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HYDRATION AND NUTRITION CONSIDERATIONS FOR ENDURANCE CYCLING EXERCISE IN THE HEAT

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KEY POINTS

- Road cycling is considered one of the most metabolically demanding competitions in endurance sports with daily energy expenditures 4–5 times greater than basal metabolic rates.
- The combination of hypohydration and heat stress observed while cycling for extended durations in warm environments may lead to impairments in cardiovascular function and performance at higher intensities.
- Both hydration status and fuel replenishment may impact endurance exercise performance when exercising in the heat.
- Heat exposure can further exacerbate the increased reliance on carbohydrate as a fuel source during exercise, leading to a reduction in muscle glycogen levels and increased prevalence of fatigue.
- Heat acclimation and proper “gut training” may serve as practical means to maintain fluid balance, preserving plasma volume and protecting cardiovascular function while exercising in the heat.

INTRODUCTION

Cycling races can last from minutes (i.e., time–trial) to several hours, where riders may face a combination of periods of long-duration, moderately intense sections (i.e., peloton), and mountainous conditions with high power outputs and sprints that combine high speeds and power outputs. Road cycling is considered one of the most metabolically demanding competitions in endurance sports, with daily energy expenditures 4–5 times greater than basal metabolic rates, equating to 6,000–8,500 kcals expended during a stage (Areta et al., 2024; Barranco-Gil et al., 2024; Van Hooren et al., 2023). The energetic demand increases metabolic heat production by the contracting muscles, placing additional strain on the thermoregulatory system to maintain core temperature. Sweating is the primary mechanism to reduce core temperature, with average sweat rates during road cycling ranging from 0.5–2.0 L/h (Jay et al., 2024). Without proper fluid intake, combined with long race durations, increased sweat rates can severely impact fluid balance, with studies showing cyclists can lose > 2% body mass (BM) (Armstrong et al., 2015; Sharwood et al., 2004), which has been shown to reduce endurance exercise performance (Cheuvront et al., 2003).

Along with the burden of multi-day stage races covering hundreds of miles, riders also need to contend with unrelenting environmental conditions. During the first stage of 2024 Tour de France, the heat index reached 40°C (104°F). This was following the 2023 tour, in which ambient temperatures exceeded 30°C (86°F) for 5 of the 21 stages. Along with the ambient temperature, reflected radiant heat can also impact riders, with the hottest stage in the 2023 Tour de France reporting road surface temperatures up to 60°C (140°F). As races typically start in the early afternoon, riders regularly compete during the warmest hours of the day. With variable race stages under extreme environmental stressors, it is imperative to understand the physiological changes that occur with cycle exercise in the heat to aid in developing proper hydration and fueling strategies to optimize performance. The aim of this Sports Science Exchange (SSE) article is to provide an overview of the physiological burdens of cycle exercise in the heat, with a primary focus on the impact of fluid balance and metabolism on performance under these conditions. The article provides hydration and nutrition recommendations for cycling in the heat, as well as identifies future considerations for athletes and coaches to optimize cycling performance under extreme environmental heat stress. It will also briefly discuss how heat mitigation strategies (i.e., heat acclimation) and “gut training” promote positive changes in fluid balance and metabolism.

PHYSIOLOGICAL DEMANDS

Fluid Balance

It is generally recognized that the loss of 2% or more in BM leads to significant reductions in endurance exercise capacity and performance (Cheuvront & Kenefick, 2014). A number of physiological alterations due to hypohydration (i.e., a body water deficit greater than normal daily fluctuation) during exercise have been outlined, including the reduction in circulating plasma volume (Sawka et al., 2015), stroke volume (SV) and cardiac output (Q) (Montain & Coyle, 1992), and the increase in body temperature (Sawka et al., 1985), muscle glycogen use (Logan-Sprenger et al., 2012) and perceived exertion (Funnell et al., 2019). When combined with heat stress, the physiological strain on the body is exacerbated, due to the increased competition for the limited blood volume between the central and peripheral circulatory systems (Kenefick et al., 2010), inhibiting the ability of the human body to maintain proper cardiovascular function during prolonged exercise.

The interaction between exercise-induced hypohydration and heat stress while cycling has been characterized through an increase in total peripheral resistance (TPR) and reductions in Q, mean arterial pressure and SV (González-Alonso et al., 1997; Montain & Coyle, 1992), particularly at intensities greater than 60% maximum aerobic capacity (VO_{2max}). TPR (i.e., the resistance in the circulatory system that is used to mediate the flow of blood) has been shown to be 10-17% higher in endurance-trained male cyclists, following 2 hr of continuous moderate-intensity cycling (62–71% VO_{2max}) in a hot environment (35°C, 95°F) when in a ~4.4 - 4.9% BM deficit , as compared to euhydrated (i.e., < ±2% change in total body water) (González-Alonso et al., 1997). Under similar conditions, Montain & Coyle (1992) reported a strong linear correlation between the degree of hypohydration and the observed decline in SV (r = 0.99) following 2 hr of continuous moderate-intensity cycling (62–67% VO_{2max}). González-Alonso et al. (1997) demonstrated that exercise-induced hyperthermia (i.e., body temperature > 40°C, 104°F) and hypohydration separately decreased SV 7–8% (11 mL/beat), but increased heart rate adequately to prevent a significant decrease in Q. However, when exercise-induced hyperthermia and hypohydration were superimposed, the observed reduction in SV was significantly greater (26 mL/beat) and Q was not preserved (-2.8 L/min) (González-Alonso et al., 1997). Watanabe et al. (2020) observed similar reductions in SV (27 mL/beat) and Q (2.1 L/min) in both male and female cyclists following 2 hr of continuous moderate-intensity (50-55% maximum power output) cycling in a hot environment (35°C, 95°F; 50% relative humidity (RH)), and concluded that the observed declines in SV and Q may have been from limitations in venous return and left ventricle filling due to the reduction in total body water. Under normal conditions, an increase in TPR could be used as a countermeasure to moderate blood pressure and oxygen delivery, due to acute changes in plasma volume. However, the significant decrease (~5%) in mean arterial pressure (i.e., the product of Q and TPR) observed by Gonzalez-Alonso et al. (1995, 1997) suggested that exercise-induced hypohydration may limit the body's ability to maintain cardiovascular function, impairing exercise capacity.

Evidence suggests that the physiological changes that occur with ≥ 2% loss in BM may impair cycling performance in warmer temperatures, with decrements being reported for power output, speed (Adams et al., 2018, 2019) and time trial (TT) completion (Funnell et al., 2019). For instance, Adams et al. (2018) reported lower power output and cycling speeds during a 5-km TT following 2 hr of continuous moderate-intensity cycling (55% VO_{2max}) in a hot-dry environment (35°C, 95°F; 30% RH) when male subjects were in a ~2% BM deficit, as compared to euhydrated. Under similar conditions, comparable decrements in cycling performance were reported with male subjects completing a 15 min TT slower (2–18%) after ~3% loss in BM, as compared to euhydrated, following 2 hr of continuous cycling at 50% peak power output (Funnell et al., 2019). Together, these results support the understanding that the combination of hypohydration and heat stress observed while cycling for extended durations in warm environments may lead to impairments in performance at higher intensities. In addition to the physiological changes due to hypohydration, further decrements in performance while cycling for extended durations in warmer environments, may occur through alterations in the sympathetic nervous system and fuel selection.

Metabolic Alterations

Cyclists rely heavily on oxidative metabolism, with energy derived from intramuscular, non-muscular (i.e., blood, liver, adipose) carbohydrate and fat sources (Hargreaves & Spriet, 2020). The primary determinants of substrate use include exercise intensity and duration (Hargreaves & Spriet, 2020; Romijn et al., 1993). At the highest level of competition, athletes regularly compete at higher exercise intensities (80–100% VO_{2max}) even during long duration events, such as endurance cycling (Hargreaves & Spriet, 2020; Hawley & Leckey, 2015; O'Brien et al., 1993). As the energy yield is more efficient than fat, carbohydrate oxidation is heavily relied on during competition, with increased use of carbohydrate muscle glycogen stores (Romijn et al., 1993). However, muscle glycogen stores are finite (i.e., ~1,000-3,000 kcal), and a reduction in muscle glycogen levels leads to an increased prevalence of fatigue and decreased performance (Hargreaves & Spriet, 2020).

Heat exposure can further exacerbate the increased reliance of carbohydrates as a fuel source during exercise. Previous studies have shown an increased respiratory exchange ratio in endurance-trained athletes during cycling exercise in a hot (40°C, 104°F) environment, in comparison to cooler (20°C, 68°F) conditions (Febbraio et al., 1994a, b; Hargreaves et al., 1996), suggesting a greater reliance on carbohydrate use. Greater reliance on carbohydrate use during cycling exercise in the heat may stem from differences in exercise intensity, environmental conditions (e.g., temperature, RH, radiant heat, wind speed) and changes in core/muscle temperature. Specifically, Maunder et al. (2020) reported that, at moderate heat stress (34-35°C, 93-95°F), increases in carbohydrate oxidation were only evident at higher exercise intensities, (~81% VO_{2max}) when compared to cooler conditions (18°C, 64°F). However, when environmental temperature was elevated (40°C, 104°F), both moderate (~69% VO_{2max}) and high intensity exercise (~81% VO_{2max}) increased carbohydrate oxidation, in comparison to cooler conditions (Maunder et al., 2020). In contrast to previous studies (Febbraio et al., 1994a, b; Hargreaves et al., 1996), Charoensap et al. (2023) showed that cycle exercise in the heat led to a decrease in carbohydrate use. However, despite exercising at similar heart rates, power output was also reduced (Charoensap et al., 2023), further solidifying the role of exercise intensity in mediating environment-induced changes in exercise metabolism. Along with environmental temperature and exercise intensity, the increased reliance on carbohydrates during exercise in the heat may be dependent on changes in body core temperature, with 0.5°C or greater increase in body core temperature leading to an increase in carbohydrate use (Febbraio, 2000; Febbraio et al., 1994a). Further, heat-induced dehydration may play a role in substrate utilization. Logan-Sprenger et al. (2012, 2013, 2015) showed that fluid restriction during cycling exercise, causing > 2% BM losses, led to higher rates of carbohydrate oxidation and muscle glycogen use, which coincided with > 0.5°C increases in body core temperature, in comparison to euhydrated conditions.

The greater reliance on carbohydrate utilization during exercise in the heat may be due to alterations in skeletal muscle metabolism. Previous work has shown a decrease in muscle glycogen content in skeletal muscle following exercise in the heat (Febbraio, 2000; Febbraio et al., 1994a; Fink et al., 1975), potentially due to an increase in systemic epinephrine levels (Febbraio et al., 1994). However, despite the increased reliance during exercise, previous reports revealed that muscle glycogen levels are not severely depleted following fatiguing exercise in the heat (Parkin et al., 1999), suggesting substrate availability is not limiting performance under these environmental conditions. Exercise in the heat has also been shown to increase muscle and blood lactate concentration, (Febbraio, 2000; Febbraio et al., 1994a; Fink et al., 1975) and increased muscle inosine monophosphate (IMP) levels at the point of fatigue (Febbraio, 2000; Parkin et al., 1999). An increase in blood lactate concentration would suggest a mismatch between lactate formation via glycogen breakdown and lactate use by the mitochondria (Brooks, 2020). Further, the accumulation of IMP is indicative of decreased flux through the tricarboxylic acid cycle and reduced energy production via mitochondrial oxidative phosphorylation (Sahlin et al., 1990). Previous studies have shown that the efficiency of mitochondria to produce energy is impaired at temperatures over 40°C (104°F) (Brooks et al., 1971; Willis & Jackman, 1994). This is important, as Parkin et al. (1999) showed that fatigue during exercise in the heat coincided with muscle temperatures > 40°C (104°F). Together, these data suggest alterations in muscle substrate metabolism may be responsible for greater whole-body carbohydrate utilization during exercise in the heat, with combined reductions in muscle glycogen stores and reduced mitochondrial energetics, leading to fatigue under these environmental conditions.

FLUID INTAKE RECOMMENDATIONS

To mitigate the physiological changes caused by hypohydration during extended bouts of cycling in the heat, it is imperative to properly replace the fluid and electrolytes lost through sweating. The average whole body sweat rates reported in one study with 255 endurance athletes in warm and humid environments (29°C, 84°F; 56% RH) was ~1.28 L/h, however, some athletes experienced sweat rates of up to 3-4 L/h (Barnes et al., 2019). Moreover, within an individual athlete, this can vary based on exercise intensity, environmental conditions, training/heat acclimation status and clothing (Baker, 2019). In a perfect world, athletes would be able to limit their sweat losses during exercise to less than 2% BM. However, logistical challenges (i.e., carrying sufficient fluid), gastrointestinal (GI) distress and beverage palatability may serve as hurdles in the fluid replacement process (Passe, 2001). Therefore, it is common for endurance athletes to experience gradual involuntary dehydration, finding themselves hypohydrated at the end of competition (Sharwood et al., 2004). Nonetheless, cycling presents a variety of situations in which dehydration is likely to be observed, therefore it is important to consider the proper hydration strategies (i.e., timing, amount, and type) to limit any potential decrements in performance.

To achieve proper hydration, the American College of Sports Medicine (ACSM) suggests athletes consume a fluid volume equivalent to 5–10 mL/kg BM during the 2–4 hr leading up to the exercise session (Thomas et al., 2016). During exercise, it is recommended that athletes consume fluid at a rate that is sufficient to prevent > 2% BM deficit and to avoid overdrinking, leading to body mass gain (Thomas et al., 2016). Inclusion of sodium in a fluid-replacement drink may increase voluntary fluid ingestion through improvements in beverage palatability, which may help athletes maintain plasma volume during bouts of prolonged exercise in the heat (Clapp et al., 2000; Wemple et al., 1997). Interestingly, Wemple et al. (1997) found that beverages containing ≥ 50 mmol/L of sodium decreased palatability and voluntary fluid ingestion, and therefore should be avoided. Previous research has suggested that endurance athletes should consume beverages with sodium concentrations between 30 – 50 mmol/L during prolonged bouts of exercise (i.e., > 3 hr) (Maughan, 1991), however, the amount of sodium that athletes should ingest as part of their rehydration strategy may vary, especially for athletes with high sweat rates > 1.2 L/h or "salty sweaters" (i.e., > 60 mmol/L whole body sweat sodium) (Thomas et al., 2016). Post-exercise, athletes should focus on the consumption of water and sodium at a moderate rate, accounting for additional urinary losses and post-exercise sweat loss (Sawka et al., 2007). For this, the ACSM recommends that athletes consume 1.25–1.5 L/kg of any remaining BM deficit (Thomas et al., 2016). Lastly, the presence of carbohydrates in a sports beverage is important for the stimulation of water absorption in the gut. Previous research has indicated that carbohydrate type (Jentjens et al., 2006; Shi & Passe, 2010) and concentration (Jeukendrup et al., 2009; Murray et al., 1999) can impact fluid absorption. Specifically, the presence of 1–3% carbohydrates in a sports beverage may positively impact the rate of fluid delivery, but fluid delivery may be compromised when > 6% carbohydrate beverages are ingested (Jeukendrup et al., 2009). Once the fluid is absorbed, it is imperative that it is retained in the blood to maintain plasma volume, promoting proper cardiovascular and thermoregulatory function. As such, there are two main ways to promote fluid retention: 1) stimulating renal water reabsorption and 2) slowing the appearance of fluid into the circulatory system. While the former is largely regulated by plasma sodium concentration, the latter can be modified by increasing the energy density of the sports beverage. Several studies have reported that sports beverages containing 6–12% carbohydrates may promote greater fluid retention, following ~2-3% dehydrating exercise, as compared to electrolyte-matched beverages (Baker & Jeukendrup, 2014). However, future research is needed to determine the exact mechanism(s) involved in this interaction. In all, no individual rehydration strategy will be right for all athletes, so differences in environmental conditions, sweat rate, BM and exercise intensity/duration should always be considered (Armstrong, 2021). Moreover, it is important for athletes to experiment with various rehydration strategies during training sessions, prior to use during competition in hot environments. This will provide the athlete time to account for their individual sweat rates, gut tolerance, logistical challenges and need to consume other nutrients (i.e., carbohydrates and electrolytes) to maximize their performance.

NUTRITIONAL CONSIDERATIONS

The benefits of carbohydrate feeding to provide contracting muscles a fuel source have been known since the early 20th century (Krogh & Lindhard, 1920), with seminal studies in the 1980s showing a direct link between carbohydrate ingestion and exercise capacity (Coggan & Coyle, 1987; Coyle et al., 1983). By providing an external (i.e., exogenous) carbohydrate source, internal (i.e., endogenous) carbohydrate sources, such as muscle and liver glycogen, may be preserved and help to provide a constant source of carbohydrates, preventing a drop in blood glucose concentration during competition. Together, this has led to formulation of carbohydrate-containing products aimed to optimize exercise performance, with a variety (i.e., beverages, gels, bars) commercially available to meet the practical needs of a cyclist (Pfeiffer et al., 2012). With endurance cycling events lasting over 1 hr, carbohydrate feeding is critical for performance. The ACSM has recommended that athletes consume 30-60 g carbohydrate/hr (Thomas et al., 2016), basing this guideline on research showing that absorption of single carbohydrate sources in the intestine is limited to ~1 g/min (Jeukendrup, 2014; Jeukendrup & Jentjens, 2000). However, a combination of carbohydrate sources, such as glucose and fructose, which are absorbed separately in the gut via different transporters (i.e., multiple transportable carbohydrates), has been shown to increase exogenous carbohydrate use to > 1 g/min. This has led cyclists to increase carbohydrate intake (> 90 g/h of multiple transportable carbohydrates) during long-duration rides lasting over 4 hr (Jeukendrup, 2014; Stellingwerff & Cox, 2014), with recent data suggesting carbohydrate intake of ~120 g/h of mixed glucose/fructose sources using various product types is tolerable for trained cyclists (Hearris et al., 2022).

While the impact of exercise in the heat on endogenous carbohydrate use is well established, few studies have examined how heat affects exogenous carbohydrate use during exercise. The limited studies have shown that the composition of a carbohydrate drink may impact the availability and use of carbohydrate to fuel cycling exercise in the heat. Jentjens et al. (2002) reported that exogenous glucose oxidation of an 8% glucose beverage was reduced to ~0.7 g/min when cycling in the heat, which was ~10% lower to that seen during a similar cycling bout in cooler conditions. In comparison to single-source carbohydrates, multiple transportable carbohydrates have been shown to increase the use of ingested carbohydrates during cycling in the heat. In a follow-up from their 2002 study, Jentjens et al. (2006) showed that ingesting a 2:1 glucose:fructose beverage increased exogenous carbohydrate oxidation to ~1.14 g/min when cycling in the heat, which was 36% higher than glucose alone. The authors also reported that endogenous carbohydrate use was reduced when a glucose:fructose beverage was provided. Along with the metabolic benefits, ingestion of a multiple transportable carbohydrate beverage may increase fluid absorption, in comparison to a single-source carbohydrate beverage, contributing to an improvement in fluid balance (Jentjens et al., 2006). Together, these studies suggest multiple transportable carbohydrate sources are ideal to fuel cycling performance of well-trained athletes in the heat, with 30-60 g/h ingestion for stages lasting 1-2.5 hr and > 90 g/h, based on individual tolerability of the cyclist, for stages lasting more than 2.5 hr (Coggan & Coyle, 1987; Coyle et al., 1983; Jeukendrup, 2014).

Previous research has indicated that carbohydrate feeding may improve exercise capacity in the heat (Carter et al., 2003, 2005; Pitsiladis & Maughan, 1999). The reason for the improvement in exercise performance does not appear to be metabolic. Specifically, some (Angus et al., 2001; Jentjens et al., 2002) but not all (Yaspelkis & Ivy, 1991) studies have shown that the use of muscle glycogen remains elevated when exercising in the heat, following feeding with 6-8% glucose solution. Further, the benefits of carbohydrates in the heat are apparent during the early stages of exercise (< 1 hr of cycling), a timepoint in which ingested carbohydrates do not influence muscle metabolism. Carter et al. (2003) suggested the benefits of carbohydrate feeding on cycling performance in the heat may be due to the ergogenic effects on the central nervous system (Chambers et al., 2009; Gant et al., 2010). However, the receptors and mechanism of action in the brain that mediate these beneficial effects have not been identified (Jeukendrup, 2014). Interestingly, studies have shown that mouth rinsing with carbohydrates does not influence cycling performance in the heat (Cramer et al., 2015; Watson et al., 2014); therefore, the mechanisms in which carbohydrates improve cycling performance, particularly in bouts < 1 hr in duration, are unclear.

OTHER CONSIDERATIONS

Heat Acclimation

Heat acclimation is developed through repeated exposure to environmental conditions that sufficiently elevate core and skin temperatures, inducing profuse sweating (Périard et al., 2015). The intensity, duration, frequency and number of heat exposures, as well as differences in environmental conditions (i.e., dry vs humid heat), determine the magnitude to which one acclimates (Périard et al., 2015). It is widely accepted that heat acclimation improves thermoregulation by increasing sweat rate, decreasing sweat sodium concentrations and initiating sweating at lower core temperatures (Nielsen et al., 1997; Roberts et al., 1977; Sawka et al., 2011; Taylor, 2014). To sustain the elevated sweat rates, previous studies have suggested that the eccrine sweat glands become more resistant to fatigue (Périard et al., 2015) and total body water stores are increased by ~5-7% (Patterson et al., 2014; Wyndham et al., 1968). Previous research has indicated that heat acclimation training improves VO_{2max}, Q, and TT performance in endurance-trained male cyclists (Nielsen et al., 1993; Périard et al., 2024; Sekiguchi et al., 2022). While the changes in Q may stem from an increase in aldosterone production (Nielsen et al., 1993), the gains in performance metrics may partly be attributed to the improvement in metabolism (Young et al., 1985). Specifically, studies have reported altered whole-body (Sawka et al., 1996) and skeletal muscle metabolism (Young et al., 1985) via reductions in muscle glycogen utilization (King et al., 1985; Kirwan et al., 1987) and oxygen uptake during submaximal exercise (Sawka et al., 1983). Further, previous studies have reported a reduction in blood and muscle lactate accumulation during exercise at ~70% VO_{2max} (Febbraio et al., 1994a) and an increase in power output at lactate threshold following a 10-day heat acclimation program in trained cyclists (Lorenzo et al., 2010). In all, the adaptations observed after acclimating to the heat may lead to reduced physiological strain and improvements in comfort and performance during prolonged bouts of exercise in warm environments.

Gut Training

Consuming the amount of fluid and carbohydrates required for proper hydration and fueling may cause GI discomfort and distress, especially when combined with high intensity or prolonged exercise in warm environments (Neufer et al., 1989). To better handle the stress caused by increased fluid and carbohydrate intake, it has been suggested that athletes participate in so called "gut training" to improve gastric emptying and absorption of high carbohydrate and/or fluid loads, leading to reduced GI problems (Jeukendrup, 2017). Previous studies investigating carbohydrate "gut training" have shown similar effects on gastric emptying rate despite differences in amount and duration of the training period (Cox et al., 2010; Horowitz et al., 1996). Horowitz et al. (1996) reported that the supplementation of 440 g glucose/day for 4–7 days significantly accelerated gastric emptying for both glucose and fructose in untrained subjects. Moreover, when investigating the effects of long-term (28-day) carbohydrate supplementation, Cox et al. (2010) reported improved exogenous carbohydrate oxidation rates in endurance-trained cyclists who consumed an additional 1.5 g carbohydrate/kg BM for every hour of exercise completed each day (~8.5 $g \cdot kg^{-1} \cdot day^{-1}$). Together, these results suggest that proper "gut training" may allow endurance athletes to consume sports beverages with higher carbohydrate concentrations, optimizing intestinal fluid and carbohydrate absorption. However, the impact of gut training on fluid and carbohydrate reabsorption during exercise in the heat is unclear and requires future investigation.

KNOWLEDGE GAPS

Despite the known physiological impact of exercise in the heat and potential strategies to minimize the detrimental effects, several research questions remain to optimize cycling performance under these environmental conditions. Previous research has suggested that increasing the carbohydrate content of the beverage may improve fluid retention due to slower gastric emptying, however, future research is needed to determine the exact mechanism(s) involved in this interaction. While recent research suggests, if tolerable, that carbohydrate loads > 90 g/h may be used during prolonged cycling bouts (> 2.5 hr), the impact of carbohydrate amount and type (i.e., beverage, gels, bars) on exercise performance and GI distress in the heat is unknown. Finally, further studies are needed to understand the mechanism(s) that link carbohydrate intake to improved performance in the heat, in bouts lasting less than 1 hr.

SUMMARY

Environmental heat exposure can negatively impact fluid balance and fuel utilization in cyclists, severely impairing performance. However, with proper hydration and optimal carbohydrate feeding strategies, the impacts of extreme heat can be minimized. Further, training strategies, such as heat acclimation and "gut training", allow the cyclist to withstand the stress of environmental heat exposure and the higher fluid and fuel requirements, respectively, to further enhance performance. Collectively, by understanding the physiological impact of heat exposure on athletic performance, cyclists and their coaches can optimize personalized fueling and training strategies to meet the individual needs during races under extreme heat conditions.

PRACTICAL APPLICATIONS

- While some dehydration is expected, endurance athletes should aim to consume a sufficient amount of an electrolyte-containing sports beverage to limit body mass deficits to < 2%, especially when exercising in warm environments.
- Athletes should aim to consume 1.25–1.5 L/kg of any remaining body mass deficit of an electrolyte-containing beverage at a moderate rate post-exercise to restore euhydration.
- No individual rehydration strategy will be right for all athletes, so athletes should experiment with various rehydration strategies during training sessions, prior to use during competition in hot environments.
- To maximize performance, endurance cyclists should consume a combination of multiple transportable carbohydrate sources at a rate of 30–60 g/h for stages lasting 1–2.5 hr and > 90 g/h for stages lasting > 2.5 hr.
- With proper "gut training" carbohydrate intakes of 120 g/h of mixed glucose/fructose sources using various product types may be tolerable in well-trained cyclists.

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