*, *42* (5), 84.

Smith, J. W., Zachwieja, J. J., Peronnet, F., Passe, D. H., Massicotte, D., Lavoie, C. et al. (2010b). Fuel selection and cycling endurance performance with ingestion of [13C]glucose: Evidence for a carbohydrate dose response. *Journal of Applied Physiology*, *108*, 1520–1529.

Speedy, D. B., Noakes, T. D., Rogers, I. R., Thompson, J. M., Campbell, R. G., Kuttner, J. A. et al. (1999). Hyponatremia in ultradistance triathletes. *Medicine and Science in Sports and Exercise*, *31*, 809–815.

Speedy, D. B., Thompson, J. M., Rodgers, I., Collins, M., & Sharwood, K. (2002). Oral salt supplementation during ultra-distance exercise. *Clinical Journal of Sport Medicine*, *12*, 279–284.

Stellingwerff, T., & Jeukendrup, A. E. (2011). Authors' reply to Viewpoint by Joyner et al. entitled "The Two-Hour Marathon: Who and When?" *Journal of Applied Physiology*, *110*, 278–293.

Tarnopolsky, M. A. (1994). Caffeine and endurance performance. *Sports Medicine*, *18*, 109–125.

Tsintzas, K., & Williams, C. (1998). Human muscle glycogen metabolism during exercise: Effect of carbohydrate supplementation. *Sports Medicine*, *25*, 7–23.

Tsintzas, O. K., Williams, C., Boobis, L., & Greenhaff, P. (1995). Carbohydrate ingestion and glycogen utilisation in different muscle fibre types in man. *Journal of Physiology*, *489*, 243–250.

van Rosendal, S. P., Osborne, M. A., Fassett, R. G., & Coombes, J. S. (2010). Guidelines for glycerol use in hyperhydration and rehydration associated with exercise. *Sports Medicine*, *40*, 113–129.

Van Soeren, M. H., Sathasivam, P., Spriet, L. L., & Graham, T. E. (1993). Caffeine metabolism and epinephrine responses during exercise in users and nonusers. *Journal of Applied Physiology*, *75*, 805–812.

Wee, S. L., Williams, C., Gray, S., & Horabin, J. (1999). Influence of high and low glycemic index meals on endurance running capacity. *Medicine and Science in Sports and Exercise*, *31*, 393–399.