Legal nutritional supplements during a sporting event

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Abstract

Nutrition significantly influences sports performance; however, the efficacy of any nutritional supplement or strategy should be carefully considered in relation to the event and the sex, training and nutritional status of the participant. The causes of fatigue, mechanism of action, safety and legality of the supplement, together with the scientific evidence from studies with an appropriate experimental design, should all be taken into account before incorporating into the training and/or competition diet. The efficacy of ingesting nutritional supplements immediately before and/or during endurance exercise (duration 45–180 min) is reviewed in this chapter. The ingestion of CES (carbohydrate–electrolyte solutions) have been shown to improve both exercise capacity and performance, either due to the maintenance of euglycaemia throughout exercise or the sparing of muscle glycogen early on in exercise. The addition of caffeine to CES may improve endurance performance as a consequence of a reduced perception of effort. Research suggests that the addition of protein to CES may only be effective when a suboptimal amount of CHO (carbohydrate) is ingested during exercise (<60 g of CHO·h⁻¹); however, recovery of performance may be enhanced due to a reduction in subsequent muscle soreness and the promotion of muscle protein synthesis after exercise. The findings from studies investigating the effects of ingesting MCTs (medium-chain triacylglycerols) and BCAAs

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(branched-chain amino acids), either on their own or in combination with CES, on endurance performance have been equivocal and therefore would not be recommended. Any nutritional strategy should be practised in training before being used during a competition.

**Introduction**

Ever since humans began participating in sports competitions it has been believed that physical performance and nutrition are linked. Subsequent research has shown that not only are ingested nutrients metabolized to provide the ATP for muscle contraction, but altering the macronutrient intake of an individual can significantly affect performance [1]. However, such findings cannot be applied to all events under every circumstance. For any supplement or nutritional strategy to be effective during a sporting event (which includes individual and team sports), there are several factors which the athlete should consider before taking the supplement or using the strategy. These are: (i) what are the causes of fatigue during the event and what is the rationale for the efficacy of the strategy or supplement?; (ii) what is the evidence for an ergogenic effect?; (iii) was this evidence obtained from studies which included appropriate standards of experimental design?; (iv) how do the findings relate to the event in terms of mode, distance, intensity, characteristics of subjects?; (v) is it safe?; and (vi) is it legal?

For the purpose of this chapter, only supplementation immediately before and/or during prolonged exercise that can be sustained for 45–180 min will be considered as it is generally accepted that supplementation during exercise of less than 45 min has not demonstrated any ergogenic effects [2]. Prolonged exercise may be performed continuously (as during cycling or running events) or intermittently (such as during the multiple sprint sports of soccer, rugby and hockey). Several supplements have been reported to improve performance when ingested in the days before or the hours before exercise [3–5], but it is supplementation during the event itself that is the focus of this chapter. In the first instance, energy metabolism and causes of fatigue will be considered. Then it is the aim to highlight the rationale for ingestion of several nutrients and supplements during prolonged exercise and provide a summary of their effects on performance (see Table 1). The ingestion of CES (carbohydrate–electrolyte solutions) alone during exercise and when combined with caffeine, protein, BCAAs (branched-chain amino acids) and MCTs (medium-chain triacylglycerols) will be discussed.

**Energy metabolism and fatigue during prolonged exercise**

The level of skill and the muscles’ capacity to perform work will determine the ability of each athlete to perform any given task [6]. When the upper limits have been reached, fatigue occurs and this is generally defined as the failure to maintain an expected or required force or power output [7]. Fatigue can be physiological or psychological, and in physiological terms,
Table 1. Rationale for nutritional supplementation during exercise and effects on performance

<table>
<thead>
<tr>
<th>Supplement</th>
<th>Rationale</th>
<th>Study</th>
<th>Effect on metabolism</th>
<th>Effect on performance/capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>CES</td>
<td>Maintenance of euglycaemia</td>
<td>Coggan and Coyle [16]</td>
<td>Increased glucose and CHO oxidation</td>
<td>Increased endurance capacity</td>
</tr>
<tr>
<td></td>
<td>Sparing of muscle glycogen</td>
<td>Nicholas et al. [17,22]</td>
<td>Glycogen sparing [22]</td>
<td>Increased endurance capacity [17]</td>
</tr>
<tr>
<td>CES+caffeine</td>
<td>Increased fat oxidation</td>
<td>Kovacs et al. [39]</td>
<td>Not measured</td>
<td>Performance improved</td>
</tr>
<tr>
<td></td>
<td>Increased CHO oxidation</td>
<td>Millard-Stafford et al. [41]</td>
<td>No changes in metabolism, decreased RPE</td>
<td>Performance improved</td>
</tr>
<tr>
<td>CES+protein</td>
<td>Alterations in insulin</td>
<td>Cureton et al. [43]</td>
<td>Decreased RPE</td>
<td>More work performed</td>
</tr>
<tr>
<td></td>
<td>Faster absorption of CHO</td>
<td>Ivy et al. [48]</td>
<td>No changes</td>
<td>Increased endurance capacity</td>
</tr>
<tr>
<td></td>
<td>Enhanced recovery</td>
<td>Saunders et al. [49]</td>
<td>No changes, but lower post-exercise CK</td>
<td>Increased endurance capacity</td>
</tr>
<tr>
<td>CES+BCAAs</td>
<td>Decreased plasma f-TRP/BCAA ratio</td>
<td>Madsen et al. [61]</td>
<td>No changes in oxidation rates, increased ammonia</td>
<td>No effect</td>
</tr>
<tr>
<td>CES+MCTs</td>
<td>Increased fat oxidation</td>
<td>Van Zyl et al. [68]</td>
<td>Increased fat oxidation</td>
<td>Improved 40 km TT</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Jeukendrup et al. [66]</td>
<td>No changes</td>
<td>No effect</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Goedecke et al. [71]</td>
<td>No changes</td>
<td>Decrement in performance</td>
</tr>
</tbody>
</table>
fatigue is considered to be either central or peripheral [8]. As a consequence of fatigue, the athlete must slow down or stop, and co-ordination and skill performance is also affected [6]. During prolonged exercise there are many physiological factors which determine performance, which include a high $V_{O_2\text{max}}$, a large fractional utilization of aerobic capacity, a high capacity to use fat as fuel and the ability to regulate body temperature [6]. The ability to supply energy by aerobic metabolism is vital during prolonged exercise. Anaerobic metabolism plays only a minor role at the start of exercise, or when there is a change in pace or during a sprint finish. However, despite the oxygen deficit observed at the start of exercise, highly trained endurance athletes can achieve a steady state of oxygen consumption within 1 min of exercise beginning, and, thereafter, CHO (carbohydrate) and fat oxidation become the principal means of resynthesizing ATP [6] (see Figure 1). Exercise intensity predominantly determines the metabolic response to exercise, though duration is also an important factor [10]. Energy demand increases with the intensity of exercise and there is a concomitant increase in CHO metabolism from both plasma glucose and muscle glycogen [10] (see Figure 2). As CHO stored as muscle and liver glycogen are limited, with 100 g and 300 g of glycogen stored in the liver and muscles respectively [6], the availability of CHO is a potential limitation to performance during prolonged endurance and intermittent high-intensity exercise and thus CHO depletion is the main cause of fatigue following 1–3 h of continuous exercise at 60–80% $V_{O_2\text{max}}$ [11]. Indeed, since the 1960s, it has been well-documented that there is a strong relationship

Figure 1. Summary of the main pathways of energy metabolism using CHOs, fats and protein as energy sources
between pre-exercise muscle glycogen content and endurance performance, which may be continuous [12] or intermittent [13]. Thus it is not surprising that over the last 40 years, researchers have investigated different strategies to delay fatigue by either increasing carbohydrate availability or by decreasing the utilization of endogenous CHO during exercise.

**Ingestion of CES**

The ingestion of CES has the twin aim of providing the exercising individual with both fluid to replace the losses incurred by sweating, and fuel to supplement the body’s limited CHO stores [14]. Regular fluid ingestion during prolonged exercise is important and it has been demonstrated that endurance exercise performance is impaired when dehydration exceeds approx. 2% of pre-exercise body mass (or even less in hot weather) [15]. There is a plethora of evidence which suggests that ingesting CES during exercise improves exercise capacity [16–18] and performance [19,20] compared with water or other placebo beverages. The mechanism for this ergogenic effect is probably due to the maintenance of euglycaemia, ensuring a constant supply of glucose to the brain and a high rate of exogenous CHO oxidation later during exercise [16] (see Figure 3), or the sparing of muscle glycogen early on in exercise [22,23].

At this stage, it is important to distinguish between endurance ‘capacity’ and ‘performance’ as research studies under controlled laboratory conditions have tended to use either measurement as the dependent variable. Endurance
capacity measures the time to exhaustion at a fixed work rate, whereas endurance performance measures the time taken to complete a fixed distance or workload, or is a measure of the amount of work done or distance covered in a predetermined time. The measurement of endurance capacity can be a valid approach, but results should be viewed with some caution as the reliability of some protocols has been called into question [24], as has the ecological validity [25]. In addition, it is difficult to extrapolate the results obtained from measures of capacity to a race situation. Large differences in performance can be demonstrated; however, in a simulated race situation, the advantage would be reduced to no more than a few percent, and in real competition it would probably be even less.

Figure 3. Plasma glucose (A) and rates of CHO oxidation (B) during exercise to fatigue at 70–74% \( V_{O_{peak}} \) with ingestion of either a placebo or CHO solution every 20 min

For optimal hydration and CHO ingestion, it is recommended that an athlete drinks 600–1400 ml·h\(^{-1}\) of a 4–8% CES in small doses, every 15 min during exercise [26]. Such a strategy ensures optimal delivery of CHO and a maximum CHO oxidation rate of 1.0–1.2 g·min\(^{-1}\) [27]. Improvements in endurance exercise performance and capacity are generally seen when CHO is ingested at a rate of 30–60 g·h\(^{-1}\) and when the exercise duration is 1 h or more [17,19,23]. Indeed, the ingestion of more than 60 g·h\(^{-1}\) of single CHOs (such as glucose, sucrose or glucose polymers) does not result in higher rates of exogenous CHO oxidation [27]. Exogenous CHO availability does not tend to limit performance of less than 1 h duration, as it has been recently shown that a 40 km cycling time trial performance (which lasted approximately 1 h) was improved when subjects had a 6% CHO solution mouth rinse compared with a placebo mouth rinse [28]. The authors proposed that the mechanism for improved performance was that the CHO solution stimulated CHO receptors in the mouth, resulting in an increase in motivation.

It should be pointed out that not all studies have reported an improvement in performance and capacity with CHO feedings during exercise [29–31]. The reason for these different results is not clear, and may be partly explained by differences in the type and amount of CHO given, by the different exercise models used, and by differences in the training status and nutritional status of the subjects studied. However, it should be noted that no study has reported an adverse effect of CHO ingestion (with or without electrolytes) during exercise on performance.

**Which CES is best?**

There is general agreement in the literature that sports drinks which have CHO concentrations above 6–10% do not produce additional performance benefits [16,32]. The ideal composition of a sports drink will vary, depending upon environmental conditions (temperature and humidity), the intensity and duration of exercise and on the physiological and biochemical characteristics of the individual athlete [33]. When the ambient temperature is warm, and when performance during prolonged events may be limited by dehydration, it is vital to replace fluid and, possibly, the electrolytes lost in sweat during exercise. In this situation, where fluid replacement is the first priority, the CHO content of the drinks should be low. Availability of ingested fluids depends on the rates of gastric emptying and intestinal absorption (for more information, see [33]). Where performance may be limited by CHO availability, then the concentration should be increased to 6–10% CHO. Increasing the CHO content of the drinks will increase the amount of fuel which can be supplied, but will tend to decrease the rate at which water can be made available [14] (see Figure 4).

More recently, researchers have investigated whether the co-ingestion of multiple types of CHO, other macronutrients (such as protein) or supplements (for example caffeine, BCAAs, MCTs) further increase performance, either by increasing the rate of exogenous CHO oxidation compared with single CHOs, or by a different mechanism.
An increased rate of CHO oxidation (approx. 1.7 g·min\(^{-1}\)) was reported in a study when glucose, fructose and sucrose were ingested simultaneously at high rates (2.4 g·min\(^{-1}\)) compared with the ingestion of an isocaloric amount of glucose (approx. 1.2 g·min\(^{-1}\)) [34]. Other researchers that have combined the ingestion of glucose, sucrose and maltose or glucose (and glucose polymers) and fructose have found similar results, in a thermo-neutral environment [35–37], and in the heat [38]. This increase in the rate of exogenous CHO is probably due to the fact that the intestinal absorption of sucrose and fructose
is somewhat different from that of glucose [34]. However, whether this increase in exogenous CHO oxidation and resultant decrease in endogenous CHO oxidation translates into an increase in endurance performance is yet to be established.

**Caffeine and CHO ingestion**

It has been established that in order to improve performance during endurance exercise, the primary strategy is to limit the depletion of muscle glycogen. This can be achieved either by increasing CHO availability during exercise by nutritional strategies, or by decreasing CHO utilization during exercise. The latter can occur as a consequence of an increased contribution of fatty acid oxidation to overall energy expenditure, and therefore spare the body’s limited CHO supply. Many strategies pre-exercise have been used (supplementation with caffeine or carnitine, high fat diets, intravenous infusion of triacylglycerol and heparin), which are not the focus of this chapter. Caffeine ingestion pre-exercise has been reported to have an ergogenic effect during prolonged, submaximal exercise and these studies and the underlying mechanisms are reported elsewhere in this book (see Chapter 8). However, it has also been documented that when caffeine was co-ingested with a CES beverage before and during exercise, performance during a 1 h cycling time trial was improved compared with a CES alone [39]. However, no metabolic or subjective measurements were taken in this study, and therefore no explanation could be deduced for the improvements in performance. It was suggested in a subsequent study by Jacobson et al. [40] that the co-ingestion of caffeine with CHO may improve time trial performance due to a decrease in subjective effort, rather than by enhancing substrate availability. A more recent study [41] also suggested that a reduced perception of effort contributed to improved performance with the ingestion of CES plus caffeine during exercise in the heat, despite no differences in substrate utilization. Yeo et al. [42] found that exogenous CHO oxidation during a 2 h cycle ride at 64% \( \dot{V}O_{2\text{max}} \) was increased when caffeine was co-ingested with glucose, possibly due to an increase in intestinal absorption. It has been suggested that any increase in the rate of exogenous CHO oxidation would benefit the athlete as the reliance on endogenous CHO stores is reduced [27]. However, performance was not measured in this study, so any ergogenic effect can only be speculated. Performance was measured in a study by Cureton et al. [43] who found that CES plus caffeine ingestion resulted in more work being produced during a 15 min performance ride completed after a 2 h cycle alternating between 60% and 75% \( \dot{V}O_{2\text{max}} \). Perceived rate of exertion was lower and consequently participants were able to maintain a higher rate of energy expenditure.

Not all studies have reported an ergogenic effect of CHO plus caffeine ingestion compared with a CES alone [40,44,45]. Cox et al. [44] looked at the effects of different protocols of caffeine intake on metabolism and performance and reported that regardless of whether caffeine was ingested before or at
regular intervals during exercise, time trial performance following 2 h cycling at 70% $\dot{V}O_{2\text{peak}}$ was enhanced. A caffeine plus CES consumed during the latter stages of exercise was equally as effective as a CES in enhancing time trial performance.

**Protein and CHO ingestion**

The nutritional strategies of protein and CHO ingestion post-exercise are well-documented elsewhere (for reviews, the reader is directed to [46,47]). Recently it has been suggested that adding small amounts of protein (typically 20% of total energy) to a CHO beverage ingested during exercise may be more beneficial than traditional CHO-only beverages [48,49]. It has been reported that CHO and protein beverages increased performance time to fatigue in trained cyclists by $\geq 29\%$ compared with CHO ingestion alone [48,49]. The explanation for an improved performance may be that participants in the CHO plus protein trials received more energy than in the CHO-only trial [49].

Some researchers have suggested that the addition of protein to a CHO beverage is only effective when suboptimal amounts of CHO are ingested during exercise [47,25]. Further to this, Saunders et al. [49] have proposed two possible mechanisms which may otherwise explain this ergogenic effect. The protein in the CHO plus protein beverage may facilitate faster absorption of the CHO, and alterations in insulin stimulation may have contributed to an increased exercise capacity. However, these mechanisms are questionable, as Ivy et al. [48] observed higher insulin in CHO plus protein compared with water, but there was no difference compared with the CHO-only beverage. In terms of the observations that muscle damage and soreness may be reduced, Bloomer and Goldfarb [50] have suggested that the ingestion of CHO plus protein may attenuate secondary or delayed onset damage, rather than decreasing the mechanical damage initially sustained from exercise. CHO plus protein may increase protein concentrations outside the cell, which may increase protein synthesis and repair during exercise. Further investigation is clearly warranted.

However, before an athlete concludes that it is the addition of protein which results in performance benefits for their event, it is important to establish whether the rate of CHO ingestion is optimal for the event and whether the performance measure mimics the competition. Indeed, many of the performance benefits reported in the literature have been during exercise tasks to fatigue [48,49] or the rate of CHO ingestion has been less than optimal (47 g·h$^{-1}$ [48]; 37 g·h$^{-1}$ [49]). Van Essen and Gibala [25] did not find any improvement in a 80 km time trial performance when 2% protein was added to a 6% CHO drink when the ingestion rate of CHO was 60 g·h$^{-1}$. It is not only the performance benefits during one exercise bout that are important, but also the ability of the athlete to recover between events or training. It has also been observed that the addition of protein to CES reduces post-exercise muscle damage [49,51,52], and enhances muscle glycogen repletion [53] compared with CHO-only beverages. Koopman et al. [54] observed that during
6 h of exhaustive exercise at 50% $\dot{V}O_{2\text{max}}$, the combined ingestion of protein and CHO improved net protein balance during prolonged moderate intensity exercise and post-exercise recovery in trained athletes. Protein balance was negative when only CHO was ingested, which may be linked to the observed increase in post-exercise muscle damage. Thus as it has been previously reported that there is no additional benefit to be gained from consuming a CES greater than 6–10% concentration, the addition of extra energy in the form of protein to CHO beverages may be important from a practical point of view if it produces additional performance or recovery benefits.

**Ingestion of BCAAs**

It has been proposed that fatigue during prolonged exercise may have a central as well as a physical basis. It has been suggested that an increased concentration of brain serotonin (5-hydroxytryptamine) may contribute to CNS (central nervous system) fatigue during prolonged exercise (the original central fatigue hypothesis; [55]). Brain serotonin synthesis is dependent on the availability of its amino acid precursor, free tryptophan (termed f-TRP) and the activity of the rate-limiting enzyme tryptophan hydroxylase [56]. Both BCAAs and f-TRP compete for entry to the brain on the same amino acid carrier. In the brain, tryptophan is converted into serotonin, and an increase in this neurotransmitter influences behaviour, such as sleep and mood, which may affect perceived exertion during exercise. Thus any increase in the plasma fatty acid level (tryptophan, like fatty acids, is bound to albumin in the plasma, so increasing NEFA (non-esterified fatty acid) displaces tryptophan from albumin increasing its availability for uptake) or decrease in plasma concentration of BCAAs results in an increased entry of tryptophan into the brain, and thus central fatigue [55] (see Figure 5).

Consequently, researchers have attempted to manipulate the f-TRP/BCAA ratio and subsequent central serotonergic activity during exercise. This has been achieved essentially by two main nutritional strategies which involve supplementation with BCAAs and/or CHOs before and/or during exercise.

Previous studies have shown that ingesting BCAAs before prolonged exercise may result in performance benefits [57], but ingestion of BCAAs alone during exercise [58–60] or combined with CHO [61] do not result in improvements to performance. This is possibly due to the fact that any positive effects of an increased concentration of BCAAs on brain serotonin activity, is offset by the negative effects of increased ammonia concentration in the muscle and brain [62]. However, CHO feedings alone during prolonged exercise do decrease the f-TRP/BCAA ratio and result in improved endurance performance, but it is difficult to separate the central effects from the well-established peripheral mechanisms [62]. Further to the original central fatigue theory, a more recent hypothesis is that a high ratio of serotonin-to-dopamine results in feelings of tiredness and lethargy and hence an earlier onset of fatigue, whereas a low ratio may improve performance as a consequence of increased motivation.
and arousal [56]. Since tyrosine is the amino acid precursor to dopamine, it has been proposed that an elevation in blood tyrosine during exercise would result in both a decreased uptake of tryptophan in the brain and therefore a lower synthesis of serotonin (5-HT) in serotonergic neurones. However, no improvement in performance was demonstrated during a cycling time trial when tyrosine was added to a CHO solution [63].

**Ingestion of MCTs and CHO**

Another possible nutritional strategy to increase the oxidation of fat and spare the body’s limited CHO store, and thereby improve performance, is to ingest MCTs with CHO during prolonged exercise. Dietary fat supplementation during exercise is not recommended, as not only is there a plentiful supply of...
endogenous fat, but the digestion and absorption of long-chain triacylglycerols may take 3–4 h. However, MCTs, unlike long-chain triacylglycerols, are rapidly absorbed, entering the liver via the portal vein and are therefore rapidly oxidized both at rest and during exercise [64,65]. Although theoretically plausible, the ingestion of MCTs alone have generally not produced an improvement in performance, but have had a negative effect, probably due to the gastrointestinal discomfort experienced by many subjects [66]. The addition of MCTs to a CHO beverage increases the oxidation of MCTs during exercise, and therefore they may serve as an additional fuel source for the exercising muscle, without compromising CHO oxidation and gastrointestinal comfort [67]. Van Zyl et al. [68] was one of the first studies to show that MCTs co-ingested with CHO significantly improved a 40 km time trial performance following 2 h of submaximal exercise, due to an increase in fat oxidation and therefore a reduced reliance on CHO oxidation and subsequent sparing of muscle glycogen. However, other subsequent studies have reported either no difference in performance when MCTs were co-ingested with CHO following 2 h of submaximal exercise [66,69] and a 100 km time trial performance [70], or a decrement in performance [71]. In addition, MCT ingestion had no effect on CHO or fat oxidation rates. The lack of improvement, or decrement in performance, during both endurance (<3 h) and ultra-endurance (>4 h) may be due to the adverse gastrointestinal symptoms (nausea, vomiting, stomach cramps, bloating and diarrhoea) associated with ingestion of MCT in large amounts (~85 g) [66,69,71].

Conclusion

In conclusion, there is a plethora of research documenting the benefits on endurance capacity and performance of ingesting CES during sporting events. Supplementation with either BCAAs or MCTs, either on their own or in addition to CES, do not appear to have an ergogenic effect. More equivocal is the further advantage of ingesting caffeine or protein in addition to CES during the event on performance and the efficacy of ingesting protein plus CES on muscle soreness and the recovery of performance. Further research is clearly warranted in this area.

Summary

- **Athletes must carefully consider the available evidence before deciding whether a particular supplement or strategy during their event will be effective.**
- **Factors such as environmental conditions, the type and amount of supplement given, the training and nutritional status of participants, and whether the performance measure mimics the competition should be taken into account.**
• A 6–8% CES ingested at regular intervals during an endurance event that is continuous or intermittent in nature appears to be the optimal nutritional strategy when ingested at the rate of 60 g of CHO·h⁻¹. The addition of protein to the CES may be beneficial to performance if sub-optimal amounts of CHO are ingested, and may reduce post-exercise muscle damage and soreness.

• It is vital that any proposed nutritional strategy is practised during training, before using it in competition.

References

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