Sports Drinks on the Edge of a New Era

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Introduction

Since the first modern Olympics in 1896 in Athens, fluid intake and carbohydrate (CHO) delivery practices during sports and exercise have varied greatly, reflecting the uncertainty and lack of agreement within the scientific community. The present perspective serves to summarize some of the most important milestones and advances in scientific knowledge that has shaped current recommendations in fluid and CHO intake during exercise and to encourage new research paradigms that embrace novel advances in technology and personal medicine.

There are only a few places on earth where human beings survive solely by persistence hunting. In the Kalahiri region of South Africa, the San tribe survival requires tracking prey over difficult terrain and running it down at high speeds in severe ambient conditions (46°C/115°F) until either man (the hunter) or animal (the hunted) collapses (1). During a chase, high metabolic heat production during the short, intense exercise combined with an impaired ability to lose heat would cause the core temperature (T_c) of the prey (*e.g.*, antelope) to rise with each subsequent sprint until the elevated T_c caused the animal to collapse to the ground. To compensate for the lack of sufficient speed, savanna-adapted humans developed several evolutionary adaptations, such as a higher sweat rate allowing the dissipation of metabolic heat production to the environment, a bipedal posture which reduced the heat gained from solar radiation and an enhanced ability to perform aerobic exercise for prolonged durations compared with their prey. Humans living as hunter gatherers with these evolutionary adaptations migrated from Africa as recently as 50,000 to 60,000 yr ago and spread throughout Africa, Eurasia, Oceania, and the Americas. In comparison to other large mammals and most animals considered excellent runners, antelopes, cheetahs, horses, and dogs, modern day humans are better designed to perform prolonged endurance exercise in the heat.

In the early 1900s, there was a clear lack of knowledge in the area of hydration and endurance performance. For example, at the 1904 Olympic marathon in St. Louis, on a hot and humid summer day, 32 runners began the 24.85-mile-long course with water being provided at only two stations (2). There was widespread belief during this time that drinking during exercise was unnecessary and to compete without nourishment was a worthy achievement. As such, there was little research interest in carbohydrate (CHO) and fluid consumption during sport and exercise. However, in 1923, exercise physiology advanced significantly with the pioneering research of A.V. Hill, with seminal studies investigating the limits of maximal exercise that stressed the importance of maintaining blood supply to the exercising skeletal muscles and the heart during maximal exercise as reflected in the following extract (3):

"A heart, adequate in every other way, might fail to allow its owner to undertake severe continued effort, simply because of the imperfect arrangement of its own supply of blood." A.V. Hill (1923)

Hill termed this inhibition of the heart, "the governor" that protected against increases in cardiac output ($\dot{Q}$) that could result in too great a mismatch between oxygen delivery and oxygen consumption of the heart, potentially leading to a myocardial infarction. This research was the primary impetus for the advancement of the "cardiovascular" model of physiology and thermoregulation that represents the basis of much of the subsequent research into fluid consumption during sport and exercise. The cardiovascular model of thermoregulation has been used to explain the consequences of an excessive water loss (4). This model contends that the reduction in plasma volume (PV) (caused predominately through sweating) during exercise induces a concurrent rise in $\dot{Q}$ to maintain blood flow to the exercising muscles and the skin (4–6). If the decline in PV was to continue, the model predicts that there is a point at which increases in heart rate can no longer compensate for the reduction in stroke volume and therefore $\dot{Q}$ must decline (7). In this situation, mean arterial pressure will be protected by increasing vascular resistance, leading to reduced blood flow to the skin, increasing T_c and potentially leading to heat stroke (8). Wyndham and Strydom (8) in 1969 were among the first to propose that dehydration negatively

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influenced exercise performance. They reported a strong correlation between the rise in T_c and percentage water deficit in 20 athletes during two marathons. Notably, their fastest runner incurred a deficit of 4.3% and 4.8% in the first and second marathon, respectively; suggesting the effect of dehydration in excess of 2% body mass loss is not necessarily detrimental to performance.

The cardiovascular model of exercise physiology/thermoregulation prevailed in different guises for the next four decades and is reflected in several consensus statements on exercise and fluid replacement (9,10). In 1996, it was advised that athletes undertaking exercise should drink fluids at a rate that matched fluid loss via sweat as best practice for preventing the negative symptoms associated with dehydration (*i.e.*, decreased PV, increased cardiac strain and decreased performance) (11). This recommendation was reached based on several studies demonstrating the potentially negative effects of dehydration such as impaired skin blood flow and decreased $\dot{Q}$ which could ultimately lead to heat stroke (12–14). In 2007, the American College of Sports Medicine (ACSM) released a revised consensus statement regarding fluid consumption during exercise, suggesting that preventing all dehydration may be unnecessary and that there may exist a level of "tolerable dehydration" (15). Since then, there has been substantial research into hydration and performance that would appear to support the position that there exists a level of dehydration due to sweating, about 2% body mass loss, above which exercise performance is impaired (16,17). Some of the literature on this topic, such as the article written by Wyndham and Strydom in 1969, seem to ignore or downplay the observation that the best performing athletes also were the most dehydrated as assessed by a loss in body mass. For example, using data from a review, when the relationship between running speed and percentage dehydration was plotted, the best-performing runner was dehydrated by some 8%, while the only runner to prevent body mass loss of >2% was the slowest (Fig. 1), suggesting dehydration at this modest level did not impair performance significantly (17,18).

It has been proposed that when one or more bodily systems are stressed beyond capacity and in order to prevent a cardiovascular "catastrophe" (*i.e.*, myocardial infarction in the worse case scenario), exercise intensity is dramatically reduced (19,20). There may exist a "central governor" which responds to sensory feedback from multiple organs and tissues and regulates the extent of skeletal muscle recruitment during exercise to attenuate the rate of heat storage and prevent heat stroke (21,22). A similar concept sometimes referred to as the anticipatory model of thermoregulation has gained popularity (23). The idea is that exercise in the heat is terminated or intensity reduced due to a downregulation of muscle drive by the central nervous system in response to the rate at which T_c increases (*i.e.*, to avoid a "catastrophe"). There are striking similarities between the different ideas suggesting that they may be describing similar/related phenomena. Deciding which is closer to the truth is conceptually difficult because we use the brain to study the brain.

Ideas on dehydration have divided current opinion and it remains unclear if the fastest and most dehydrated runners in some of the aforementioned studies would have benefited from a better maintenance of hydration (to <2% body mass loss) or if the runners benefited from greater levels of dehydration — *e.g.*, improved running economy. More recent research has suggested that it was not dehydration *per se* that impaired performance but rather whole-body hyperthermia (24). In this study, participants were placed under sufficient heat stress to either acutely raise skin temperature or raise skin temperature and T_c. It was found that an elevated skin temperature did not impair exercise performance, whereas the increase in whole body temperature did (24). In this context, a high sweat rate and a subsequent water deficit are the consequence of preventing hyperthermia and the high fluid loss seen in many of the fastest runners in previous studies. This may have allowed the faster athletes to continue producing higher metabolic heat (*i.e.*, run faster) than the slower runners as more heat is dissipated to the environment (8,17).

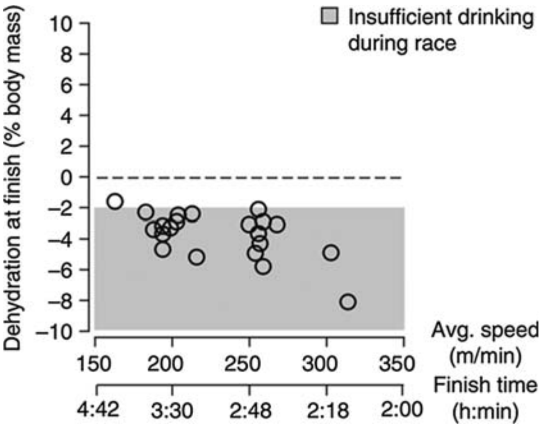

Figure 1: Finish time and % body mass loss due to dehydration. The fastest runner was the most dehydrated (~8%) and the slowest runner the least dehydrated (~1.9%) (17).

In 1970, Costill et al. (25) demonstrated the efficacy of a novel electrolyte/glucose drink on maintaining CHO metabolism during prolonged running. This study compared running for 2 h at 70% of maximal oxygen uptake ($\dot{V}O_{2max}$) while ingesting either a CHO drink containing glucose and electrolytes or water. Both drinks resulted in a levelling-off in core temperature after 45 min, whereas only with glucose ingestion was electrolyte balance and CHO metabolism maintained. Following this initial research into CHO ingestion during exercise, optimizing the formulation of CHO drinks became a popular area of research. For example, in 1970, there were 59 publications related to "exercise" and "carbohydrate," whereas in 2017, there were 849, demonstrating the rapid increase in scientific interest in this area over the last ~50 years.

It is now well accepted that CHO ingestion in various forms improves endurance performance by maintaining blood glucose and muscle glycogen stores (26) and research is now focused on determining the optimal mix of CHO (*e.g.*, glucose, maltodextrin, fructose, sucrose and galactose) (27,28). The current literature suggests that the optimum mix of CHO is a maltodextrin and fructose approaching a 1:1 ratio (28). Maltodextrin is preferred over glucose due to the lower osmolality for a given energy density that does not inhibit gastric emptying to the same extent as glucose (29). The use of glucose/maltodextrin as a single source of CHO

elicits an exogenous CHO oxidation rate of ~1.1 $g \cdot min^{-1}$ when administered at a rate of ~2.4 $g \cdot min^{-1}$ (30). Jeukendrup et al. (31) compared the ingestion rates of ~0.5 $g \cdot min^{-1}$ and ~2.7 $g \cdot min^{-1}$ during exercise. In both trials, there was a reduced fat oxidation, increased rate of appearance and disappearance of glucose and increased exogenous CHO oxidation, whereas in the ~2.7 $g \cdot min^{-1}$ trial, liver glycogen breakdown was inhibited. Despite the ingestion of a large amount of glucose, exogenous CHO oxidation did not exceed 1 $g \cdot min^{-1}$. The addition of fructose as a second CHO source has been shown to increase exogenous CHO oxidation through the utilisation of different transporters required to uptake glucose/fructose in the intestine. Glucose is absorbed into the blood via the sodium-dependent glucose co-transporter (SGLT1) and a glucose transporter (GLUT2), whereas fructose is primarily transported through a separate glucose transporter (GLUT5) via facilitated diffusion and GLUT2 (32) (Fig. 2). The combination of maltodextrin and fructose has repeatedly been shown to increase exogenous CHO oxidation compared with glucose-only ingestion up to a maximum of 1.8 $g \cdot min^{-1}$ (34).

Current ACSM guidelines recommend the ingestion of 30 to 60 $g \cdot h^{-1}$ during prolonged endurance exercise lasting between 1 and 2.5 h and up to 90 $g \cdot h^{-1}$ during ultra-endurance exercise exceeding 2 h (35). While these recommendations are generally well accepted, there is research that suggests no further benefit of ingesting CHO in excess of about 60 $g \cdot h^{-1}$ under more realistic conditions (*e.g.*, breakfast before the trial commencing) (36). However, this position is not universally accepted. A recent systematic review assessed the existing evidence related to CHO intake and running performance (37). The authors suggest that CHO beverages with a concentration of 5.0% to 6.9% are the most beneficial in improving running performance. When the concentration increases above this, CHO feedings can cause gastrointestinal (GI) discomfort during intense running, lasting 60 to 90 min, mainly due to physical distortion of the GI region while running (38).

A recent innovation for providing fluid and CHO during exercise is the use of alginate. Alginate is a naturally occurring anionic polymer typically derived from seaweed and is commonly used in oral drug delivery, wound healing, and tissue engineering due to its high biocompatibility and ease of gelation (39). The formulation of an alginate hydrogel can be tailored to form in a low pH environment that allows the hydrogel to encapsulate substrates or compounds of choice. The hydrogel subsequently dissolves in an environment with a much higher pH (*i.e.*, the intestine), releasing the substrates or compound(s) (40). When an alginate-CHO mixture reaches the gastric fluid in the stomach, a hydrogel will form and encapsulate the CHO contained within the solution. The encapsulated CHO passes into the proximal section of the duodenum, without activating the glucose receptors and subsequently gastric emptying will not be reduced as is typically the case with the ingestion of high CHO drinks (29). This novel fuel delivery system permits the ingestion of higher amounts of CHO without the associated inhibition of gastric emptying which typically occurs when CHO drinks are ingested, allowing increased water uptake (41,42).

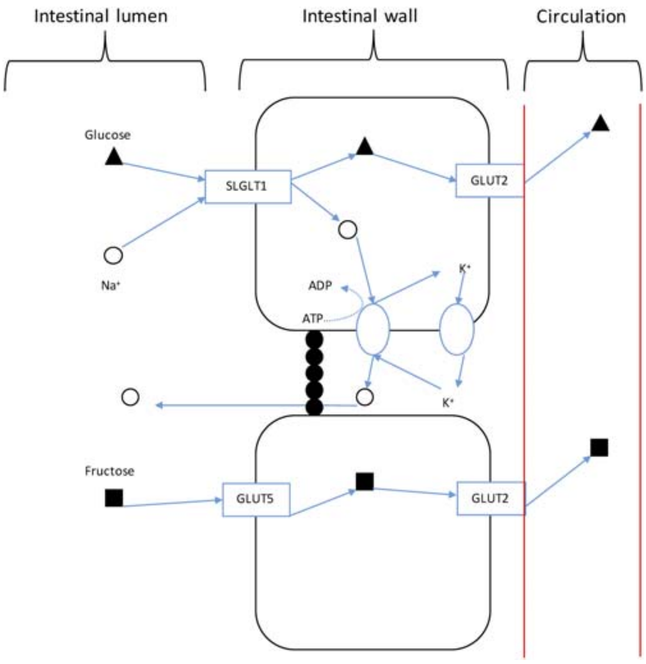

Figure 2: Glucose and fructose transporter routes across the intestinal lumen into the circulation. Adapted from Jeukendrup et al., 2015 (33).

To test this new concept, we recently conducted a pilot study in well-trained Kenyan athletes to investigate the effects of alginate hydrogel as a unique fluid and CHO delivery system. A secondary aim was to determine the loss in body mass in well-trained Kenyan runners drinking *ad libitum* during strenuous exercise conducted at moderate altitude (approximately 2000 m above sea level) to estimate the levels of dehydration. For this pilot study, 16 well-trained Kenyan runners provided written consent to be part of the study and provided near nude body mass before and after the training runs. The average body mass before the run was 54.0 ± 3.9 kg. The training run was 25.1 km, with an average temperature of 20.1°C and relative humidity of 37%. The average pace was 3:48 $min \cdot km^{-1}$ and the run was completed within 95 min; the change in altitude during the run was approximately 500 m. A CHO drink containing approximately 40 to 50 $g \cdot L^{-1}$ CHO was provided to all athletes every 5 km in sufficient volume to allow drinking *ad libitum*. Four athletes were provided with either 180 $g \cdot L^{-1}$ or 300 $g \cdot L^{-1}$ CHO using alginate hydrogel (*i.e.*, maltodextrin to fructose ratio of 1:0.7). Drinking bottles were collected following each 5 km station to assess fluid consumption; the bottles of one athlete were damaged during the run and thus this data has been omitted. After the completion of the run, the average body mass was 51.7 ± 3.7 kg, representing a water deficit of 4.2 ± 1.0% body mass loss, with a range of 2.2% to 5.9%. For the three athletes using the alginate hydrogel drink, 291.3 ± 26.4 mL was consumed over the 95 min. While this research is ongoing, there are some encouraging preliminary findings. Firstly, all athletes failed to prevent a decrease in body mass of ≤2% despite having regular access to sports drinks. Secondarily, there were no reports of any GI distress with any drink including the alginate hydrogel. Although the volumes consumed were fairly modest, the use of

alginate hydrogel as high as 300 $g \cdot L^{-1}$ of CHO was well tolerated, illustrating the unique ability of hydrogels to provide CHO in concentrations that far exceed what can typically be tolerated using commercially available sports drinks. Although there is only indirect evidence for its ergogenic effect, the winners of the 2016/2017 Berlin, Chicago, New York, Tokyo, Boston, and London marathons all used a CHO beverage containing alginate hydrogel, demonstrating its popularity in the elite field (43). Given its potential, further research is required to quantify the effect of alginate hydrogel on exogenous CHO oxidation and gastric emptying rates before the efficacy of this new delivery system can be confirmed. For example, the provision of a high concentration of CHO during exercise using this innovation can easily be modified to deliver other essential substrates/nutrients that may otherwise not be so well tolerated by the GI tract, such as protein (40) and iron status regulating drugs (44). If the efficacy of this innovative fuel and fluid delivery system is confirmed, this will represent significant progress toward the development of a personalised next generation sports drink containing a specific combination of substrates/nutrients for the athlete for any given situation.

Dental health should be considered when choosing to use a sports drink. The International Olympic Committee provides comprehensive dental treatment during the Olympic Games to all competing athletes (45). In particular, cavities and dental erosion are among the most commonly reported dental issues in athletes with incidents up to 75% and 86%, respectively, and is likely a result of a diet that contains a high amount of CHO supplements which often contain flavorings, such as citric acid (46–48). Commonly consumed sports drinks have a low pH (*i.e.*, 2.4-4.5) and therefore, these beverages could be a contributing factor in the dental problems seen in athletes (48). When using an alginate hydrogel, the beverage requires a relatively neutral pH with the encapsulation process beginning only when contact is made with gastric secretions in the stomach. In theory, a CHO beverage containing alginate hydrogel may be superior from a dental health perspective and could aid in reducing dental cavities in elite athletes. A survey at the London 2012 Olympic Games found that 18% of athletes reported that their oral health had a negative impact on their performance and 46.5% had not been to a dentist in the past year (45). The latest consensus statement aims to address such issues by embedding oral health into the wider culture of sports health care and health promotion (49).

Another research area of potential interest is the use of real-time monitoring systems to assess the drinking strategies of athletes during training and competition. Advances in technology, such as systems that can measure flow rate through an instrumented drink bottle and can estimate drinking rate are beginning to emerge to match the suggested hydration needs of each individual athlete, providing feedback to coaches and athletes through a mobile hydration app (50). These “smart bottles” communicate digitally with a band aid-like sweat patch to track the hydration of users. This technology could be used in combination with other wearable technology allowing several performance-based parameters to be measured continuously and displayed in real time, allowing intelligent, individualized decision making for an athlete.

Concluding Remarks

Recommendations regarding fluid intake and CHO delivery during exercise have change over the past century reflecting different schools of thought regarding the scientific literature. This perspective highlights some of the key milestones and changes in scientific opinion behind the current recommendations for fluid and fuel intake during exercise and seeks to encourage new research paradigms to encompass advances in technology and personal medicine. Despite claims that dehydration in excess of 2% body mass loss during exercise impairs performance, the ecological validity of this position in elite sporting competition, especially in distance running, is lacking, and some data show top performers with 4% to 6% body mass losses during activity showing no symptoms or signs of disability. Current research into sports drinks is primarily focused on optimizing the maltodextrin/fructose mix to increase the rate of exogenous CHO oxidation. Encapsulation of CHO could represent a new paradigm in the process of substrate delivery. Further research is required to quantify the effects on the rate of gastric emptying and exogenous CHO oxidation rate of this potential improvement in sports drinks.

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