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CONSENSUS STATEMENT

Sports Dietitians Australia Position Statement: Nutrition for Exercise in Hot Environments

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It is the position of Sports Dietitians Australia (SDA) that exercise in hot and/or humid environments, or with significant clothing and/or equipment that prevents body heat loss (i.e., exertional heat stress), provides significant challenges to an athlete's nutritional status, health, and performance. Exertional heat stress, especially when prolonged, can perturb thermoregulatory, cardiovascular, and gastrointestinal systems. Heat acclimation or acclimatization provides beneficial adaptations and should be undertaken where possible. Athletes should aim to begin exercise euhydrated. Furthermore, preexercise hyperhydration may be desirable in some scenarios and can be achieved through acute sodium or glycerol loading protocols. The assessment of fluid balance during exercise, together with gastrointestinal tolerance to fluid intake, and the appropriateness of thirst responses provide valuable information to inform fluid replacement strategies that should be integrated with event fuel requirements. Such strategies should also consider fluid availability and opportunities to drink, to prevent significant under- or overconsumption during exercise. Postexercise beverage choices can be influenced by the required timeframe for return to euhydration and co-ingestion of meals and snacks. Ingested beverage temperature can influence core temperature, with cold/icy beverages of potential use before and during exertional heat stress, while use of menthol can alter thermal sensation. Practical challenges in supporting athletes in teams and traveling for competition require careful planning. Finally, specific athletic population groups have unique nutritional needs in the context of exertional heat stress (i.e., youth, endurance/ultra-endurance athletes, and para-sport athletes), and specific adjustments to nutrition strategies should be made for these population groups.

***Keywords**:* fluid, food, heat, hydration, thermoregulation

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Exercise in hot and/or humid environments, or with significant clothing and/or equipment that prevents loss of body heat, can lead to exertional heat stress. Numerous sporting competitions are regularly held in outdoor environments in such conditions including high-intensity endurance events (e.g., 10-km road races and half-marathons, cycling time trials), ultra-endurance events (e.g., Badwater Ultramarathon, Ironman World Championships, and Marathon des Sables), and team (e.g., cricket and soccer) and racquet (e.g., tennis) sports played during summer months. Meanwhile, scenarios involving sports in hot and/or humid indoor environments include squash and motor racing, where in the latter case, the driver/rider can be exposed to ambient temperatures >45 °C while wearing protective clothing and equipment. Major sporting events in hot and/or humid locations, such as the 2019 International Association of Athletics Federations World Championships in Doha, Qatar, and the 2020 Summer Olympic Games in Tokyo, Japan, merit special consideration because the conditions pose a significant challenge for a large number of competitors (Gerrett et al., 2019) and require specific preparation.

What should be evident from these scenarios is that the thermal challenges faced by athletes are significant in both magnitude and variety, with individual factors such as the environmental conditions, metabolic heat production, performance characteristics, and logistics of athlete behavior around the exercise session creating unique concerns, as well as dictating the type of solutions that might be developed. Indeed, prolonged exertional heat stress can perturb the thermoregulatory, cardiovascular, and gastrointestinal systems, posing significant concerns for an athlete's health and performance. It is the position of Sports Dietitians Australia that exertional heat stress can significantly affect an athlete's nutritional status, but careful planning and implementation of nutrition strategies can assist him or her to optimize health and performance outcomes in such conditions. The following position statement summarizes these issues and the nutrition and hydration strategies with which they can be addressed.

Physiological Effects of Exertional Heat Stress

Thermoregulation

During exercise, high body temperatures arise from excess heat storage due to sustained imbalance between internal heat production and heat dissipation at the skin surface. Heat is generated in large quantities as a by-product of elevated rates of metabolism, supporting muscle contractions. Simultaneously, heat can be gained or lost via convection and radiation, and dissipated through the evaporation of sweat (Gagge & Gonzalez, 1996). Convective heat exchange is driven by temperature differences between the skin and air (in the shade) and modified by wind speed. Radiative heat exchange is determined by differences between skin temperature and mean radiant temperature, which on a clear summer day can be 10–15 °C higher than air temperature (Jay & Morris, 2018). Evaporative heat loss potential is governed by the absolute humidity difference between the skin and air and increases with wind speed. Clothing and equipment serve as a heat loss barrier dependent on garment insulation and water vapor permeability. A simple definition of "heat stress" is therefore not possible, as heat strain across a range of different air temperatures will vary according to the activity and clothing/equipment worn, as well as the prevailing sun exposure, humidity, and wind speed (Figure 1).

To minimize heat storage and prevent excessive core temperature increases, humans vasodilate and sweat. Neurons controlling these responses originate in the preoptic area of the hypothalamus, a small central region of the brain. Afferent input from thermoreceptors located in deep body structures and in the layer of the skin enables the hypothalamus to receive constant information about the thermal status of the body (Morrison, 2011). Elevations in core temperature of >0.2 °C can elicit cutaneous vasodilation, directing a greater volume of blood toward the skin to redistribute heat content and increase convective and radiative heat loss as skin temperature rises (Cramer & Jay, 2019). If nonevaporative heat loss is insufficient to offset elevated rates of heat production, core

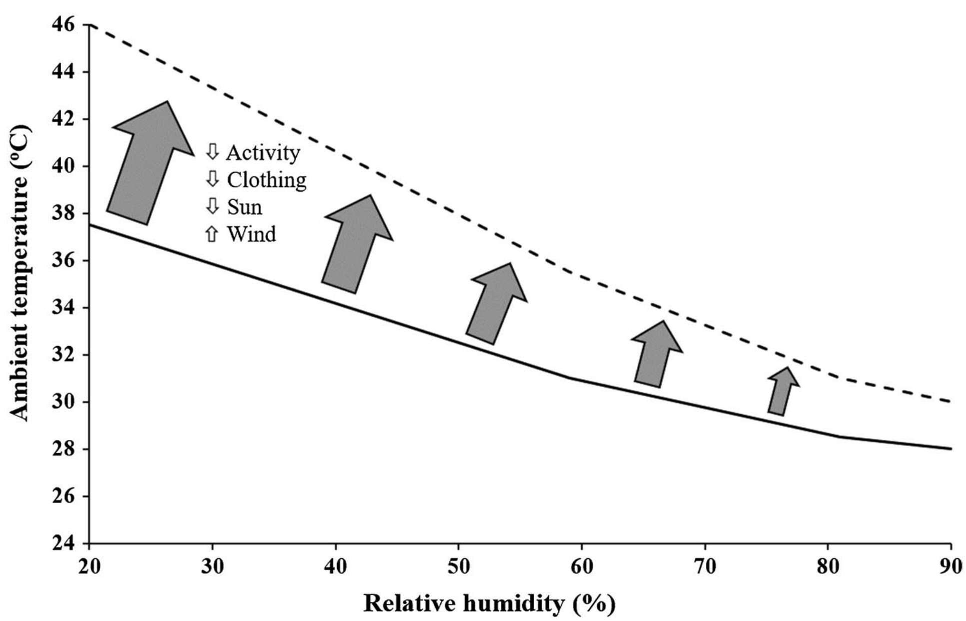

Figure 1 — A conceptual schematic illustrating that a given level of heat strain (solid and dotted lines) is dependent on the two personal parameters of clothing and activity and the four environmental parameters of ambient temperature, humidity, wind speed, and radiant temperature (sun exposure).

temperature continues to rise and eccrine sweat glands are activated via acetylcholine release (Gagnon & Crandall, 2018). If the ambient temperature permits the rate of sweat evaporation to balance the heat production, then core temperature will reach an elevated, but usually safe, plateau. However, when heat production exceeds this capacity, body temperature will continue to rise in a state known as uncompensable heat stress.

Gastrointestinal Function and Integrity

The impact of exercise in hot environments on the gastrointestinal tract merits special attention, as it contributes to the pathophysiology of exertional heat illnesses (EHIs) and/or gastrointestinal complications that compromise the athlete's capacity to address their nutritional goals and optimize thermoregulation. Prolonged exercise in hot ambient conditions, resulting in a core temperature ≥39.0 °C, exacerbates the perturbations to gastrointestinal integrity, function, and systemic responses compared with exercise in cooler conditions (Costa et al., 2019a). Such perturbations, known as exercise-induced gastrointestinal syndrome, have been linked to performance-debilitating gastrointestinal symptoms and clinical implications ranging from mild inconvenience to fatality (Costa et al., 2017). These multifaceted outcomes reflect two primary physiological changes, which occur at the onset of exercise and are exacerbated by thermal stress, creating a structural and functional burden to the gastrointestinal system (Figure 2). Redistribution of blood flow away from the gastrointestinal tract and toward skeletal muscles (i.e., metabolic kinetics) and peripheral circulation (i.e., thermoregulation) results in reduced total splanchnic perfusion and subsequent gastrointestinal ischemia (Grootjans et al., 2016; van Wijck et al., 2011). Concomitantly, an increase in sympathetic activation reduces overall gastrointestinal functional capacity, possibly via suppressed myenteric and submucosal plexus activity (Costa et al., 2017; Horner et al., 2015; Strid et al., 2011). The initiation of these physiological responses is dependent on the exercise stress per se (i.e., intensity, duration, and modality) but is exacerbated with heat exposure (Costa et al., 2017, 2019a). The secondary outcomes of these exercise-associated gastrointestinal abnormalities include mucosal erosion, epithelial cell injury and dysfunction, tight junction damage and dysfunction, luminal bacterial endotoxin translocation, local epithelium and systemic

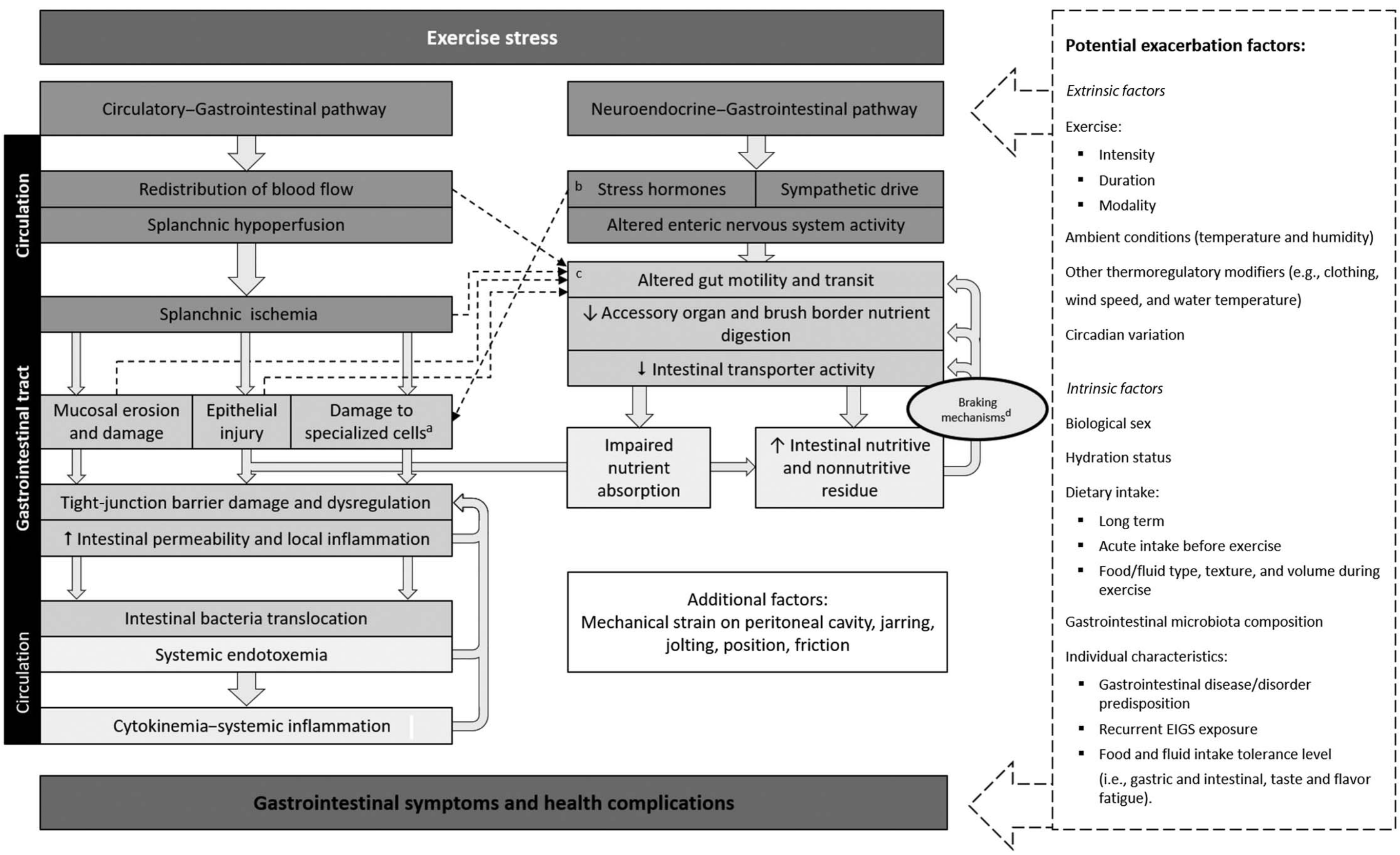

Figure 2 — Schematic description of exercise-induced gastrointestinal syndrome: Physiological changes in circulatory and neuroendocrine pathways at the onset of exercise resulting in perturbed gastrointestinal integrity and function, and may lead to gastrointestinal symptoms, and/or acute or chronic health complications. Adapted with permission from "Systematic Review: Exercise-Induced Gastrointestinal Syndrome-Implications for Health and Disease," by Costa et al., 2017, *Alimentary Pharmacology and Therapeutics, 46*, pp. 246–265. [a]Specialized antimicrobial protein-secreting (i.e., Paneth cells) and mucus-producing (goblet cells) cells, aid in preventing intestinal-originating pathogenic microorganisms gaining entry into systemic circulation. [b]Splanchnic hypoperfusion and subsequent intestinal ischemia and injury (including mucosal erosion) results in direct (egg, enteric nervous system, and/or enteroendocrine cell) or indirect (egg and nutrient malabsorption) alterations to gastrointestinal motility. [c]Increase in neuroendocrine activation and suppressed submucosal and myenteric plexus result in epithelial cell loss and subsequent perturbed tight junctions (Holzer et al., 2017; Barrett, 2012). [d]Gastrointestinal brake mechanisms: Nutritive and nonnutritive residue along the small intestine, and inclusive of terminal ileum, results in neural and enteroendocrine negative feedback to gastric activity (Miall et al., 2018; Shin et al., 2013; Layer et al., 1990; van Avesaat et al., 2015; van Citters & Lin, 2006).

innate/adaptive immune cell and inflammatory responses, suppressed gastric emptying, and suppressed nutrient digestion and absorption (Costa et al., 2017). Current and emerging evidence shows that hot and/or humid ambient conditions play a key role in determining the magnitude of exercise-induced gastrointestinal syndrome (Costa et al., 2019a; Pires et al., 2017, 2018).

Effects of Exertional Heat Stress on Performance and Health

Increases in thermal strain during prolonged exercise (i.e., elevated skin, muscle, and core body temperatures) progressively impair aerobic performance (Table 1; Ely et al., 2007). This impairment is linked to a thermoregulatory-mediated rise in cardiovascular strain, which contributes to decreased maximal aerobic capacity (Périard et al., 2011; Périard & Racinais, 2015), and a potential hyperthermia-induced reduction in voluntary drive (i.e., motivation; Bruck & Olschewski, 1987). Exertional heat stress also induces greater reliance on muscle glycogen and anaerobic metabolism (Febbraio et al., 1994), which may prematurely deplete endogenous glycogen stores during endurance exercise. In contrast, a rise in whole-body temperature, particularly muscle temperature, enhances the performance of explosive short-duration activities such as sprinting and jumping (Bergh & Ekblom, 1979; Sargeant, 1987), via temperature-related improvements in metabolic and contractile function (Allen et al., 2008; Fitts, 1994). While single efforts may be improved in hot environmental conditions, repeated-sprint activities may reach a tipping point, where muscle temperature–related benefits are overridden by exacerbated cardiovascular and metabolic responses (Girard et al., 2015). In team sport athletes (e.g., football), the effects of environmental heat stress appear to include both an impairment and improvement in performance compared with cool conditions (Table 1). More specifically, total and high-intensity running distances are decreased, whereas peak running speed is maintained or improved (Aughey et al., 2014; Mohr et al., 2012).

Regardless of performance effects, the risk of EHI, a continuum of medical conditions that can affect physically active individuals in hot and cool environments, is increased by the development of hyperthermia. The severity of EHI can escalate from heat exhaustion, to heat injury, and on to heat stroke (Leon & Bouchama, 2015). Heat exhaustion is associated with a body core temperature of 38.5–40 °C, dehydration, possibly hot dry skin due to the absence of sweating, and an inability to maintain cardiac output. A heat injury is characterized by organ (e.g., liver) and tissue (e.g., gut) damage with a body temperature typically >40 °C. In the most severe EHI, exertional heat stroke, characterized by a body temperature >40 °C, profound central nervous system dysfunction (e.g., combativeness, delirium, seizures, and coma), and organ and tissue damage, can lead to death. Other common but relatively benign conditions such as muscle cramping do not form part of the EHI continuum.

Heat Acclimation and Acclimatization

Heat acclimation is the process of exposing an individual to repeated heat stress in a controlled or artificial environment about 7–14 days, with the aim of increasing whole-body temperature and inducing profuse sweating. In contrast, heat acclimatization occurs in a natural environment with changes of season, or travel from cool to hot locations (Armstrong & Maresh, 1991). These two terms are often used interchangeably as they both induce physiological adaptations that can benefit athletic performance during prolonged events (Périard et al., 2015). Initial adaptations, including plasma volume (P_v) expansion, enhanced fluid balance, reduced heart rate, and decreased ratings of perceived exertion, begin to emerge in 3–5 days of acclimation (Gisolfi & Cohen, 1979; Patterson et al., 2004). Reductions in resting core temperature, increased sweat rate, and decreased sweat sodium ($[Na^+]_{sweat}$) and chloride ($[Cl^-]_{sweat}$) concentrations develop over a longer time frame (e.g., 3–10 days; Gerrett et al., 2019). Interestingly, the increase in sweat rate is offset by reduced $[Na^+]_{sweat}$ to the extent that overall sweat sodium losses following acclimation are equivalent or lower to those observed prior to heat acclimation (Chinevere et al., 2008).

Although heat acclimation is the most important intervention that athletes can undertake in preparation for competing in the heat (Racinais et al., 2015), the process of becoming acclimated can be challenging. Notably, athletes may need to adjust absolute training intensity and volume during heat training sessions compared with typical sessions undertaken in cooler conditions, or risk overreaching (Schmit et al., 2018) and experiencing lethargy and sleep disturbances (Taylor & Cotter, 2006). However, different approaches can be adopted based on available time and resources, as well as when the athletes will be arriving to the competition venue (Saunders et al., 2019). It should be recognized that the benefits of heat acclimation may offer different advantages, and possible disadvantages, according to the event characteristics. For example, sports in which protective clothing impedes sweat

Table 1 Influence of Environmental Heat Stress on the Development of Whole-Body Hyperthermia and Its Effects on Exercise Performance Relative to Exercising in Cool Ambient Conditions

Exercise/sport	Influence of environmental heat stress
Aerobic/endurance	Performance is progressively impaired. A given absolute workload (e.g., speed, power) is more difficult to maintain as hyperthermia and cardiovascular strain develop.
Single brief maximal efforts	Performance is acutely improved. Explosive short-duration performance (e.g., speed, power) is enhanced by a rise in whole-body and skeletal muscle temperature.
Repeated brief maximal efforts	Performance is acutely improved and then progressively impaired. Initial maximal performance (e.g., speed, power) may be enhanced in response to muscle temperature–related benefits, but subsequent efforts impaired due to lack of recovery and exacerbated cardiovascular/metabolic responses.
Team sports	Aerobic/endurance component of performance is progressively impaired and single brief maximal efforts maintained or improved. A given absolute workload is more difficult to sustain as hyperthermia and cardiovascular strain develop, leading to a decrease in aerobic performance (e.g., total distance covered). Explosive short-duration performance (e.g., single sprint) is maintained or enhanced due to a rise in whole-body and skeletal muscle temperature.

evaporation (e.g., motor racing) will not benefit from earlier and amplified sweat rates (Taylor & Cotter, 2006); nevertheless, reductions in resting core temperature and thermal perception, along with expanded P_v, may still be valuable.

Fluid and Electrolyte Balance During Exertional Heat Stress and Acclimation

The redistribution of blood flow and thermoregulatory sweating in response to exertional heat stress result in significant changes in body water and electrolyte balance (Sawka et al., 2007). Unreplaced sweat losses reduce total body water (TBW) and P_v, resulting in reduced cutaneous blood flow, increased core temperature, greater cardiovascular strain (i.e., increased heart rate and reduced cardiac output), and increased risk of exercise-induced gastrointestinal syndrome for the same exercise task (Costa et al., 2019b; Trangmar & González-Alonso, 2017). Thermoregulatory sweat also contains several solutes including Na^+ and Cl^-, the only two electrolytes whose excretion is known to be physiologically regulated (Bovell, 2015). Whole-body $[Na^+]_{sweat}$ varies considerably (11–87 mmol/L), which combined with an equally variable sweat rate (typical range 150–3,500 ml/hr), produces large interindividual differences in Na^+ losses during exercise (~50 to 3,500 mg/hr; Barnes et al., 2019). There is also substantial intraindividual variation in sweat Na^+ losses, with exercise intensity (Holmes et al., 2016), hydration status (Morgan et al., 2004), airflow (Saunders et al., 2005), habitual Na^+ intake (McCubbin et al., 2019a), and heat acclimation status (Chinevere et al., 2008), influencing the response. Such factors, however, explain less than 20% of the variation in sweat Na^+ losses between athletes (Baker et al., 2016).

Fluid and Na^+ replacement during exertional heat stress has differing effects on TBW, P_v, plasma osmolality (P_{Osm}), and plasma Na^+ concentration ($[Na^+]_{plasma}$), depending on both their absolute and relative quantities compared with sweat losses. Consuming Na^+ during exercise can result in greater P_v retention than water alone, via increased ad libitum fluid intake subsequent to increased osmotic thirst drive (Hoffman et al., 2019), reduced diuresis, and/or movement of fluid from the intracellular to extracellular space (Sanders et al., 2001). However, the influence on $[Na^+]_{plasma}$ is minor (Hew-Butler et al., 2015). Athletes often consume Na^+ during exercise in the belief that it can prevent or treat some scenarios of exercise-associated muscle cramping (McCubbin et al., 2019b). Although evidence from observational studies is somewhat equivocal (Bergeron, 2003; Schwellnus, 2009), recent publications suggest that Na^+ intake may play a role in altering the frequency threshold in an electrically induced cramping model (Earp et al., 2019; Lau et al., 2019), which warrants further investigation. Finally, specific commentary on the practice of Na^+ replacement to prevent the development of hyponatremia during prolonged events (McCubbin et al., 2019b) recognizes that although hypovolemic hyponatremia (low $[Na^+]_{plasma}$ in concert with hypohydration) does occur in scenarios of prolonged exercise in hot conditions, the most common cause of exercise-associated hyponatremia is excessive fluid intake (Hew-Butler et al., 2015).

Hydration and Electrolyte Status Assessment

Hydration status can be defined in multiple ways, including absolute values and changes in TBW, P_v, P_{Osm}, and $[Na^+]_{plasma}$. No single marker is considered definitive, as changes in fluid balance alter TBW, as well as shifts between intracellular and extracellular fluid compartments (Armstrong, 2007). Methods to assess hydration status are summarized in Table 2. Absolute hydration status is difficult to measure outside laboratory settings and is instead inferred from urinary markers (e.g., urine color, osmolality, or specific gravity); daily variation in body mass (BM); thirst; or ideally a combination of these (Armstrong, 2007). Urinary markers reflect recent homeostatic processes to maintain euhydration and are not a direct assessment of hydration status itself. Therefore, urinary markers are likely to reflect hydration status only when well rested, with waking urine samples considered most valid for this purpose (Armstrong, 2007). Bioelectric impedance analysis is increasingly used to estimate TBW and with some models, extracellular fluid. However, this should only be considered adequate when validated against reference methods and under the same conditions in which validation took place.

Changes in TBW during exercise, including rates of sweat losses, are mostly frequently determined via differences in BM. Calculations of sweat rate should be corrected for food consumption and urinary/fecal losses where relevant (Sawka et al., 2007). BM changes during ultra-endurance exercise (>4 hr) are likely to overestimate reductions in TBW, and adjustments for substrate oxidation, metabolic water production, glycogen depletion, and respiratory water losses may be necessary (Cheuvront & Kenefick, 2017; Maughan et al., 2007). Electrolyte losses can be determined from sweat sampling during exercise with the electrolyte of interest measured using appropriate techniques, including some validated for use in field settings (Baker et al., 2014). Methodological considerations for assessing sweat composition are beyond the scope of this statement; readers are directed to a recent comprehensive review on the subject (Baker, 2017). However, it should be highlighted that sweat collection from local sites does not represent whole-body fluid or Na^+ losses, and corrections should be made to reflect whole-body responses (Baker et al., 2018).

Strategies for Fluid and Electrolyte Intake Before, During, and After Exercise

Fluid and electrolyte intake strategies before, during, and after exercise must be practical and achievable, considering factors such as the mode, duration and intensity of exercise, event rules, and availability/accessibility of fluids, as well as athlete preferences and gastrointestinal tolerance. These factors will also determine whether athletes should emphasize fluid and electrolyte intake before or during exercise to optimize health and performance.

Preexercise Fluid and Electrolyte Intake

In general, athletes who are exposed to hot conditions in the days preceding competition should monitor hydration status and adjust drinking habits accordingly to ensure they commence exercise in a euhydrated state (Racinais et al., 2015). Exceptions to this include athletes in sports unaffected by hypohydration, in which a slightly lower BM may be useful (e.g., jumpers). The volume and type of fluids included in immediate (e.g., 1–2 hr pre-event) hydration strategies should be based on current hydration status, the anticipated substrate requirements, and fluid balance challenges during exercise. Ideally, such practices should be well-rehearsed and able to accommodate individual needs and gastrointestinal tolerance. When a significant mismatch between sweat losses and opportunities for fluid intake during exercise is anticipated, pre-event hyperhydration may be useful in reducing the net fluid deficit and its impact on performance.

The co-ingestion of an osmotically active agent can assist with the retention of a pre-event fluid bolus. Acute Na^+ loading

Table 2 Hydration Status Assessment Techniques, in Both Laboratory and Field Settings

Parameter	Assessment technique/s	Technique advantages	Technique disadvantages
Total body water			
Absolute quantification	Deuterium oxide dilution[a]	Accuracy and reliability	Resources required (cost, equipment, and expertise) and long equilibration time (several hours) requiring rest
	Bioelectric impedance analysis	Noninvasive and some models validated against reference method	Equipment cost, some level of expertise required to operate, high variability between models, and not valid when recent shifts in fluid compartments have occurred (e.g., postexercise)
	Body mass	Can be completed independently by athletes and low cost	Fluctuations can occur from differences in GI tract and bladder contents, and energy substrate stores
	Perceived thirst	Can be completed independently by athletes and low cost	Thirst may not be a reliable indicator at rest in some populations (e.g., younger or older athletes, side effect of some medications)
	Urine color	Can be completed independently by athletes and low cost	Indirect measure, may not be reliable if not well rested and after recent large changes in fluid balance, or with intake of water-soluble vitamin supplements
	Urine specific gravity	Simple for practitioners to operate provides quantitative result	Equipment cost, some level of expertise required to operate, indirect measure, may not be reliable if not well rested, and after recent large changes in fluid balance
	Urine osmolality	Simple for practitioners to operate and provides quantitative result	Equipment cost, some level of expertise required to operate, indirect measure, may not be reliable if not well rested, and after recent large changes in fluid balance
	Weight, urine color, and thirst combined (Armstrong, 2007).	More reliable than single parameters alone. Can be completed independently by athletes and low cost	Cannot quantitatively provide feedback to athletes on total body water/hydration status
Change over time	Fluid balance assessment/change in body mass	Can be completed independently by athletes and low cost	Can be confounded by food intake and fecal losses, and misinterpreted if athlete commences exercise hyperhydrated. Can overestimate total body water losses in ultra-endurance (>4 hr) exercise, requiring correction for substrate oxidation, metabolic water production, glycogen depletion, and respiratory water losses
Intra/extracellular fluid	Sodium bromide dilution[a]	Accuracy and reliability	Resources required (cost, equipment, and expertise) and long equilibration time (several hours) requiring rest
	Bioelectric impedance analysis	Noninvasive and some models validated against reference method	Equipment cost, some level of expertise required to operate, high variability between models, and not valid when recent shifts in fluid compartments have occurred (e.g., postexercise)
Plasma volume	Evans blue dye[a]	Accuracy and reliability	Invasive and resources required (cost, equipment, and expertise)
Absolute quantification	Estimate from previously published data (Malczewska-Lenczowska et al., 2013)	Noninvasive, low cost, and no equipment required	Estimate rather than measurement, only valid within the population studied
Change over time	Relative changes in hemoglobin and hematocrit	Can perform analysis quickly on portable machines and using whole blood	Blood sample and resources required (cost, equipment, and expertise)
Plasma osmolality	Freeze point osmometry[a]	Direct measure and can perform analysis quickly on compact equipment	Blood sample and resources required (cost, equipment, and expertise)
Plasma sodium concentration	Ion-selective electrode[a]	Direct measure and common clinical laboratory measure	Blood sample and resources required (cost, equipment, and expertise)

[a]Reference method of assessment.

(20–40 mg/kg BM, with 10 ml/kg BM fluid) 1–2 hr prior to exercise can expand P_v and improve thermoregulation during constant workload exercise in the heat (Hamouti et al., 2014; Sims et al., 2007a, 2007b) and is equally or more effective than Na^+ loading over an extended period (McCubbin et al., 2019a). Glycerol, a three-carbon alcohol, is another effective osmolyte that enhances fluid retention and results in expansion of P_v and a reduction in urine output. Glycerol was removed from the World Anti-Doping Agency Prohibited List in January 2018 and can now be used for hyperhydration and postexercise rehydration strategies. Studies in endurance athletes support ingestion of 1.2–1.4 g/kg fat-free mass (FFM) glycerol in the 90- to 180-min pre-event, in conjunction with ~25 ml/kg FFM fluid (Goulet et al., 2018; van Rosendal et al., 2010). The combination of glycerol (1.4 g/kg FFM) and sodium (3.0 g/L) in ~25 ml/kg FFM water may be more effective than either osmolyte alone (Goulet et al., 2018), and such protocols can achieve an additional fluid retention of ~1,300 ml for a 70-kg athlete (Goulet et al., 2018), for up to 4-hr postingestion (Montner et al., 1996; Wingo et al., 2004). The translation into a performance benefit is unclear (Goulet et al., 2007) and may be dependent on ambient conditions and the characteristics of the exercise bout. All protocols should be practiced to determine their effectiveness and potential side effects including gastrointestinal discomfort and headaches.

Fluid and Electrolyte Intake During Exercise

Opportunities to drink during exercise are often contingent on practicality and/or regulations associated with specific sports/events. The benefits of fluid consumption during exercise continue to be debated, with contention surrounding the level at which dehydration begins to impair performance and how fluid replacement should occur. Numerous laboratory-based studies suggest that fluid deficits ≥2% BM are associated with the initiation of impaired exercise performance in hot and/or humid ambient conditions (Adams et al., 2018; Cheuvront et al., 2007; James et al., 2017; Kenefick et al., 2010). However, these studies generally compare protocols involving complete fluid replacement to those where no or minimal fluid is provided and therefore cannot establish a dose–response relationship with regard to optimizing performance. While both ad libitum drinking and planned fluid intake (of a volume greater than ad libitum) improve endurance performance compared with no fluid ingestion (Holland et al., 2017), a recent meta-analysis of exertional heat stress >1-hr duration concluded that planned fluid intake did not further improve performance beyond that of ad libitum drinking, even with BM losses up to 3.1% in the ad libitum condition (compared with <0.5% with planned drinking), and with exercise intensities up to 90% of maximum heart rate (Goulet & Hoffman, 2019). However, the divergence in total fluid intake between planned and ad libitum drinking may increase with exercise duration, particularly under heat stress, and where opportunities to access and ingest fluid during real-life sporting events are more limited than those encountered in laboratory studies. Therefore, individualized fluid replacement plans—informed by prior assessment of fluid balance, perceived thirst, gastrointestinal tolerance, and performance metrics in similar situations, and adjusted according to real-time assessment—can address both the practicality and value of fluid intake during a competitive event.

Fluid choices during exercise should consider substrate requirements, electrolyte content, palatability, and access. Despite previous concern about delayed gastric emptying associated with the addition of solutes to an exercise beverage, carbohydrate-containing drinks can be formulated to minimize this issue (Jeukendrup & Moseley, 2010); this may address the higher rates of carbohydrate utilization during exercise in the heat (Stellingwerff & Cox, 2014). Cooler beverages (<22 °C) tend to increase fluid palatability and voluntary consumption during exercise (Burdon et al., 2012), while planned consumption of cold (<10 °C) or iced beverages may convey additional perceptual or performance benefits when exercise is undertaken in hot ambient conditions (Burdon et al., 2010a; Lee et al., 2008). Sodium replacement during prolonged exertional heat stress has been less rigorously studied, preventing conclusions about the value of quantifying or replacing sweat Na^+ losses to address issues of cramp prevention or optimal performance (McCubbin & Costa, 2018). Nevertheless, individualized protocols for electrolyte replacement may offer some benefit for specific scenarios until further research can offer a more evidence-based approach. It is noted again that exercise-associated hyponatremia is mostly associated with excessive intake of fluid rather than Na^+ loss, and its outcomes, secondary to excess fluid osmotically driven into the intracellular pool, including the brain, can be fatal (Hew-Butler et al., 2015). This can be prevented by simply ensuring that fluid intake during exercise does not exceed losses, and it should be noted that ad libitum drinking and drinking to thirst does not necessarily guarantee this (Hew-Butler et al., 2015).

Postexercise Fluid and Electrolyte Intake

When rapid reversal of moderate–severe fluid deficits is desired postexercise, it may be necessary to drink a volume up to 150% of the net deficit to account for ongoing fluid losses during the hours of fluid re-equilibration (Sawka et al., 2007). However, the postexercise environment (i.e., food/beverage access), immediate requirements for other recovery purposes (e.g., refueling and adaptation) and overall body composition goals are important contextual considerations. Drinking large volumes of fluid can be challenging in the short term, especially if the athlete has experienced significant thermoregulatory strain or impairment of gastrointestinal integrity/function during exercise (Russo et al., 2019).

The consumption of nutrients within a rehydration fluid, or in food consumed at the same time, can assist with fluid retention/minimization of urine losses. Sweat Na^+ losses during exercise are accompanied by significant renal Na^+ conservation in the postexercise period (Lichton, 1957), making complete replacement of sweat Na^+ losses unnecessary. However, the consumption of Na^+ in rehydration strategies supports less disturbance to P_{Osm} as P_v is being restored, maintaining the secretion of vasopressin and minimizing subsequent urine production (Evans et al., 2017). The presence of carbohydrate and/or protein is also helpful because the delayed absorption characteristics of such fluids (e.g., milk-based beverages) also reduce P_{Osm} changes; this has been incorporated into a beverage hydration index (Maughan et al., 2016). However, it is important to recognize that consuming any beverage makes a contribution to total fluid intake and advice to avoid specific beverages (e.g., caffeinated options) may result in lower total fluid intake when these drinks are otherwise part of normal dietary practices (Maughan et al., 2016).

The simultaneous consumption of food is likely to facilitate postexercise rehydration (Campagnolo et al., 2017). When combined with voluntary food intake, the choice of postexercise beverage does not appear to influence restoration of hydration status (Campagnolo et al., 2017; McCartney et al., 2018, 2019), but in the case of energy-containing fluids (e.g., sports drinks and milk-based drinks), it may lead to a greater energy consumption than when water is consumed. Therefore, fluid and food intake during recovery should be considered in terms of overall nutrition goals.

Nutritional Pre- and Per-Cooling Strategies During Exercise

Preparing athletes to safely exercise in uncompensable heat can be addressed by cooling both before (i.e., pre-cooling) and during (i.e., per-cooling) the activity. Different strategies can provide acute relief from the thermal stress posed by training or competing in the heat (Ross et al., 2013). Ingestion of cold/icy drinks (or internal cooling strategies) also provides opportunities to simultaneously address other exercise goals, such as maintaining fluid balance (Sawka et al., 2007), providing nutrient support (Wendt et al., 2007), defending the integrity of the gastrointestinal tract (Snipe et al., 2018), and alleviating thermal discomfort (Stevens et al., 2017a, 2017b). Internal cooling is highly practical and can be implemented separately or in addition to externally applied strategies (e.g., ice baths, ice jackets) to benefit from the potentiating effects of the combination of cooling techniques (Hasegawa et al., 2006) immediately before exercise. Further discussion of external and combined cooling techniques can be found in existing comprehensive reviews (Ross et al., 2013; Stevens et al., 2017b). It is important to recognize that effective strategies are also required to fit within the rules and schedules of competition and be practical to implement.

As ice is a more powerful cooling agent due to the thermal energy required to phase change a solid into liquid (Jay & Morris, 2018; Ross et al., 2013), ice-slurry beverages allow for a greater heat storage capacity and level of thermal comfort than a similar volume of ingested fluid (Ihsan et al., 2010; Siegel et al., 2010; Siegel et al., 2011). Adding glycerol and other solutes (e.g., carbohydrate and/or electrolytes) lowers the freezing point, allowing the formation of a supercooled crystalline liquid served at subzero temperatures. While improving consistency so that the frozen beverage can be readily ingested using a straw, a practical limitation may involve the discomfort associated with subsequent brain freeze (i.e., sphenopalatine ganglioneuralgia).

Preexercise ingestion of cold (Burdon et al., 2010b; Lee et al., 2008) and ice-slurry (Burdon et al., 2013; Dugas, 2011; Siegel et al., 2012) beverages may be effective in cooling athletes during exercise in hot, humid, and still environments. However, this may not be the case in warm, dry, and windy environments, where evaporative heat loss potential is greater; this is due to a reduction in sweating that occurs when consuming cold beverages following the stimulation of abdominal thermoreceptors (Jay & Morris, 2018). Nevertheless, performance advantages may still be seen in response to a perceptual benefit. Although the value of creating a larger heat sink by internal cooling alone may be modest in comparison with the thermal challenges of the event (i.e., exogenous and endogenous heat stress), there is strong evidence for oral temperature–sensitive regions of the brain being activated when cold fluid is placed in the mouth (Guest et al., 2007), enhancing the perception of thermal comfort.

Other Nutritional Strategies to Enhance Thermal Comfort

Another nutrition strategy that alters thermal sensation is the use of L(-) menthol. Menthol is a cyclic terpene alcohol found in mint leaves, which activates oropharyngeal cold receptors and increases the threshold temperature for their activation, creating a feeling of coolness (McKemy et al., 2002; Peier et al., 2002). Menthol can be applied externally to skin or clothing as a gel or spray, but the most effective method is oral ingestion in the form of mouth rinse or an aromatized beverage (Stevens & Best, 2016). The cooling effect of menthol has the potential to improve performance in hot and/or humid conditions, with observations of enhanced exercise capacity following mouth rinsing with a liquid menthol solution during exercise (Mündel & Jones, 2010). The beneficial effect of menthol can be further enhanced by administering menthol at cold (~3 °C) temperatures (Trong et al., 2015) or in the form of an ice slurry (Riera et al., 2014; Trong et al., 2015). Indeed, performance was enhanced by the combination of thermal and sensory cooling achieved by ingesting a menthol-slushie before and during a 20-km cycling time trial (Riera et al., 2014). It is recommended that athletes experiment to determine the concentration and amount of ingested menthol solution that is tolerable and beneficial. The suggested preparation involves the addition of 0.1–0.5 g of crushed menthol crystals (dissolved in alcohol) to 1 L of water or the use of a commercial premixed menthol/alcohol solution (Stevens & Best, 2016). Light green or blue menthol solutions appear to illicit the most positive response, potentially due to their subjective qualities and association with coolness (Best et al., 2018). Extreme caution should be taken if preparing menthol solutions from basic ingredients for oral ingestion. Given the small quantity of menthol required and potential for toxicity if not prepared correctly (e.g., burning, irritation, pain, and potential fatality in large quantities; Kumar et al., 2016), it is suggested that practitioners, coaches, and athletes utilize commercially available products wherever possible.

Practical Implementation of Nutrition Plans for the Heat

The ability of athletes, coaches, and support staff to implement nutrition and hydration strategies to optimize health and performance in hot environments is frequently compromised by specific physiological, cultural, and practical challenges unique to particular sports or athlete subgroups. The following section describes these challenges in a variety of sports settings, with practical recommendations summarized in Table 3.

Team Sports

Training and competition for team sports are undertaken in varying seasonal and geographical locations, requiring the development of population- and environment-specific plans to address these challenges. Indeed, team sports present unique challenges because the thermal strain between players (e.g., different positions) can differ significantly and vary based on match location. Nevertheless, team sports may offer some useful characteristics for heat management in the form of player rotations and routine breaks within the game. The intermittent nature of many team sports offers some respite from the heat-generation aspects of exercise, while also providing good opportunities to implement strategies for thermal strain management and nutrition goals. Some team sports have rules that impede access to fluid during lengthy competition periods (e.g., original Fédération Internationale de Football Association rules limit fluid intake to the break between 45-min halves). When team sports are played in hot environmental conditions, local authorities or match officials should have the opportunity and understanding to implement specific rules or conditions that are better suited to the environment (e.g., Fédération Internationale de Football Association updated the Heat Policy with additional

Table 3 Physiological, Cultural, and Practical Challenges for Specific Athletic Subgroups Exercising in Hot Environments, and Practical Strategies for Their Management

Area of practice	Physiological, cultural, or practical challenge	Recommendations
Team sports	Large variation between teammates in fluid and electrolyte losses, thermoregulatory function, and personal preferences for food and fluid intake strategies.	Monitor hydration status and fluid intake behaviors (e.g., fluid balance assessment, appropriately used urinary hydration markers) prior to and during competition to ensure appropriate hydration plans have been developed for individual team members.
	Diverse ambient conditions encountered and reduced ability for evaporative cooling in some sports due to protective clothing and equipment.	Implement nutrition-related cooling strategies (e.g., ice-slurry ingestion) and trialing novel heat management strategies (e.g., hyperhydration, menthol mouth rinse/ingestion) may be included in the broader plan.
	Availability of cold food and fluids in appropriate quantities for athletes during training and competition.	Ensure that team support staff and coaches provide ready access to appropriate nutrition-related heat management strategies during competition and training sessions.
	Limited opportunities to consume food and fluids during team sports competition due to the rules/regulations of the sport.	Ensure that sport-specific heat policies around additional cooling/drinks breaks are followed. This includes ensuring that team support staff and coaches are aware of, and prepared for, such additional opportunities and adjust food and fluid availability to suit.
	Risk of exertional heat illness due to the high-intensity demands of many team sports, when performed in hot ambient conditions.	Train team support staff and coaches to recognize the signs of heat illness in athletes and act accordingly to mitigate the risk of exertional heat illness.
Endurance and ultra-endurance sports	Potential for large accumulated fluid and electrolyte deficits during prolonged endurance exercise, resulting in reductions in TBW and potential fluid shifts between compartments.	Undertake fluid and electrolyte balance assessment during training sessions that mimic a thermally challenging event to monitor sweat losses, current fluid intake practices, perceived thirst and exertion, thermal comfort and management, gastrointestinal tolerance, and performance metrics. Individualize fluid intake practices in terms of the amount, frequency, and type of drinks, accounting for potential variations in ambient conditions, exercise intensity, and heat acclimation status.
	Potential for significant variation in ambient conditions throughout endurance events, with subsequent changes over time in whole-body temperature, thermoregulatory responses, and fluid and electrolyte balance.	Plan for flexibility in fluid and electrolyte intake strategies, ensuring access to sufficient fluid for upper estimates of fluid and electrolyte needs, but adjusting to prevent overhydration if exercise intensity or ambient temperature is lower than expected. In many cases, ad libitum fluid intake will be adequate to achieve this; however, the suitability of this approach for each individual should be evaluated using an appropriate fluid balance assessment.
	Gastrointestinal tolerance of food and fluid may limit voluntary fluid intake, and the maintenance of euhydration. This may be further exacerbated in hot ambient conditions due to both increased fluid requirements and increasing disturbance to gastrointestinal function.	Practice fluid intake strategies (i.e., volume and composition) during training that mimics competition intensity, with the goal of increasing fluid intake toward that required for the maintenance of euhydration.
	Competition-specific logistics may limit opportunities to access fluid in some events.	Plan ahead to understand the opportunities to access fluid during each specific event, adjust athlete plans to obtain and carry fluids accordingly, and practice these in training.
	Risk of experiencing gastrointestinal symptoms, or structural and functional impairment, due to prolonged splanchnic hypoperfusion, and/or increased sympathetic drive that results from prolonged exertional heat stress. This may be further exacerbated by feedback from unabsorbed food components that reduce gastrointestinal motility further up the gastrointestinal tract.	Provide consistent macronutrient intake throughout exercise (existing literature has used 45 g/hr of carbohydrate in small, evenly distributed boluses) to prevent significant intestinal injury, possibly by attenuating gastrointestinal hypoperfusion. Ensure euhydration during exercise to prevent large P_v losses, which may exacerbate splanchnic hypoperfusion. Consider pre- and per-cooling strategies to attenuate the rise in core body temperature, which increases sympathetic drive. Undertake short-term restriction of dietary fermentable oligo-, di-, mono-saccharidesand polyol sources 24 hr before and during exertional heat stress to reduce the severity of gastrointestinal symptoms. Plan carbohydrate intake strategies that are not entirely dependent on ad libitum fluid intake, which may result significant under- or overfueling if fluid intake varies from what was anticipated.

(continued)

Table 3 (continued)

Area of practice	Physiological, cultural, or practical challenge	Recommendations
Junior and adolescent athletes	Reduced thermoregulatory sweating compared with adults.	In hot and dry conditions that encourage evaporative cooling, athletes are advised to keep skin exposed and damp while cooling. Use air conditioning or fans before and during exercise where practical. In hot and humid environments where evaporative cooling is limited, encourage ingestion of cold fluids (e.g., ice slurries, chilled water bottles) to mitigate the rise in core temperature.
	Attitudes to fluid intake among young athletes can be dependent on knowledge, education, access to fluids, and opportunities to rehydrate/refuel	Ensure education of athletes, parents, and coaches about appropriate hydration strategies before, during, and after exercise. Ensure education is provided in the early season for summer sports, as athletes may be at higher risk for hypohydration and exertional heat illness due to a lack of heat acclimation/ acclimatization.
Travel to compete in hot and humid environments	Travel may cause fatigue and suboptimal nutritional/hydration status.	Implement nutrition strategies to minimize the effect of travel on performance include manipulating the timing and composition of meals, the use of caffeine and melatonin, and the development of nutrition and hydration plans for athletes to suit the needs en route and on arrival.
	The new environment/location may not provide the athlete and/or support staff with the resources or opportunities to implement their desired or optimal heat management plan.	Investigate access to adequate ice, water, electrical power, and the feasibility of hydrotherapy precompetition prior to departure. Customize cooling strategies to both the individual and the competition setting, noting that a mixed-methods approach is often practical and preferable.
	Access to infrastructure to undertake heat acclimation (e.g., heat chambers) prior to departure may be challenging for some athletes.	Consider alternate heat acclimation strategies (e.g., hot bath or sauna posttraining) and subsequent nutrition protocols.
	Difficulties in maintaining benefits of heat acclimation due to the logistics and demands of travel, and the nature of decay of adaptations.	Perform heat acclimation as close to departure as possible or on arrival where travel is likely to cause significant decay in adaptations. Consider alternate heat acclimation strategies (e.g., hot bath or sauna posttraining).
Para-sport athletes	Reduced thermoregulatory sweating and cutaneous blood flow in athletes with spinal cord lesions, with greater impairments with higher spinal cord lesions. Amputees have reduced skin surface area to dissipate heat, and additional heat can result from skin interfacing with prostheses and/or prosthetic liners. Reduced thermal perception in some para-sport athletes.	Ensure fluid intake strategies are appropriate and do not promote overhydration. Consider external cooling strategies including keeping skin exposed and damp using spray bottles in hot, dry environments and pre- and per-cooling strategies in hot and humid environments.
	Large volumes of fluid ingestion may be undesired due to the impracticality of managing the toileting requirements needed to excrete excess fluid.	Use a combination of cooling strategies including fluid-based strategies in smaller quantities. Consider the use of high sodium fluids to increase fluid retention and reduce urine production.

cooling/drinking breaks at 30 and 75 min when wet-bulb globe temperature exceeds 32 °C). Teams should be aware of, and able to exploit, opportunities to implement better plans for hydration and heat management.

Endurance and Ultra-Endurance Sports

Endurance (30 min to 4 hr) and ultra-endurance (>4 hr) exercise encompasses a range of exercise modalities, terrain and environments. Sustained elevations in thermal strain during endurance exercise present unique physiological challenges to athletes, including large accumulated fluid and electrolyte deficits (Shirreffs & Sawka, 2011), increased risk of gastrointestinal disturbance during exercise (Costa et al., 2019a), and EHI (Leon & Bouchama, 2015). The unique challenges of endurance sports include the potential for large variations in ambient conditions within an event, as well as increased emphasis on during-event nutrition and hydration strategies due to the continuous nature of most sports. Practical considerations include the availability of nutrition supplies, the logistics of ingestion during exercise, and the interaction with gastrointestinal comfort/function. Endurance athletes can both under- and overconsume fluid during competitive events based on these factors, as well as erroneous calculations of likely sweat losses and misguided aspirations of performance enhancement (Burke et al., 2019). Indeed, the net effect of fluid intake strategies on performance is a complex trade-off between manipulations of physiology and homeostasis, perceptions of comfort and exertion, and the cost of the plan (e.g., time lost in obtaining and consuming fluids). Such issues are unlikely to be solved by conventional research techniques. The ability for endurance athletes to ingest food and fluids is frequently limited by gastrointestinal tolerance, as well as opportunities for consumption. For example, elite male marathon runners may allow less than 60 s to consume nutrition during competition (Beis et al., 2012), and anecdotal reports suggest great difficulty consuming and tolerating ideal fluid intake due to exercise intensity and the required ventilation.

Junior and Adolescent Athletes

Young athletes are typically considered to be at a thermoregulatory disadvantage compared with adults due to lowered sweat rates and higher surface area to body mass ratios. However, more recent reports suggest that when euhydrated and heat-acclimatized, young athletes face similar cardiovascular or thermoregulatory challenges during exercise as adults matched for fitness, hydration, and acclimation status (Bergeron, 2015; Bergeron et al., 2015; Rowland, 2008). Notwithstanding, during the transition from early childhood to late adolescence, it is important to accommodate greater sweat losses and potential increases in thermal strain and EHI risk that accompany physical growth, maturation, and enhanced fitness and athletic/sport skill. As such, combined strategies to manage heat stress in younger athletes may be more effective (e.g., fluid replacement to support evaporative losses and exposure to cool clothing/towels for conduction). Attitudes to fluid intake among young athletes can be dependent on knowledge, education, access to fluids, and opportunities to rehydrate/refuel (Meyer et al., 2012). The extent to which biological sex influences the impact on hydration during exertional heat stress is still unclear, but men may be at greater risk of dehydration due to increases in muscle tissue (and subsequent water content) during adolescence (Meyer et al., 2012; Timmons et al., 2007).

Travel to Compete in Hot and Humid Environments

Travel for competition can add another layer of complexity to the challenge of exertional heat stress. The trip can contribute a range of factors that cause fatigue and suboptimal nutritional/hydration status (Fowler et al., 2016), while the new environment/location may not provide the athlete (or support staff) with the resources or opportunities to implement their desired or optimal heat management plan. Heat acclimation prior to travel for competition in hot and/or humid environments is a commonly employed strategy, particularly among elite and professional athletes. However, there are many complexities involved in implementing an optimal acclimation plan, especially when the athlete is traveling from a cold location to compete in a vastly different environment. Accessing sophisticated resources (e.g., heat chambers) prior to departure may be not feasible for some athletes, and alternate heat acclimation strategies (e.g., hot bath or sauna posttraining) and subsequent nutrition protocols may be required (Saunders et al., 2019). However, even when heat acclimation is achieved, there may be difficulties in maintaining its benefits due to the logistics and demands of travel. The rate of decay of physiological benefits of heat acclimation is reported to be ~2.5% per day without heat exposure (Daanen et al., 2018) and is an important consideration in relation to the travel itinerary (Saunders et al., 2019). The maintenance of heat acclimation adaptations and the adjustment of the athlete's nutrition and hydration strategies to suit the environmental conditions upon arrival is imperative. Real-world competition settings can present logistical challenges for established pre- and per-cooling strategies. The practicalities of providing ice slurries, ice vests, plunge baths, and ice towels at the competition venue must be considered.

Para-Sports

Para-sport athletes are classified by their impairment type (i.e., visual, intellectual, or physical) and compete across a wide range of sports. Several conditions present higher risk of thermal strain than is experienced by able-bodied athletes (Pritchett et al., 2019). Spinal cord injury has received most attention in the sports science literature, as it is associated with complete or partial loss of neural function below the level of injury and a failure to initiate normal thermoregulatory mechanisms like sweating and skin blood flow redistribution. Athletes with spinal cord injuries experience greater increases in core temperature at a given exercise and/or heat load than able-bodied athletes, which is more pronounced with higher spinal cord lesions (Price & Campbell, 1999). Fluid needs are lower due to reduced sweat rates, which along with practicalities around toileting underscores the need for an individualized hydration plan (Pritchett et al., 2019).

Other impairment types also face challenges. For example, 60–80% of people with multiple sclerosis have worsening physical and cognitive symptoms with heat stress (Davis et al., 2010). Athletes with cerebral palsy face increased fatigue and symptomology, likely due to increased metabolic heat production from movement inefficiency (Pritchett et al., 2019). Amputees have reduced skin surface area to dissipate heat, and additional heat can result from skin interfacing with prostheses and/or prosthetic liners (Andrews et al., 2016). Finally, visually impaired athletes may have reduced pace and hydration awareness, a potential challenge in hot conditions (Pritchett et al., 2019). These specific differences underscore the need for individual assessments of heat tolerance, fluid needs, and strategies to manage core temperature in para-sport athletes.

Conclusion

Exercise in the heat is associated with varying levels of thermal stress and potential effects on the health and performance of the athlete. Nutritional strategies before, during, and after exercise can address different aspects of exertional heat stress. These strategies need to be implemented using protocols that are individualized and made practical for the specific needs of the athlete and their event.

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