Susan M. Shirreffs

School of Sport & Exercise Sciences, University of Loughborough, Loughborough, United Kingdom

The optimal sports drink

Summary

There is a large amount of evidence showing that exercise-induced dehydration has a negative impact on exercise performance and restoration of fluid balance must be achieved after exercise. It is equally well known that muscle glycogen must be restored after exercise if subsequent performance is not to be negatively affected. Sports drinks are ideally placed to fill both these roles.
Clear evidence is available that drinking during exercise improves performance, provided that the exercise is of a sufficient duration for the drink to be emptied from the stomach and be absorbed in the intestine. Generally, drinking plain water is better than drinking nothing, but drinking a properly formulated carbohydrate electrolyte sports drink will allow for an even better exercise performance.
Of importance for rehydration purposes after exercise is consumption of both an adequate volume (greater than the sweat volume lost) and quantity of sodium. Without both of these, rehydration will be neither rapid nor complete. There is, however, no good evidence for the inclusion of any other electrolytes.
The current generation of commercially available sports drinks are generally a good compromised formulation to meet the needs of many athletes in many different situations.

Zusammenfassung

Eine grosse Anzahl an stichhaltigen Hinweisen zeigt klar auf, dass der belastungsbedingte Flüssigkeitsverlust eine Verschlechterung der Leistungsfähigkeit verursacht und dass die Flüssigkeitsbilanz nach einer Belastung wiederhergestellt werden muss. Ebenfalls bekannt ist, dass die Muskelglycogenspeicher nach einer Belastung wieder aufgefüllt werden müssen, sofern keine Einbusse bei der nächsten Belastung in Kauf genommen werden soll. Sportgetränke können beiden Aspekten gerecht werden.
Trinken während einer physischen Aktivität verbessert ganz eindeutig die Leistungsfähigkeit, sofern die Aktivität von genügend langer Dauer ist, damit das Getränk aus dem Magen entleert und im Darm absorbiert werden kann. Generell gesehen ist das Trinken von reinem Wasser besser als nichts trinken, aber die Verwendung eines sinnvoll zusammengesetzten Kohlenhydrat-Elektrolyt-Getränkes wird die Leistungsfähigkeit stärker verbessern.
Für die Rehydratation nach einer Belastung sind sowohl das Trinken eines angemessen grossen Volumens (mehr als das Schweissvolumen) wie auch die Menge an Natrium im Getränk von Bedeutung. Ohne Berücksichtigung dieser beiden Aspekte wird die Rehydratation weder rasch noch vollständig erfolgen. Für den Zusatz irgendeines anderen Elektrolyten gibt es aber keine guten Hinweise.
Die aktuelle Generation von kommerziell erhältlichen Sportgetränken weist, im Hinblick auf ihren Einsatz bei vielen Athleten und Athletinnen in vielen unterschiedlichen Situationen, in der Regel einen guten Kompromiss in ihrer Zusammensetzung auf.

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Introduction

Sports drinks are different things to different people. In its simplest sense, a sports drink is a drink consumed in association with sport or exercise – either in preparation for exercise, during exercise itself or as a recovery drink after exercise.

By definition, a drink is a liquid substance and as such, water is a main ingredient. However, in a sports drink a variety of nutrients and other substances will be dissolved in the water to make the final consumed product. The main role of sports drinks is probably, therefore, to provide a large amount of water in addition to other components which could otherwise be obtained from food.

The basic science of the formulation of sports drinks is related to that of oral rehydration solutions designed for the treatment of diarrhoea and in that regard water, carbohydrate and sodium are the key ingredients. The majority of sports drinks generally have a carbohydrate content of 6% to 9% weight/volume and contain small amounts of electrolytes, the main one being sodium *(Table 1)*.

The main aim or aims of sports drink consumption do vary according to the exercise situation, but are likely to be one or more of the following: to stimulate rapid fluid absorption, to supply carbohydrate as a substrate for use during exercise, to speed rehydration, to reduce the physiological stress of exercise, and to promote recovery after exercise. What is clear is that moderate levels of dehydration (2–3% reductions in body mass) will impair performance, and when an Olympic medal is at stake, it might be wise to assume that even very low levels of dehydration may have a negative impact on performance: it is certainly the case that hypohydration of only 1% of body mass has a measurable effect on the thermoregulatory response to exercise. Severe dehydration (losses of more than about 6–7% of body mass) can result in a life-threatening situation, and this scenario is rendered more likely when the ambient temperature is high. Such extremes of water depletion should not occur in any athlete in the case of sports competition if a conscious effort is made to ensure adequate fluid replacement. However, even if the health concerns are ignored, the effects on performance of a fluid decrement should be enough to persuade all individuals to attempt to remain fully hydrated at all times, and particularly to ensure that they begin each bout of exercise in a water replete state.

As highlighted above, in addition to flavours and colourings, the traditional ingredients of sports drinks are water, carbohydrate, sodium and potassium. However, some commercially available sports drinks do have numerous other non-traditional ingredients including carbohydrate derivatives (fibre, pyruvate, lactate), protein and protein derivatives (intact protein, branched chain amino acids, individual amino acids, keto-analogues, creatine, carnitine), fats (glycerol, medium chain triacylglycerols, choline), micronutrients (B vitamins, antioxidant vitamins, chromium and vanadium, oxygenated fluids), and non-nutritive ingredients (caffeine, bicarbonate buffers, herbs, ginseng, ciwujia, ginkgo biloba, hydroxycitric acid). Full details of these can be found in a recent in depth publication on sports drinks [Maughan and Murray, 2001].

In this manuscript I will focus on the role of water and electrolytes in sports drinks as the role of their carbohydrate content is discussed elsewhere in this publication.

	Carbo-hydrate (%)	Sodium ($mmol·l^{-1}$)	Potassium ($mmol·l^{-1}$)	Osmolality ($mosmol·kg^{-1}$)
Gatorade	6	20	3	280
Isostar	7	30	*	289
Lucozade Sport	6.4	22	3	285
Powerade				
European	8.2	23	2	315
UK	6	23	2	280/290
USA	8	5	3	381
Fruit juice				
Orange	10	4	45	660
Apple	13	1	26	*
Tomato	3	10	7	*
Cola	11	3	1	700
Oral rehydration solution	2	45	20	250
Bottled water	0	0	0	9
Milk	5	26	37	288

Table 1: The composition of selected sports drinks and other beverages.

Sports drinks during exercise: fluid and electrolyte replacement

Limitations to replacement

In any exercise task lasting longer than about 30–40 minutes, carbohydrate depletion, elevation of body temperature and reductions in the circulating fluid volume are likely to be important factors in causing fatigue. All of these can be manipulated by the ingestion of fluids, but the most effective drink composition and the optimum amount of fluid will depend on individual circumstances. Water is not the optimum fluid for ingestion during endurance exercise, and there is compelling evidence that drinks containing added substrate and electrolytes are more effective. Increasing the carbohydrate content of 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 [Vist and Maughan, 1995]. Where provision of water is the priority, the carbohydrate content of drinks and their total osmolality should be low, thus restricting the rate at which substrate is provided. The composition of drinks to be taken will thus be influenced by the relative importance of the need to supply fuel and water, which in turn depends on the intensity and duration of the exercise task, on the ambient temperature and humidity, and on the physiological and biochemical characteristics of the individual athlete. Carbohydrate depletion will result in fatigue and a reduction in the exercise intensity which can be sustained, but is not normally a life-threatening condition. Disturbances in fluid balance and temperature regulation have potentially more serious consequences, and it may be, therefore, that the emphasis for many participants in endurance events should be on proper maintenance of fluid and electrolyte balance.

The optimum type and concentration of sugars to be added to drinks will depend on individual circumstances. High carbohydrate concentrations will delay gastric emptying, thus reducing the amount of fluid that is available for absorption: very high concentrations will also result in secretion of water into the intestine and thus temporarily increase the danger of dehydration (Merson et al., 2002). Perhaps because of this effect, high sugar concentrations (>10%) may result in an increased risk of gastro-intestinal disturbances. Where there is a need to supply an energy source during exercise, however, increasing the sugar content of drinks will increase the delivery of carbohydrate to the site of absorption in the small intestine.

The available evidence indicates that the only electrolyte that should be added to drinks consumed during exercise is sodium, which is usually added in the form of sodium chloride, but which may also be added as sodium citrate or other salts. The use of citrate rather than chloride helps stabilise pH and affects taste. Sodium will stimulate sugar and water uptake in the small intestine and will help to maintain extracellular fluid volume as well as maintaining the drive to drink by keeping plasma osmolality high [Noakes et al., 1985; Maughan, 2001]. As is clear from *Table 1*, most soft drinks of the cola or lemonade variety contain virtually no sodium (1–2 $mmol·l^{-1}$), and drinking water is also essentially sodium-free; sports drinks commonly contain 10–30 $mmol·l^{-1}$ sodium, and oral rehydration solutions intended for use in the treatment of diarrhoea-induced dehydration have higher sodium concentrations, in the range 30–90 $mmol·l^{-1}$. A high sodium content may be important in stimulating jejunal absorption of glucose and water, but it tends to make drinks unpalatable. Drinks intended for ingestion during or after exercise, when thirst may be suppressed and large volumes must be consumed, should have a pleasant taste in order to stimulate consumption. Sports drinks must, therefore, strike a balance between the twin aims of efficacy and palatability.

Hyperthermia and hypernatraemia are relatively common in endurance events held in the heat, and often affect the less well prepared participants. It has, however, become clear that a small number of individuals at the end of very prolonged events may be suffering from hyponatraemia: this may be associated with either hyperhydration or dehydration. The total number of reported cases is rather small, and the great majority of these have been associated with ultramarathon or prolonged triathlon events; there are few reports of cases of exercise-associated hyponatraemia where the exercise duration is less than 4 h. Many of the drinks consumed in endurance events, whether plain water, soft drinks, or sports beverages, have relatively little or no electrolyte content. Even among the carbohydrate electrolyte drinks intended for consumption by sports men and women during prolonged exercise, most have a low electrolyte content, with sodium concentrations typically in the range of 10–25 $mmol·l^{-1}$. This is adequate in most situations, but may not be so when sweat losses and fluid intakes are high. Some supplementation with sodium chloride in amounts beyond those normally found in sports drinks may be required in extremely prolonged events where large sweat losses can be expected and where it is possible to consume large volumes of fluid. It remains true, however, that electrolyte replacement during exercise is not a priority for most participants in most sporting events. Extra salting of food is an effective strategy for athletes living and training hard in hot weather conditions.

Cardiovascular, metabolic and performance effects

Many of the published studies investigating the effects of fluid ingestion on exercise performance have failed to include appropriate control trials that allow the separate effects of water replacement and substrate provision to be assessed. Generally, the studies in the literature have reported either no effect of fluid ingestion on exercise performance or a beneficial effect. In many cases, the absence of a statistically significant effect simply reflects the variability in the assessment methods used and inadequate subject numbers. There seems to be a lessened hyperthermia and cardiovascular drift during prolonged moderate intensity exercise [Hamilton et al., 1991; Montain et al., 1992 a,b; Bosch et al., 1994] which is attributed to fluid replacement during the exercise. A better maintenance of blood glucose, which can be used by the exercising muscles with a consequent reduction in the need for mobilisation of the limited liver glycogen reserves [e.g. Maughan et al., 1989; McConnell et al., 1994] appears to be the major benefit of carbohydrate consumption during exercise. The studies that have reported adverse effects of fluid ingestion on exercise performance have generally been studies in which the fluid ingestion has resulted in gastro-intestinal disturbances.

Drinking plain water can improve performance in endurance exercise, but there are further performance improvements when carbohydrate and electrolytes are added. The study of Below et al. [1995] attempted to distinguish between the effects of carbohydrate provision from the water replacement properties of a drink.

Briefly, eight men undertook the same cycle ergometer exercise on four separate occasions. After 50 min exercise at 80% of VO_2max, a performance test at a higher exercise intensity (completion of set amount of work as quickly as possible) was completed; this test lasted approximately 10 min. On each of the four trials, a different beverage consumption protocol was followed during the 50 min exercise; nothing was consumed during the performance tests. The beverages were electrolyte-containing water in a large (1330 ml) and small (200 ml) volume and carbohydrate-electrolyte solutions (79 g) in the same large and small volumes; the electrolyte content of each beverage was the same and amounted to 619 mg (27 mmol) and 141 mg (3.6 mmol) of sodium and potassium respectively. The results of the study indicated that performance was 6.5% better after consuming the large volume of fluid in comparison to the smaller volume and was 6.3% better after consuming carbohydrate-containing rather than carbohydrate-free beverages; the fluid and carbohydrate each independently improved performance and the two improvements were additive. The mechanism for the improvements in performance with the large fluid replacement versus the small fluid replacement was attributed to a lower heart rate and oesophageal temperature when the large volume was consumed. The authors were unable, however, to identify the mechanism by which carbohydrate ingestion improved performance.

Sports drinks after exercise: fluid and electrolyte replacement

The primary factors influencing the post-exercise rehydration process are the volume and composition of the fluid consumed. The volume consumed will be influenced by many factors, including the palatability of the drink and its effects on the thirst mechanism, although with a conscious effort some people can still drink large quantities of an unpalatable drink when they are not thirsty. The ingestion of solid food, and the composition of that food, may also be important factors, but there are many situations where solid food is avoided by some people between exercise sessions or immediately after exercise.

Beverage composition

Sodium

Plain water is not the ideal post-exercise rehydration beverage when rapid and complete restoration of fluid balance is necessary and when all intake is in liquid form. Early studies in the area [e.g. Costill and Sparks, 1973; Nielsen et al., 1986] established that a high urine flow that followed ingestion of large volumes of electrolyte-free drinks did not allow subjects to remain in positive fluid balance for more than a very short time. They also established that the plasma volume was better maintained when electrolytes were present in the fluid ingested, and this effect was attributed to the presence of sodium in the drinks. In none of these studies, however, could the mechanism of the action be identified, as the drinks used differed from each other in a number of respects, including flavouring, carbohydrate and electrolyte content.

The first studies to investigate the mechanisms of post-exercise rehydration showed that the ingestion of large volumes of plain water after exercise-induced dehydration resulted in a rapid fall in plasma osmolality and sodium concentration [Nose et al., 1988a], leading to a prompt and marked diuresis caused by a rapid return to control levels of plasma renin activity and aldosterone levels [Nose et al., 1988b].

The addition of sodium to post-exercise rehydration beverages can therefore be justified on two accounts. First, sodium stimulates glucose absorption in the small intestine. The active co-transport of glucose and sodium creates an osmotic gradient that acts to promote net water absorption. This sodium can either be consumed with the drink or be secreted by the intestine. Second, replacement of sweat losses with plain water will, if the volume ingested is sufficiently large, lead to haemodilution: the fall in plasma osmolality and sodium concentration that occurs in this situation reduces the drive to drink and stimulates urine output [Nose et al., 1988a] and has potentially more serious consequences such as hyponatraemia. In a systematic investigation of the relationship between whole body sweat sodium losses and the effectiveness of beverages with different sodium concentrations in restoring fluid balance, Shirreffs and Maughan [1998] showed that, provided that an adequate volume is consumed, euhydration is achieved when the sodium intake is greater than the sweat sodium loss, although, as discussed below, not all studies have reported similar findings [Mitchell et al., 2000]. It has also been demonstrated that a drink's sodium concentration is more important than its osmotic content for increasing plasma volume after dehydration [Greenleaf et al., 1998].

Potassium

Sodium is the major ion in the extracellular fluid but potassium is the major ion in the intracellular fluid. Potassium may therefore be important in achieving rehydration by aiding the retention of water in the intracellular space. An initial study on rats investigating this [Yawata, 1990] indicated that there was a tendency for a greater restoration of the intracellular fluid space in rats ingesting a KCl solution in comparison to those ingesting a NaCl solution. This was subsequently investigated in men dehydrated by approximately 2% of body mass by exercise who then ingested of a glucose beverage (90 $mmol \cdot l^{-1}$), a sodium-containing beverage (NaCl 60 $mmol \cdot l^{-1}$), a potassium-containing beverage (KCl 25 $mmol \cdot l^{-1}$) or a beverage containing all three components [Maughan et al., 1994]. All drinks were consumed in a volume equivalent to the mass loss, but a smaller volume of urine was excreted following rehydration when each of the electrolyte-containing beverages were ingested (about 250–300 ml) compared with the electrolyte-free beverage (a mean volume of 577 ml). Therefore, there was no difference in the fraction of ingested fluid retained 6 h after finishing drinking the drinks which contained electrolytes. This may be because the beverage volume consumed was equivalent to the volume of sweat lost and, because of the ongoing urine losses, subjects were dehydrated throughout the entire study, even immediately following the drinking period. The volumes of urine excreted were close to basal levels and significant further reductions in output may not have been possible when both sodium and potassium were ingested. An estimated plasma volume decrease of 4.4% was observed with dehydration over all trials but the rate of recovery was slowest when the KCl beverage was consumed. Potassium may therefore be important in enhancing rehydration by aiding intracellular rehydration, but further investigation is required to provide conclusive evidence.

Other electrolytes

The importance of the inclusion of magnesium in sports drinks has been the subject of much discussion. Magnesium is lost in sweat and many believe that this causes a reduction in plasma magnesium levels which are implicated in muscle cramp. Even though there can be a decline in plasma magnesium concentration during exercise it is most likely to be due to a redistribution between compartments rather than due to sweat loss. There does not, therefore, seem to be any good reason for including magnesium in post-exercise rehydration and recovery sports drinks.

Sodium, thereafter, is the most important electrolyte in terms of recovery after exercise. Without its replacement, water retention is hampered. Potassium is also included in sports drinks in similar concentrations to that which it is lost in sweat. Unlike the strong evidence available for the inclusion of sodium, there is not the same for potassium. There is no evidence for the inclusion of any other electrolytes.

Drink volume

Obligatory urine losses persist even in the dehydrated state, because of the need for elimination of metabolic waste products. The volume of fluid consumed after exercise-induced or thermal sweating must therefore be greater than the volume of sweat lost if effective rehydration is to be achieved. This contradicts earlier recommendations that athletes should match fluid intake exactly to the measured body mass loss. Shirreffs et al. [1996] investigated the effect of drink volumes equivalent to 50%, 100%, 150% and 200% of the sweat loss consumed after exercise-induced dehydration equivalent to approximately 2% of body mass. To investigate the possible interaction between beverage volume and its sodium content, a relatively low sodium drink (23 mmol·l^{-1}) and a moderately high sodium drink (61 mmol·l^{-1}) were compared. Subjects could not return to euhydration when they consumed a volume equivalent to, or less than, their sweat loss, irrespective of the drink composition. When a drink volume equal to 150% of the sweat loss was consumed, subjects were slightly hypohydrated 6 h after drinking when the test drink had a low sodium concentration, and they were in a similar condition when they drank the same beverage in a volume of twice their sweat loss. With the high sodium drink, enough fluid was retained to keep the subjects in a state of hyperhydration 6 h after drink ingestion when they consumed either 150% or 200% of their sweat loss. The excess would eventually be lost by urine production or by further sweat loss if the individual resumed exercise or moved to a warm environment. Calculated plasma volume changes indicated a decrease of approximately 5.3% with dehydration. At the end of the study period, the general pattern was for the increases in plasma volume to be a direct function of the volume of fluid consumed, with the increase tending to be greater for those individuals who ingested the high sodium drink. Whilst other studies have also shown the importance of drinking a larger volume of drink than the sweat volume lost [Mitchell et al., 1994] an interaction between sodium intake, volume intake and whole body rehydration has not always been reported [Mitchell et al., 2000]. However, it seems likely that in this study the length of subject observation after rehydration may not have been sufficient to observe the urine production response to the treatments.

Beverage palatability and voluntary fluid intake

In the majority of scientific studies in the area, a fixed volume of fluid is consumed, but in everyday situations intake is determined by the interaction of physiological and psychological factors. When the effect of palatability, together with the solute content of beverages in promoting rehydration after sweat loss was studied [Wemple et al., 1997] subjects drank 123% of the sweat volume losses with flavoured water and 163% and 133% when the solution had 25 and 50 mmol·l^{-1} sodium. Three hours after starting the rehydration process the subjects were in a better whole body hydration status after drinking the sodium containing beverages than the flavoured water. In another similar study [Maughan and Leiper, 1993], subjects drank a greater volume of sports drink (2492 ml) and orange juice/lemonade mixture (2488 ml) than of either water (1750 ml) or an oral rehydration solution (1796 ml) reflecting their taste preferences. As expected, urine output was greatest with the low electrolyte drinks that were consumed in the largest volumes (the sports drink and the orange juice/lemonade mixture), and was smallest after drinking the oral rehydration solution. These studies demonstrate the importance of palatability for promoting consumption, but also confirm earlier results showing that a moderately high electrolyte content is essential if the ingested fluid is to be retained in the body. The benefits of the higher intake with the more palatable drinks were lost because of the higher urine output. Other drink characteristics, including carbonation, influence drink palatability and therefore need to be considered when a beverage is being considered for effective post-exercise rehydration [Passe et al., 1997].

Practical issues

Team doctors, coaches and athletes must be aware of the factors which influence rehydration and of the electrolyte content of available drinks. The amount of electrolytes lost in sweat is highly variable between individuals and although the optimum drink may be achieved by matching electrolyte loss with equal quantities from the drink, this is virtually impossible in a practical situation. Sweat composition varies considerably between individuals, but also varies with time during exercise and will be further influenced by the state of acclimation. However, a moderate excess of salt intake would appear to be beneficial as far as hydration status is concerned without any detrimental effects on health provided that fluid intake is in excess of sweat loss and that renal function is not impaired. Concerns over the possible adverse effects of a high salt intake have led some athletes to restrict dietary salt intake [Bergeron, 1996]. For the athletes with large sweat losses, sodium loss will be correspondingly high: loss of 5 litres of sweat with a sodium content of 50 mmol·l^{-1} requires ingestion of almost 15 g of sodium chloride to restore balance. This amount of sweat can easily be lost in 2–3 hours of hard training or match practice in hot, humid conditions. Although the diet will make a major contribution to replacement, normal daily salt intake from food is only about 6–8 g for the UK population, about half of whom rarely or never add salt to food at the table [Gergory et al., 1990]. There is clearly a high risk of salt deficit when losses are high, unless a conscious effort is made to increase intake.

The scientific studies reported here were generally carried out in a systematic way and did not attempt to replicate real life situations where many other factors will intervene. On the whole, in these studies when a heat stress was used, following the exercise in the heat, individuals were removed to a relatively cool indoor environment and undertook no further exercise. For athletes living in training camps or in the Village at major Championship events where the outside environment is hot for the majority of most days, it is highly likely that they will be unable to avoid some exposure to a thermally stressful environment. Team support staff, officials and spectators will also be at risk. All must be aware of the need to maintain fluid balance and should consider rehydration after passive heat exposure as well as after exercise. Indicators such as a reduction in urine output, a high urine osmolality and/or a failure to maintain body mass are more reliable measures of dehydration than is the feeling of thirst.

Conclusions

A properly formulated sports drink has a valuable role to play in the diet of virtually all athletes. This is particularly true in situations where solid food is either not available or not desired by the athlete.

During exercise, there are few situations where sports drinks have had a negative impact on exercise performance and where this has occurred it is generally because of gastrointestinal distress rather than via another physiological mechanism. Therefore, provided that the exercise is of a sufficient duration for the drink to be emptied from the stomach and be absorbed in the intestine, drinking is a wise intervention to be used in exercise. Generally, drinking plain water is better than drinking, nothing but drinking a properly formulated carbohydrate electrolyte sports drink will allow for an even better exercise performance with benefits being gained from both its carbohydrate content and the water and electrolyte content.

In order to achieve effective rehydration following exercise in the heat or heat exposure or any type of exercise sufficient to cause sweat loss, the rehydration beverage should contain moderately high levels of sodium (at least 50 mmol·l^{-1}), plus possibly some potassium; a source of substrate is not necessary for rehydration although a small amount of carbohydrate (<2%) may improve the rate of intestinal uptake of sodium and water. The volume of beverage consumed should be greater than the volume of sweat lost in order to make a provision for the ongoing obligatory urine losses. Therefore, the palatability of the beverage is of importance: many individuals may lose substantial amounts of sweat and will therefore have to consume large amounts of fluid to replace them and this is more likely to be achieved if the taste is perceived as being pleasant.

Ultimately the choice of drink to be consumed may and indeed should be different depending on the individual and their particular circumstances. Replacement of substrate in addition to water and electrolyte losses may be of concern in the post-exercise period in preparation for a further bout of exercise. In terms of sustaining life, substrate (muscle and liver glycogen) depletion is unlikely to have an adverse effect in an otherwise healthy individual, but water depletion if not replaced may have serious consequences. The current generation of commercially available sports drinks are generally a good compromised formulation to meet the needs of many athletes in many different situations.

Address for correspondence:

School of Sport & Exercise Sciences, University of Loughborough, Loughborough, LE 11 3 TU, UK

References

Below R.P., Mora-Rodriguez R., Gonzalez-Alonso J., Coyle E.F.: Fluid and carbohydrate ingestion independently improve performance during 1h of intense exercise. Med. Sci. Sports Exerc. 27: 200–210, 1995.

Bergeron M.F.: Heat cramps during tennis: a case report. Int. J. Sport Nutr. 6: 62–68, 1996.

Bosch A.N., Dennis S.C., Noakes T.D.: Influence of carbohydrate ingestion on fuel substrate turnover and oxidation during prolonged exercise. J. Appl. Physiol. 76: 2364–2372, 1994.

Costill D.L., Sparks K.E.: Rapid fluid replacement following thermal dehydration. J. Appl. Physiol. 34: 299–303, 1973.

Greenleaf J.E., Jackson C.G.R., Geelen G., Keil L.C., Hinghofer-Szalkay H., Whittam J.H.: Plasma volume expansion with oral fluids in hypohydrated men at rest and during exercise. Aviat. Space Environ. Med. 69: 837–844, 1998.

Gregory J., Foster K., Tyler H., Wiseman M.: The dietary and nutritional survey of British adults. HMSO, London, 1990.

Hamilton M.T., Gonzalez-Alonso J., Montain S.J., Coyle E.F.: Fluid replacement and glucose during exercise prevent cardiovascular drift. J. Appl. Physiol. 71: 871–877, 1991.

Maughan R.J., Fenn C.E., Leiper J.B.: Effects of fluid, electrolyte and substrate ingestion on endurance capacity. Eur. J. Appl. Physiol. 58: 481–486, 1989.

Maughan R.J.: Physiology and nutrition for middle distance and long distance running. In: Lamb D.R., Knuttgen H.G., Murray R. (Eds.): Perspectives in Exercise Science and Sports Medicine. Vol. 7: Physiology and nutrition for Competitive Sport. Carmel, Cooper Publishing, 329–372, 1994.

Maughan R.J.: Sports drinks before, during and after running. In: Tunstall Pedoe D. (Ed.): Marathon Medicine. Royal Society of Medicine Press, London. 147–158, 2001.

Maughan R.J., Leiper J.B.: (1993) Post-exercise rehydration in man: effects of voluntary intake of four different beverages. Med. Sci. Sports Exerc. 25 (Supplement): S2.

Maughan R.J., Murray R.: Sports Drinks: Basic Science and Practical Aspects. CRC Press LLC, Boca Ranton, FL, USA, 2001.

Maughan R.J., Owen J.H., Shirreffs S.M., Leiper J.B.: Post-exercise rehydration in man: effects of electrolyte addition to ingested fluids. Eur. J. Appl. Physiol. 69: 209–215, 1994.

McConell G., Fabris S., Proietto J., Hargreaves M.: Effect of carbohydrate ingestion on glucose kinetics during exercise. J. Appl. Physiol. 77: 1537–1541, 1994.

Merson S.J., Shirreffs S.M., Leiper J.B., Maughan R.J.: Changes in blood, plasma and red cell volume after ingestion of hypotonic and hypertonic solutions. Proc. Nutr. Soc. (In the press), 2002.

Mitchell J.B., Grandjean P.W., Pizza F.X., Starling R.D., Holtz R.W.: The effect of volume ingested on rehydration and gastric emptying following exercise-induced dehydration. Med. Sci. Sports Exerc. 26: 1135–1143, 1994.

Mitchell J.B., Phillips M.D., Mercer S.P., Baylies H.L., Pizza F.X.: Post-exercise rehydration: effect of Na^+ and volume on restoration of fluid spaces and cardiovascular function. J. Appl. Physiol. 89: 1302–1309, 2000.

Montain S.J., Coyle E.F.: Influence of graded dehydration on hyperthermia and cardiovascular drift during exercise. J. Appl. Physiol. 73: 1340–1350, 1992a.

Montain S.J., Coyle E.F.: Fluid ingestion during exercise increases skin blood flow independent of increases in blood volume. J. Appl. Physiol. 73: 903–910, 1992b.

Nielsen B., Sjogaard G., Ugelvig J., Knudsen B., Dohlmann B.: Fluid balance in exercise dehydration and rehydration with different glucose-electrolyte drinks. Eur. J. Appl. Physiol. 55: 318–325, 1986.

Noakes T.D., Goodwin N., Rayner B.L., Branken T., Taylor R.K.N.: Water intoxication: a possible complication during endurance exercise. Med. Sci. Sports Exerc. 17: 370–375, 1985.

Nose H., Mack G.W., Shi X., Nadel E.R.: Role of osmolality and plasma volume during rehydration in humans. J. Appl. Physiol. 65: 325–331, 1988a).

Nose H., Mack G.W., Shi X.R., Nadel E.R.: Involvement of sodium retention hormones during rehydration in humans. J. Appl. Physiol. 65: 332–336, 1988b.

Passe D.H., Horn M., Murray R.: The effects of beverage carbonation on sensory responses and voluntary fluid intake following exercise. Int. J. Sports Nutr. 7: 286–297, 1997.

Shirreffs S.M., Taylor A.J., Leiper J.B., Maughan R.J.: Post-exercise rehydration in man: effects of volume consumed and drink sodium content. Med. Sci. Sports Exerc. 28: 1260–1271, 1996.

Shirreffs S.M., Maughan R.J.: Volume repletion following exercise-induced volume depletion in man: replacement of water and sodium losses. Am. J. Physiol. 274: F868–F875, 1998.

Vist G.E., Maughan R.J.: The effect of osmolality and carbohydrate content on the rate of gastric emptying of liquids in man. J. Physiol. 486: 523–531, 1995.

Wemple R.D., Morocco T.S., Mack G.W.: Influence of sodium replacement on fluid ingestion following exercise-induced dehydration. Int. J. Sport Nutr. 7: 104–116,1997.

Yawata T.: Effect of potassium solution on rehydration in rats: comparison with sodium solution and water. Jap. J. Physiol. 40: 369–381, 1990.