Dehydration, Hyperthermia, and Athletes: Science and Practice

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Objective: To present the recent research that underscores the value of preventing both dehydration and hyperthermia. Such efforts will improve the athlete's capacity to perform physical activity and reduce the risk of heat-related problems.

Data Sources: Data were drawn from an extensive review of the scientific literature over the past 50 years with an emphasis on recent research (>1990) that focuses on the physiological and performance benefits of fluid replacement.

Data Synthesis: Even low levels of dehydration (eg, less than a 2% loss of body weight) impair cardiovascular and thermoregulatory response and reduce the capacity for exercise. Heat exposure also reduces the athlete's ability to train and compete, an effect that can be independent of hydration status. Even if athletes are well hydrated, hot weather alone will reduce their capacity to exercise. Optimal performance is possible only when dehydration and hyperthermia are minimized by ingesting ample volumes of fluid during exercise and by taking common-sense precautions in keeping cool. Recent research has demonstrated that consuming fluid in volumes approximating sweat loss maintains important physiological functions and significantly improves exercise performance, even during exercise lasting only 1 hour. Carbohydrate ingestion also improves exercise performance, an effect that is independent of, and additive to, preventing dehydration.

Conclusion/Application: Athletes should follow an aggressive fluid replacement and temperature regulation regimen. Successful implementation of this regimen requires that athletic trainers, coaches, athletes, and support personnel are made aware of the benefits of adequate fluid replacement, that appropriate fluid replacement strategies are developed and implemented, that athletes have the opportunity to train themselves to ingest larger volumes of fluid more frequently, and that other practical steps are taken to keep athletes cool during both training and competition.

Key Words: dehydration, hyperthermia, exercise performance, heat illness, sports drinks

An increase in body temperature and the onset of sweating are two normal responses to physical activity. However, the dehydration and hyperthermia that often accompany sports training and competition are perhaps the most common and most preventable causes of premature fatigue among athletes. Dehydration often contributes to hyperthermia by reducing the body's capacity for heat loss, and even low levels of dehydration can impair performance.[35]

Although overheated athletes are often dehydrated, dehydration is not necessarily a prerequisite for hyperthermia; it is possible—but far less likely—for hyperthermia to occur even in well-hydrated athletes. Regardless of the manner in which hyperthermia develops, it is now more apparent than ever that it is in the best interest of the athlete's health and performance to take steps to prevent dehydration and limit the rise in core temperature that naturally occurs during exercise.

DEHYDRATION AND HYPERTHERMIA: PHYSIOLOGICAL CONSEQUENCES FOR PERFORMANCE AND HEALTH

When body temperature rises too high, performance is reduced, an impairment that can be caused by both central and peripheral factors. For example, exercise in the heat increases the use of muscle glycogen,[9,10] potentially hastening fatigue. Increases in body temperature can also result in premature fatigue, ostensibly due to the effect of increased temperature upon brain function.[22] The negative impact of increased core temperature upon brain and nervous system function, although not well understood, can occur independent of decrements in peripheral responses such as muscle blood flow and metabolism.

"The ultimate cause for the exhaustion in the severely hyperthermic condition may be due to an effect of heat stress on brain function. The central nervous system and mental functions are susceptible to high temperatures, as can be observed in the dizziness and confused behavior of heat-stressed subjects in long distance sports events... it may be that core temperatures >39°C (102.2°F) reduce the function of motor centers and the ability to recruit motor units required for the activity, perhaps via an effect on the 'motivation' for motor performance."[22]

The performance consequences of this "central inhibition" have been demonstrated by Febbraio et al[9] who required subjects to cycle to exhaustion at three different ambient temperatures. At the coolest temperature (37°F), subjects exercised for 95 ± 10 minutes before fatiguing. When exposed to moderate temperature (68°F), fatigue occurred at 75 ± 12 minutes. At 104°F, subjects were only able to exercise for 33 ± 3 minutes, their high core temperatures resulting in reduced performance capacity. Interestingly, the subjects had plenty of muscle glycogen remaining and no metabolic perturbations were noted. The likely cause of fatigue was central inhibition due to high body temperatures.

PROTECTING PHYSIOLOGICAL FUNCTION AND PERFORMANCE

Sweating is a thermoregulatory response for which there is no substitute in terms of the quantity of heat that can be lost by

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evaporative cooling. The evaporation of 1 gram of sweat from the skin liberates approximately 0.58 kcal of heat, allowing for large rates of heat transfer to the environment. During light physical activity in a cool and dry environment, sweat loss can be as little as 250 mL/h; in a hot and humid environment, the sweat rate of a well-acclimated, physically fit athlete can be in excess of 2,500 mL/h.[29] The high sweat rates that are needed to sustain heat loss during vigorous exercise inevitably lead to dehydration unless fluid is ingested to match the volume of sweat lost.

Dehydration in athletes is most often produced by the inadequate replacement of sweat loss during and following training and competition. During exercise, one of the most-important benefits of fluid intake is to prevent the additional rise in body temperature that accompanies even low levels of dehydration.[17] Unfortunately, dehydration occurs frequently during physical activity, because humans rarely ingest enough fluid to match their sweat loss, even when fluid is readily available. The voluntary ingestion of fluid during physical activity can result in wide ranges of fluid intake, but generally approximates only 50% of sweat loss, even on those occasions when fluid is conveniently available.[7,15,24] This "voluntary dehydration" was recognized long ago and has been well characterized by researchers since then.[12,27]

"In the course of experiments in both the desert and the hot room, we found that men failed to replace by ingestion all of the water they lost by sweating, even when adequate supplies of drinking water were available. In some cases this failure to maintain water balance resulted in considerable dehydration, even approaching dehydration exhaustion."[27]

The dehydration that inevitably results from inadequate fluid intake causes an inevitable deterioration in cardiovascular and thermoregulatory responses, the details of which may be found in the Table. (For more-detailed reviews, see References 15, 19, 20, 28, and 29.)

Physiological Responses to Dehydration[18]

Gastric emptying rate	Decreased
Incidence of gastrointestinal distress	Increased
Splanchnic and renal blood flow	Decreased
Plasma volume	Decreased
Plasma osmolality	Increased
Blood viscosity	Increased
Central blood volume	Decreased
Central venous pressure	Decreased
Cardiac filling pressure	Decreased
Heart rate	Increased
Stroke volume	Decreased
Cardiac output	Decreased
Sweat rate at a given core temperature	Decreased
Core temperature at which sweating begins	Increased
Maximal sweat rate	Decreased
Skin blood flow at a given core temperature	Decreased
Core temperature at which skin blood flow increases	Increased
Maximal skin blood flow	Decreased
Core temperature at a given exercise intensity	Increased
Muscle glycogen use	Increased
Endurance performance (simulated races)	Decreased
Endurance capacity (exercise to exhaustion)	Decreased

The deterioration in thermoregulatory function that accompanies dehydration markedly increases the risk of heat-related problems. The least serious of these disorders is *heat syncope*, which is likely related to acute cutaneous vasodilatation and a concomitant drop in central venous pressure. Although the symptoms of heat illness can vary widely among individuals, *heat exhaustion* due to dehydration is often evidenced by irritability, sudden fatigue, and lightheadedness, with nausea and headache also possible. Skin color is often pale with normal-to-profuse sweating. *Heat stroke* is characterized by high core temperature, reddened skin, and normal-to-profuse sweating. Severe heat stroke is characterized by central nervous system dysfunction (eg, loss of motor coordination, delirium), and, in the most serious cases, loss of consciousness leading to coma. In these circumstances, sweating may be minimal or absent. The "classical" form of heat stroke that often occurs during summer heat waves primarily affects older adults, particularly those suffering from illness or disease. The victims of exercise-induced heat stroke are often young, healthy, competitively minded males who overextend themselves during intense training and competition in warm weather.[4] All forms of heat illness are usually responsive to aggressive fluid replacement (oral or intravenous), with severe hyperthermia treated most effectively by immersing the victim in an ice or cool-water bath for as little as 15 to 20 minutes, making certain that core temperature does not drop below 37°C.[23] Because heat stroke is a life-threatening disorder, the best approach is to use whatever cooling method is available (ice baths, fans, alcohol rinses, ice packs, etc) to reduce core temperature quickly.

THE GOAL: FULLY REPLACE SWEAT LOSS DURING EXERCISE

There is no evidence that humans can adapt to chronic dehydration.[28] Therefore, the only way to avoid dehydration during exercise is by ingesting adequate amounts of fluid. In terms of protecting health and maximizing performance, there is no alternative.

In the 1930s and 1940s, scientists became interested in assessing the ability of soldiers to withstand the stress of physical activity in the desert. The fluid intake patterns of the soldiers were a matter of particular interest, because the importance of evaporative cooling was well appreciated. The researchers quickly realized that the large sweat rates required for evaporative cooling necessitated fluid intakes often in excess of 10 L/d, in contrast to the 2 to 3 L/d fluid intake that is typical in a temperate environment.[1]

More recently, scientists have studied the physiological effects of ingesting fluid to determine the extent to which the volume of ingested fluid affects physiological response. The work by Montain and Coyle[17] has demonstrated the physiological advantages associated with attempting to closely match sweat loss with fluid intake. In their study, subjects exercised in the heat for 2 hours on four separate occasions. On one trial, subjects ingested no fluid and lost about 4% of their body weight. During the other trials, the subjects periodically ingested enough fluid to replace 20%, 50%, or 80% of their sweat loss, resulting in dehydration of 3%, 2%, and 1% of body weight, respectively.

"We found that the magnitude of increase in core temperature and heart rate and the decline in stroke volume were directly related to the body weight loss (and thus dehydration accrued) during exercise. Thus, when subjects exercise at 62% to 67% $\dot{V}O_2$max under the present environmental conditions (33°C dry bulb, 50% relative humidity, wind speed 2.5 m/sec), the optimal rate of fluid ingestion to attenuate hyperthermia and cardiovascular drift is the rate that most closely matches fluid loss through sweating, at least until the rate of fluid ingestion replaces 81% of sweat loss."[17]

In the Montain and Coyle[17] study, fluid ingestion reduced the rise in body temperature by promoting higher skin blood flow. The greatest rates of skin blood flow occurred when the largest volumes of fluid were ingested during exercise.[17]

The physiological mechanisms by which fluid ingestion attenuates the rise in core temperature may include maintenance of a greater plasma volume, reduction in plasma osmolality and sodium concentration, and a blunting of the rise in catecholamines that occurs with dehydration, all of which might provide a signal for sustained skin blood flow.[19] Future research will likely elucidate the primary mechanisms by which adequate fluid intake exerts its positive thermoregulatory effects. Nonetheless, ingesting fluid in proportion to sweat loss best maintains cardiovascular function and prevents body temperature from rising too high. Montain and Coyle[17] concluded that the optimal rate of fluid replacement is the rate that most closely matches sweat loss.

The research of Walsh et al[35] underscores the performance-related value inherent in avoiding even slight dehydration. Subjects in this experiment were dehydrated by only −1.8% of body weight with 60 minutes of exercise before cycling to exhaustion at 90% $\dot{V}O_2$max. When dehydration was prevented by fluid consumption during the 60-minute exercise bout, the subjects cycled for nearly 10 minutes. With dehydration, the subjects lasted only about 6 minutes. The authors concluded that the goal of fluid ingestion should be to fully replace sweat and urine losses.[35]

The benefits of preventing dehydration have been recognized in the 1996 position stand of the American College of Sports Medicine, "Exercise and Fluid Replacement."[2] The American College of Sports Medicine (ACSM) recommendations read, "During exercise, athletes should start drinking early and at regular intervals in an attempt to consume fluids at a rate sufficient to replace all the water lost through sweating, or consume the maximal amount that can be tolerated."[2]

The ACSM guidelines also recommend that fluids be cool and flavored to enhance palatability and increase voluntary fluid intake, contain carbohydrate to enhance performance, and include sodium chloride to promote rehydration.[2]

Moreover, peak performance during exercise in the heat requires the provision of fluid *and* carbohydrate. This conclusion was illustrated by Below et al.[5] In their study, subjects cycled for 50 minutes at 80% $\dot{V}O_2$max before completing a "sprint to the finish" that required about 10 to 12 minutes. The main finding of their study was that both fluid replacement and carbohydrate ingestion improved high-intensity cycling performance. Performance was improved by about 6% when subjects ingested either a large volume of fluid (replacing 80% vs 13% of fluid losses) and when they consumed 79 ± 4 g of carbohydrate compared to 0 g. When dehydration was prevented and carbohydrate was ingested (by consumption of a sports drink), the benefits were additive, resulting in a 12% improvement in performance.[5]

TIMING OF FLUID INTAKE IS ALSO IMPORTANT

Cardiovascular and thermoregulatory responses are also influenced by the *timing* of fluid ingestion.[16] In a study designed to assess the effects of the timing of fluid intake, subjects ingested 1,183 mL of a sports drink (~43% of predicted sweat rate during 140 minutes of cycling exercise) at the onset of exercise, or in a bolus at 40 or 80 minutes of exercise, or at 15-minute intervals throughout exercise. This protocol resulted in similar dehydration in each trial (−2.9% body weight). In all trials, drinking attenuated the increase in serum osmolality and sodium concentration, increased forearm blood flow, maintained blood volume, and reduced the rate of heat storage. When the fluid was ingested in one large bolus at 0, 40, or 80 minutes, the aforementioned changes were transient, lasting about 40 minutes postingestion. There were no differences in ratings of perceived exertion among the 0-, 40-, and 80-minute trials. When fluid was ingested at 15-minute intervals throughout exercise, the mean values at 140 minutes for esophageal temperature, rectal temperature, heart rate, and rating of perceived exertion were all lower than when fluid was ingested at 80 minutes; the only statistically significant difference was with rectal temperature. Brown[8] reported similar findings for heart rate and rectal temperature when water was ingested at regular intervals throughout 165 minutes of exercise rather than waiting until 135 minutes to drink.

Montain and Coyle[16] hypothesized that a possible advantage of drinking at regular intervals is that the act of drinking stimulates heat loss by maintaining sweat rate. For example, sweating is known to increase almost immediately following drinking in dehydrated subjects.[31] From a practical standpoint, these data indicate that ingesting ample volumes of fluid at regular intervals during exercise appears to confer "optimal" physiological response; similarly positive—but transitory—responses can be provoked by ingesting a relatively large bolus of fluid. This latter knowledge may be valuable for those circumstances when it is not possible to ingest fluid at regular intervals during physical activity (eg, during a soccer match).

Glycerol ingestion has been touted as a possible method of hyperhydrating before exercise in an attempt to provide a cardiovascular and thermoregulatory advantage during exercise in the heat. Ingestion of glycerol solutions before exercise results in a reduction in urine production and the retention of fluid.[26] This transient state of hyperhydration is provoked by the lingering osmotic effect of the glycerol molecules, which are cleared slowly from the body water. Glycerol ingestion increases the osmolality of the blood and most other body fluid compartments (the aqueous humor and the cerebral-spinal fluid being two notable exceptions), prompting a temporary reduction in urine production.

The weight gain that goes hand-in-hand with glycerol ingestion may be particularly problematic for most athletes who pay a metabolic—and perhaps a performance—cost for carrying extra body weight. All things considered, it is unwise to recommend this practice to athletes, in part because the side effects of ingesting glycerol can range from mild sensations of bloating and lightheadedness to more-severe symptoms of headaches, dizziness, nausea, and vomiting.[18]

OTHER CONSIDERATIONS: BEVERAGE PALATABILITY, GASTRIC EMPTYING, AND INTESTINAL ABSORPTION

In addition to the volume and timing of fluid intake, other factors contribute to optimizing the effects of fluid consumption. For example, beverage palatability can be a key determinant of the volume of fluid exercising subjects voluntarily ingest.[6,12,13,33] Temperature, perceived sweetness, flavor type and intensity, tartness, and feel inside the mouth are all characteristics of beverages that, when altered, can influence voluntary fluid intake.[6,12,13]

The gastric emptying characteristics of a beverage must also be taken into consideration, because slow gastric emptying "traps" fluid in the stomach, reducing the rate at which fluid can be emptied into the duodenum and made available for absorption through the intestinal epithelium into the bloodstream.[14] Carbohydrate-electrolyte beverages containing up to about 6% carbohydrate (CHO) (ie, 60 g of CHO/L) have been shown to empty from the stomach at rates similar to water during rest and exercise.[20,21] Beverages containing 8% carbohydrate exhibit gastric-emptying rates slower than water,[3] an indication that the "threshold" for reduced gastric emptying lies just above 6% to 7% carbohydrate, at least for beverages containing multiple types of carbohydrate. Dehydration, perhaps in concert with high core temperature, appears to reduce gastric emptying rate[21,25] and increases the risk of gastrointestinal distress.[25]

Assuring rapid fluid absorption across the intestinal mucosa requires the ingestion of carbohydrate (in the form of glucose, sucrose, or corn-syrup solids) and the presence of ample amounts of sodium in the intestinal lumen.[30] As has been known since the 1950s, glucose and sodium are actively cotransported across the intestinal epithelium, establishing an osmotic gradient for water absorption.[30] Once again, carbohydrate concentrations up to 6% appear to maximize the rate of water and solute absorption in the proximal small intestine.[11,32] Combinations of sucrose, glucose, fructose, and maltodextrins appear to promote similar rates of water flux, provided that the fructose and maltodextrin concentrations do not predominate.[11,32]

There are, of course, intraindividual variations in the perceptions of beverage palatability and in the rates of gastric emptying and intestinal absorption. For this reason, the "ideal" fluid replacement beverage must be determined on an individual basis, with the goal of selecting a drink that: 1) tastes good *during exercise* (to help assure adequate fluid intake), 2) is emptied rapidly from the stomach (to reduce the risk of gastrointestinal distress and optimize fluid absorption), and 3) is absorbed rapidly from the small intestine (to reduce the risk of gastrointestinal distress and assure rapid entry of fluid and carbohydrate into the bloodstream).

PRACTICAL RECOMMENDATIONS: KEEPING ATHLETES COOL

A number of practical steps can be taken to help athletes stay well hydrated and adequately nourished during training and competition. For example, a good base of aerobic training should be an integral part of an early season training program, because increased fitness helps increase the athlete's ability to train and compete in warm environments. Acclimatization is also an essential part of preparing athletes for training and competing in the heat. At least 1 to 2 weeks of training in the heat (for 60 to 90 minutes per day) are required to provoke the physiological benefits associated with acclimatization. However, even highly fit, well acclimated athletes will have difficulty coping with exercise in the heat if they become dehydrated. For this reason, make certain that athletes have easy access to cold fluids during training and competition.

Other steps that can be taken to help athletes better cope with the demands of exercise in the heat include reducing the intensity of training on warm days, extending the length of rest breaks to allow additional time for cooling as well as for fluid and carbohydrate intake, and reducing the intensity and duration of the warm-up to help prevent body temperature from rising too high too quickly. It is also wise to take advantage of the cooling effects of shade. Alternatively, electric fans can be used to help cool athletes during breaks. Minimizing the amount of equipment worn during practice can markedly increase heat loss during exercise. This is especially true with headgear which should be removed whenever possible. Finally, when the environmental conditions are particularly adverse, practice should be cancelled or, at a minimum, the amount of high-intensity exercise (eg, sprints) should be curtailed.

PRACTICAL RECOMMENDATIONS: KEEPING ATHLETES HYDRATED

The ACSM guidelines[2] recommend that athletes ingest about 500 mL (~17 oz) of fluid 2 hours before exercise to help assure adequate hydration. On particularly hot days, it would be wise for athletes to drink an additional 250 to 500 mL (8 to 17 oz) of fluid (sports drink, fruit juice, water) 30 to 60 minutes before exercise.

Athletes should be educated to pay attention to the color and volume of their urine. Within 60 minutes of exercise, passing a light-colored urine of normal to above-normal volume is a good indicator of adequate hydration. If the urine is dark yellow in color, is of small volume, and has a strong odor, the athlete should continue drinking. Ingesting vitamin supplements often results in a dark-yellow urine, so urine color, volume, and odor must all be considered as indicators of hydration status.

Educating coaches and parents about the absolute necessity of keeping well hydrated can help underscore this message with athletes. Similarly, it is important to make it easy for athletes to drink whenever they desire by taking steps to keep cool, flavored fluid conveniently available at all times.[2] Athletes should be given the necessary instruction and ample opportunity to practice drinking during training with the goal of trying to match fluid intake with sweat loss as closely as is practically possible.[2,17,35] During training sessions in warm environments, coaches must allow athletes the opportunity to ingest fluid at 10- to 20-minute intervals. Recording pre-exercise and postexercise body weights is an easy way to remind athletes of the importance of minimizing dehydration and to identify those athletes who are predisposed to large weight deficits. Both proper hydration and carbohydrate intake improve performance, and ingestion of carbohydrate and water in combination (eg, a sports drink) provides an additive performance benefit.

Rapid and complete rehydration requires that athletes ingest both fluid and sodium chloride. During one-a-day training sessions, athletes usually have ample opportunity to consume the needed fluid and salt. However, during two-a-day practices or day-long bouts of competition (eg, wrestling, gymnastics, track and field, etc), special attention should be paid to assure that athletes ingest ample fluid and salt, either from sports drinks or food. Athletes should also be encouraged to take their time during meals; those who rush through their meals lose an important chance to rehydrate.

Even under the best of circumstances, 24 hours will be needed to fully restore the muscle glycogen that is used during just two hours of hard exercise. To accomplish this important goal, athletes should ingest 3.5 to 4.5 grams of carbohydrate per pound of body weight each day.[34]

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