Dehydration, Rehydration, and Exercise in the Heat: Rehydration Strategies for Athletic Competition

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Abstract/Résumé

Exercise capacity and exercise performance are reduced when the ambient temperature is high. This has mainly been attributed to the large sweat losses which lead to hypohydration, a failure of thermoregulation, and eventually circulatory collapse. Exercising athletes rarely drink enough before or during exercise to replace the ongoing fluid losses, especially in hot conditions. In order to combat dehydration, hyperthermia, and impending circulatory collapse, athletes should drink fluids before, during, and after exercise. Preexercise strategies include attempts to maintain euhydration but also to hyperhydrate. Hyperhydration is relatively easy to achieve, but thermoregulatory benefits during prolonged exercise have not been observed in comparison to euhydration. In prolonged continuous exercise, fluid and carbohydrate (CHO) ingestion has clearly been shown to improve performance, but the evidence is not so clear for high-intensity intermittent exercise over a prolonged period. The general consensus is that fluid ingestion should match sweat losses during exercise and that the drink should contain CHO and electrolytes to assist water transport in the intestine and to improve palatability. Postexercise rehydration is essential when the strategies adopted before or during exercise have not been effective. The best postexercise rehydration strategy would be to ingest a large volume of a beverage that contains a CHO source and a high sodium content.

La capacité de travail et la performance physique sont réduites quand la température ambiante est élevée. Cette baisse dépend surtout de l'importance perte de sueur entraînant une hypohydratation, une panne de la thermorégulation et, ultimement, une défaillance de la circulation. Les athlètes à l'effort ne boivent généralement pas assez avant ou durant

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l'epreuve pour couvrir les pertes de liquide et c'est particulièrement le cas par temps chaud. Pour contrer la déshydratation, l'hyperthermie et la menace d'une défaillance de la circulation, il faut incorporer des stratégies d'hydratation avant, pendant et après l'effort physique. Avant l'exercice, il faut tendre vers l'euhydratation et même l'hyperhydratation. Il est relativement aisé de s'hyperhydrater mais, comparativement à l'euhydratation, les bénéfices thermorégulateurs n'ont pas encore été établis. Il est cependant bien établi, qu'au cours d'un exercice prolongé, l'ingestion de liquide et d'hydrates de carbone (CHO) contribue à l'amélioration de la performance mais, au cours d'un intense effort intermittent, la démonstration n'est pas encore faite. Le consensus est à l'effet qu'il faut apparier les pertes de sueur à l'effort par l'ingestion de liquide contenant des CHO et des électrolytes pour donner plus de saveur au breuvage et faciliter le transport de l'eau dans l'intestin. L'hydratation post-exercice est essentielle si les stratégies d'hydratation avant et durant l'effort n'ont pas été suffisamment suivies. La meilleure boisson à prendre après l'effort devrait contenir beaucoup de liquide, des CHO, et de sodium.

Exercise and Environmental Heat Stress

Major sporting events are now commonly staged in hot environments and this has led to an increased awareness of the effects of dehydration on thermoregulation, cardiovascular function, and exercise performance. Fatigue during prolonged moderate intensity exercise is typically attributed to a depletion of muscle glycogen stores (Bergstrom and Hultman, 1967). However, when the ambient temperature is high (30–40 °C), muscle glycogen stores do not become fully depleted at exhaustion when the exercise intensity is moderate (Febbraio et al., 1996), and total carbohydrate (CHO) oxidation is less (Galloway and Maughan, 1997) than when exercise is performed in cool or moderate temperatures (5–20 °C). These recent findings, combined with others which have shown decreases in performance with moderate dehydration (Armstrong et al., 1985), and which have associated the onset of fatigue with a critical core temperature (Nielsen et al., 1990), have highlighted the importance of rehydration to combat the effects of dehydration and improve thermoregulation.

An effective rehydration strategy can mean the difference between life and death. More commonly, however, it will be the difference between completing a period of prolonged exercise in the heat or failing to cross the finish line or complete the match due to a failure in thermoregulation or to circulatory collapse. So important is fluid ingestion before, during, and after exercise that a huge amount of research has been conducted in this field and the data are summarised in a number of excellent recent reviews (Burke and Hawley, 1997; Coyle and Hamilton, 1990; Horswill, 1998; Maughan, 1997; Noakes, 1993; Shi and Gisolfi, 1998; Tsintzas and Williams, 1998). It is not the purpose of this brief review to cover the content of all of these scientific reviews, but it will highlight the factors that are important when considering rehydration strategies for competition.

VOLUNTARY DEHYDRATION

In practical terms, the fluid requirements of an exercising athlete are rarely met through voluntary intake of fluid. Therefore a progressive dehydration will occur throughout exercise in most environmental temperatures regardless of the duration or mode of exercise (Noakes, 1993). An inadequate fluid intake is linked to a number of factors including individual rates of gastric emptying, poor thirst responses, palatability of fluids to be ingested, and whether the athlete is aware of the need for fluid ingestion. However, even when the modifiable factors such as palatability of fluids and awareness on the part of athletes have been addressed, it is still uncommon to find athletes who routinely drink enough fluids to keep from becoming dehydrated to a significant degree (2–3%) during exercise in moderate or hot environments (20–30 °C). This inability to ingest sufficient fluid when beverages are provided ad libitum indicates that preexercise hydration strategies are crucial to ensure that euhydration is achieved before exercise and that performance may be optimized.

Preexercise Hydration

In spite of continuing efforts to educate athletes about the negative effects of dehydration, it is still common for some to begin their events in a hypohydrated condition. This increases their risk of developing severe dehydration and heat illness especially when exercising in a hot environment. Clearly the aim of all athletes who are to train or compete in any environment should be to begin exercise in a euhydrated condition.

Guidelines for achieving euhydration before exercise have been published by the American College of Sports Medicine in their latest position stand on exercise and fluid replacement (1996). The ACSM suggests that 400–600 ml of fluid should be ingested 2 hours before exercise to ensure euhydration. This 2-hour period is sufficient to ensure that excess body water is excreted in the form of urine prior to exercise. The ACSM position stand does not recommend whether this volume should be increased when the ambient temperature is high, nor does it indicate the preferred composition of the ingested fluid. An increase in the volume of fluid ingested may possibly compensate for the ongoing fluid losses that will occur through sweating in the 2 hours prior to exercise. Ingestion of a CHO/electrolyte solution may be preferable to water in that it may allow the body to retain more fluid. The literature on fluid provision before and during exercise indicates that this practice of ingesting approximately 500 ml water or CHO/electrolyte solution 2 hours before exercise is still not common, but it is essential for any well-controlled study examining rehydration strategies during exercise.

Recent research has taken the preexercise hydration strategy one step further and has examined whether it is possible to hyperhydrate prior to exercise in the heat. The potential advantages this may confer on an athlete exercising in the heat include a delay in dehydration, a smaller rise in core temperature and heart rate, and an improvement in performance.

To date there is insufficient evidence of a beneficial effect to warrant widespread use of hyperhydration strategies. Many studies have examined hyperhydration using a variety of methods in an attempt to increase, and maintain an increase in, total body water. The main methods have included water ingestion alone (Greenleaf and Castle, 1971), water and glycerol ingestion (Freund et al., 1995; Lyons et al., 1990; Riedesel et al., 1987), saline ingestion (Barr et al., 1991), saline infusion (Castellani et al., 1998), and use of plasma volume expanders such as Dextran (Luetkemeier and Thomas, 1994). Of these methods, it appears the most successful and practical for maintaining an increase in total body water is combined glycerol and water ingestion.

Several other studies have examined the effects of glycerol and water ingestion before or during exercise (Gleeson et al., 1986; Maughan and Gleeson, 1988; Miller et al., 1983; Murray et al., 1991). Some of these studies have administered small water volumes and small amounts of glycerol while others have given large amounts of glycerol in small volumes, presumably with more interest in the effects of glycerol as a metabolic substrate during exercise than with regard to hyperhydration and potential benefits on thermoregulation and fluid balance. These studies, however, may prove useful in identifying whether glycerol addition to ingested fluids during exercise is beneficial.

Of the studies specifically addressing glycerol hyperhydration, that of Freund et al. (1995) has been the most recent to clearly show that glycerol and water ingestion can increase, and maintain an increase in, total body water above that of water alone. Freund et al. observed an increase in total body water of approximately 1 L of fluid maintained over a 3-hour period. Using a similar hyperhydration protocol, two studies from the same laboratory (Lyons et al., 1990; Riedesel et al., 1987) had previously observed that hyperhydration with large volumes of glycerol and water could result in increased water retention and decreased urine output. Lyons et al. (1990) also observed that hyperhydration resulted in a lower rectal temperature during moderate intensity exercise lasting 1.5 hours in a hot dry environment (42 °C). Theirs was the first study to suggest that glycerol hyperhydration could improve thermoregulation during exercise in hot conditions.

Since the early studies of Riedesel et al. and Lyons et al., research in this area has increased and several recent studies have examined the effects of glycerol-assisted hyperhydration on total body water, exercise capacity, and thermoregulation. It is apparent from the literature in this area that different hyperhydrating protocols are being used. This discrepancy, combined with the different environmental conditions used in various studies, has made it difficult to compare studies and come to any conclusion regarding effects on thermoregulation and exercise performance.

Table 1 briefly summarises the main studies that have examined preexercise glycerol hyperhydration. It is clear that study protocols have sometimes varied, ambient temperature has not always been high, and effects on thermoregulation and fluid balance are not always observed. Of the studies detailed in Table 1, only those of Montner et al. (1996) and Inder et al. (1998) have examined exercise capacity, with only Montner et al. observing an improvement in exercise capacity. A closer examination of the data reveals that 2 of the 11 subjects assessed in the first part of Montner et al.'s study actually showed a decrease in exercise capacity with glycerol hyperhydration.

The data available at present do not provide sufficient evidence of an effect on performance, thermoregulation, or cardiovascular function. It is clear that if enough water is ingested with glycerol, the hyperhydration procedure can increase total body water through a decrease in urine output. Koenigsberg et al. (1995) have shown that this increase in total body water can be sustained for up to 49 hours with repeated water and glycerol ingestion. Few studies have noted the potential side effects of glycerol hyperhydration, which include blurred vision and headaches. These side effects are related to glycerol's early use as a treatment for relief of high intraocular and cerebral spinal fluid pressure. The action of glycerol is mediated through removal of water from these areas by an osmotic effect. Whether these side effects are bad enough to affect performance may depend on

Table 1 Summary Table of the Main Studies

Author & year publ.	Preexercise glycerol hyperhydration protocol	Ambient temp.	Findings
Riedesel et al. (1987)	1.4 L saline w/ 0.5–1.5 $g \cdot kg^{-1}$ glycerol, monitored 4 hrs	21 °C	1.5 $g \cdot kg^{-1}$ glycerol lowest urine output, ↑ TBW ~0.8 L
Lyons et al. (1990)	1.9 L water w/ 1.2 $g \cdot kg^{-1}$ glycerol, 4 hrs before exercise	42 °C	0.7 L ↑ in TBW, ↓ T_{re}, ↑ sweat volume
Freund et al. (1995)	1.8 L water w/ 0.9 $g \cdot kg^{-1}$ glycerol, monitored 3 hrs, no exercise	22 °C	1.1 L ↑ in TBW, retained after 3 hrs
Montner et al. (1996)	1.8 L water w/ 1.2 $g \cdot kg^{-1}$ glycerol, 2.5 hrs before exercise	24 °C	0.67 L ↑ in TBW, no effect on thermoregulation
Latzka et al. (1997)	1.8 L water w/ 1.4 $g \cdot kg^{-1}$ glycerol, 1 hr before exercise	35 °C	1.5 L ↑ in TBW, no effect on thermoregulation
Inder et al. (1998)	0.5 L water w/ 1.0 $g \cdot kg^{-1}$ glycerol, 4 hrs before exercise	22 °C	No change in TBW, no measured effects on thermoregulation

Abbreviations: TBW (total body water), T_{re} (rectal temperature).

the individual or the dose of glycerol administered. However, it seems that doses of glycerol up to 1.5 $g \cdot kg^{-1}$ body mass are tolerated (Riedesel et al., 1987), but typically doses do not exceed 1.2 $g \cdot kg^{-1}$ body mass. More research must and is being conducted to identify exactly how glycerol may exert a beneficial effect. Areas to be examined should include glycerol's effect on body fluid compartments, its metabolic effects, and potential thermoregulatory effects in hot environments.

Rehydration During Exercise

Fluid replacement during exercise in the heat has been studied intensively over the past 20 years and to some extent since the 1940s (Pitts et al., 1944). Much of this research has focused on identifying the optimum balance of water, electrolytes, and CHO in oral rehydration solutions in order to offset disturbances in fluid balance and delay the onset of substrate depletion during exercise.

Our knowledge of effective fluid replacement has been greatly enhanced by gastric emptying and intestinal perfusion studies (for reviews see Costill, 1990; Gisolfi et al., 1990). These studies indicate there is a compromise between the provision of substrate and fluid: increasing the substrate content of a solution will limit the rate of fluid delivery to the intestine, while increasing fluid provision requires a reduction in the CHO content to prevent gastrointestinal distress. Formulation studies have examined CHO type, CHO content, electrolyte content, osmolality, temperature, flavour, and carbonation of ingested fluids. Temperature, flavouring, and carbonation are all associated with the palatability of ingested fluids and have been studied in an attempt to increase the volume of fluid ingested during ad libitum drinking.

An overview of the studies examining the effects of these aforementioned factors on gastric emptying and intestinal absorption has been presented in Maughan's review in this symposium, but some factors may again be touched upon briefly in this section. In this review the focus will remain on more practical points such as detailing the benefits and drawbacks of ad libitum drinking versus prescribed drinking, examining water ingestion studies, summarising the studies that have examined administration of different volumes of fluid, and identifying the optimum frequency for ingestion of fluids during exercise.

Ingestion of water during exercise was not always considered beneficial. Many athletes believed that prolonged training without water ingestion could result in adaptation and allow them to cope better without water during competition (Noakes, 1993). However, we now know this is not so and that fluid ingestion is extremely important during exercise, particularly for events of long duration conducted in hot environments.

Many studies have shown that exercise capacity can be improved with water ingestion compared with no fluid ingestion during exercise (for review see Coyle and Hamilton, 1990), even in the absence of heat stress, though this is not always the case (Robinson et al., 1995). The mechanism for this improved exercise capacity is generally associated with a maintenance of blood volume, thus allowing for improved thermoregulation and cardiovascular function in the face of ongoing fluid losses through sweating. Pitts et al. (1944) were probably the first to observe that water ingestion could reduce the rectal temperature response to exercise, compared with no fluid. They found that the reduction in rectal temperature was greatest when fluid was prescribed equivalent to sweat losses versus when ad libitum drinking was allowed. This early data indicating that prescribed drinking is better than ad libitum drinking has been supported by recently published data (Noakes, 1993; Schroeder et al., 1997).

In addition, Hamilton et al. (1991) have shown that water, compared with no fluid ingestion, can reduce the rise in core temperature, prevent a reduction in stroke volume and cardiac output, and decrease the reduction in plasma volume that occurs with prolonged exercise. Hargreaves et al. (1996) have added to the hypotheses regarding the beneficial effects of water by observing that an improvement in exercise capacity with water ingestion compared to no fluid may also be linked to muscle glycogen utilisation. They observed a mean reduction in muscle glycogen utilisation of 62 $\text{mmol} \cdot \text{kg}^{-1}$ dry weight over a 2-hour exercise period when water was ingested compared with no fluid. Mean total muscle glycogen use in the water and no-fluid trials was 318 and 380 $\text{mmol} \cdot \text{kg}^{-1}$ dry weight, respectively. The mechanism behind this effect warrants further investigation.

On a more practical note regarding rehydration strategies during exercise, alterations in environmental temperature, intensity and duration of exercise, and also the mode of exercise must be considered. Environmental temperature conditions affect the athlete's ability to perform prolonged moderate-intensity exercise (Galloway and Maughan, 1997). When the ambient temperature is high, an increase in sweat loss, subsequent dehydration, and hyperthermia all lead to a reduction in exercise capacity. Galloway and Maughan (1997) have shown that this reduction in exercise capacity results in a lower total CHO oxidation during exercise. This indicates that muscle glycogen depletion is unlikely to be a limiting factor in such environmental conditions.

Exercise in the heat has been associated with an increased rate of muscle glycogen utilisation (Fink et al., 1975), but Febbraio et al. (1996) have observed that despite an increase in the rate of muscle glycogen utilisation, muscle glycogen stores are not depleted upon exhaustion when the ambient temperature is high (40 °C). These studies clearly show that the need for fluid replacement is greater than that for CHO provision during exercise in high ambient temperatures.

In view of these findings, it is somewhat disconcerting to note that a majority of studies examining fluid replacement during exercise have been conducted in the absence of severe heat stress. Nevertheless, these studies constitute a large portion of our understanding of the effects of fluid replacement during exercise on thermoregulation, fluid balance, and cardiovascular function, and have helped improve our knowledge in this area.

Following on from the studies showing that fluid provision should be the main emphasis of drinks ingested in hot environments, Galloway and Maughan (unpublished data) have observed that ingestion of a large volume of a dilute CHO/electrolyte solution (2% CHO) improved prolonged (70–120 min duration) moderate-intensity exercise capacity by 66% over that when no fluid was administered in a hot environment (30 °C). The same study observed that a smaller volume of a 15% CHO/electrolyte solution improved exercise capacity by 19% over that when no fluid was given. The difference in amount of improvement between 2% and 15% CHO solutions and no fluid ingestion was hypothesised to be due to the difference in volumes administered: 2.0 L of the 2% CHO drink compared with 1.2 L of the 15% CHO drink in the first hour of exercise. The volumes ingested over the whole exercise period—3.1 L of 2% CHO solution and 1.5 L of 15% CHO solution—were equivalent to 123% and 75% of the total sweat loss in the 2% and 15% CHO trials, respectively. These large volumes were well tolerated by all subjects and none experienced any gastrointestinal distress. The plasma volume response to the two administered drinks revealed that the 2% CHO solution effectively restored plasma volume to resting levels throughout the exercise period, but this did not occur in the 15% CHO trial.

Previous studies have indicated that the fluid volume ingested is the most influential factor affecting performance in hot (31 °C) conditions (Below et al., 1995). Below et al. (1995) observed that CHO and fluid ingestion independently improved exercise performance to a similar extent, but the effects were also additive. They administered a large fluid volume to match sweat loss (1.3 L) and a small fluid volume (0.2 L) during continuous exercise lasting 50 minutes. This practice of ingesting fluid volume to match sweat losses appears to be a good guideline for athletes to individualize their fluid replacement strategies. However, individual differences in gastric emptying and intestinal absorption do not necessarily match individual differences in sweat loss, so an imbalance may still occur in some athletes and could result in either voluntary dehydration or gastrointestinal distress.

Several studies have advocated this strategy of replacing fluid losses (Barr et al., 1991; Coyle and Montain, 1992; Montain and Coyle, 1992), and this appears to be the best solution at present to the practical problem of preventing voluntary dehydration. However, athletes are often unaware of their ongoing fluid losses, especially if the ambient temperature conditions are unexpectedly hot or cold. The practical solution is that athletes must assess their fluid requirements on a regular basis (by monitoring nude weight) during training so they can alter their fluid replacement strategies accordingly. A change may occur either as a result of changes in training status or heat acclimatization.

The maximum rate of exogenous substrate oxidation appears to be around 1 g $\cdot$ min^{-1} during the latter stages of prolonged exercise (Massicotte et al., 1989; Rehrer et al., 1992), with a more conservative estimate being approximately 0.5–0.6 g $\cdot$ min^{-1} throughout an exercise period (Pirnay et al., 1977). Given that fluid provision is vital when the ambient temperature is high and that fluid with a high substrate content will limit fluid delivery to the intestine, it would seem logical that the exogenous substrate provided not exceed the maximum rate of oxidation by very much. However, most studies on substrate and fluid provision during exercise have examined solutions with a CHO content around 6–8%. If these solutions are ingested in sufficient quantities to replace sweat losses, they will often provide more than 120 g per hour, double the maximum rate of exogenous substrate oxidation. Thus, administering a solution of 2–4% CHO with electrolytes should result in more effective fluid replacement during exercise of long duration in the heat. Unfortunately, few studies have examined fluid replacement with solutions of 2–4% CHO in the heat (Davis et al., 1988; Maughan et al., 1996), so more research is warranted.

REHYDRATION DURING INTERMITTENT EXERCISE

Voluntary dehydration of approximately 2–3% body mass routinely occurs during intermittent high-intensity exercise, especially when the ambient temperature is high. Sports involved in this type of exercise are often played over a long duration (90 min or longer), so fluid replacement and CHO provision during exercise should certainly be an issue. However, studies examining the effects of fluid replacement during exercise in team sports or individual activities have not always conclusively shown beneficial effects (Nicholas et al., 1995). Part of the reason for this might be the difficulty in assessing performance improvements in team sports.

Studies have attempted to examine sprint times during the early stages of a match compared to near the end of a game with and without fluid replacement, or with water compared to a CHO/electrolyte solution. These field study approaches are often the ones that show inconclusive results. More often than not, it is the laboratory studies that clearly demonstrate beneficial effects of ingesting CHO/electrolyte solutions during intermittent high intensity exercise (for reviews see Burke and Hawley, 1997; Shi and Gisolfi, 1998). But the laboratory studies are often so far removed from the real sport in terms of rest-to-work schedules and intensity of effort that their findings may not equate to real benefits for an exercising athlete.

Further research should be undertaken with a focus on the practicalities of fluid replacement during particular sports and in identifying whether fluid replacement is beneficial to events lasting 30–60 minutes. To date the evidence suggests that events of 30–60 minutes duration which may require a sprint finish or increased effort near the end of the event may benefit from CHO/electrolyte replacement early in exercise (Coyle and Montain, 1990; Maughan, 1997).

Gastric emptying studies have clearly shown that as the intensity of exercise increases beyond about 75% of $\dot{V}O_2$ max, the rate of gastric emptying declines (Costill and Saltin, 1974). This could prove problematic to team sport athletes who are attempting to ingest fluid in a volume equivalent to sweat losses while maintaining high-intensity work. Added to this complication is the fact that athletes in team sports such as soccer, hockey, field hockey, and basketball often have difficulty ingesting sufficient fluid due to the nature of the game and the rules regarding fluid replacement. In soccer and field hockey, for example, players are only allowed to consume fluid on the sidelines during the game.

The key points in creating a fluid replacement strategy for intermittent high-intensity exercise should be the same as for endurance events: (a) The fluid replacement should provide enough volume to replace sweat loss; (b) the CHO content should be high enough to provide substrate but not too high to limit the rate of gastric emptying; (c) fluids should be ingested frequently if possible to maintain gastric volume; and (d) players should monitor their drinking behaviour so as to keep track of the fluid volumes they are ingesting (Burke and Hawley, 1997).

There has been little work on exogenous substrate oxidation during intermittent exercise, so it is not possible to recommend an upper limit for the CHO content of drinks. However, if the response during intermittent exercise in the heat is similar to that during endurance events, the CHO content of a drink should not exceed the estimated maximum exogenous substrate oxidation when fluid provision is of prime importance. Thus, 60 g per hour can be attained from either 1 L of a 6% solution or from 2 L of a 3% solution. Ideally, the volume and CHO content should be altered to adapt to the demands of differing ambient temperatures. To date, few sports drink makers have attempted to provide a full range of products to suit all individuals in all ambient temperature conditions, as this is impractical.

MODE OF EXERCISE: CYCLING VS. RUNNING

To date, most studies examining the effects of rehydration strategies before, during, and after exercise have focused on endurance cycling capacity or cycling performance. This has led to some concern about applying the same strategies to studies on running and runners. However, Tsintzas et al. (1993; 1995; 1996) have observed that runners can ingest large volumes (approximately 1 L in the first hour of exercise) of fluid in a laboratory and race setting, and that CHO/electrolyte beverages can prolong exercise capacity and improve performance compared with water alone. Houmard et al. (1991) observed no difference in the rate of gastric emptying during 1 hour of running and cycling at the same absolute exercise intensity, so there should be no difference in fluid and substrate provision between exercise modes. Despite this evidence, it is still uncommon for runners to ingest much fluid during a race (Rehrer et al., 1990a; Tsintzas and Williams, 1998). This may be due to their being unfamiliar with the feeling of running on a full stomach, or purely to the practicalities of carrying and ingesting sufficient fluid between the sometimes distant aid stations.

Voluntary dehydration is common and thirst is a poor indicator of fluid balance. Due to this problem, it is vital for all athletes to ingest fluid during the early stages of long-duration exercise, regardless of whether it is continuous or intermittent in nature. Often athletes do not use aid stations until it is too late and significant dehydration has occurred. Ingesting a large amount of fluid late in the race is likely to cause gastrointestinal distress because the rate of gastric emptying is reduced when the runner is dehydrated (Rehrer et al., 1990b); the contents of the stomach will either be emptied onto the road or remain in the stomach until after the race, thus providing no benefit during the event.

Postexercise Rehydration

Assuming that the rehydration strategies before and during exercise have been effective, there should be no need for rehydration postexercise. This appears to be the view in the ACSM position stand (1996), as there is no mention of postexercise rehydration in their document. However, as has been highlighted in this review, fluid replacement before and during exercise is unlikely to be sufficient to offset the ongoing fluid losses. This is especially true during prolonged exposure to hot environments. Athletes are then faced with the possibility that they are significantly dehydrated and are due to compete again soon. A decision must be made as to the most effective postexercise rehydration strategy to restore body fluid balance while providing CHO to restore depleted muscle glycogen stores.

If there is limited time (~2 hours) before the next event, athletes should replace their fluid losses to achieve euhydration. If sufficient time is available (~6 hours), fluid ingestion or fluid plus solid food are the options. Several studies have examined the time course of rehydration postexercise following ingestion of different fluid volumes with varying composition in an attempt to identify the optimum solution for postexercise rehydration (for review see Maughan et al., 1997).

Shirreffs et al. (1996) have clearly shown that the ingested volume is crucial to the rehydration process. In their study, euhydration was only maintained after the recovery period (6 hours) when 150% or 200% of fluid losses were replaced. When 50% and 100% of fluid losses were replaced, there was a net fluid loss of 958 and 286 ml, respectively, at the end of the 6-hour period. In another study, Maughan and Leiper (1995) observed that the sodium content of the rehydration solution was crucial to the maintenance of euhydration after a recovery period of 5.5 hours. In their study, euhydration was only maintained when the sodium content of the ingested solution was $>50 \text{ mmol} \cdot \text{L}^{-1}$.

These two studies suggest that the fluid volume and sodium content should be high for optimum rehydration. However, the study designs used in these experiments were aimed at assessing the effectiveness of volume and sodium content on maintaining a positive net fluid balance during recovery, rather than at practical rehydration strategies. In these studies a 30-min or 60-min period was allowed for rehydration, followed by 5 to 6 hours of no fluid ingestion. In reality, athletes would continue to ingest fluids and probably solid food to replace losses over this length of time.

Maughan et al. (1996) went on to partly address this practical problem by assessing the effectiveness of solid food and water ingestion compared to a commercially available fluid replacement solution. The rehydration period was over 1 hour and subjects were monitored for a further 5 hours of recovery. The results of this study revealed that subjects were euhydrated at the end of the recovery period when the solid food was taken, and this was better than when the CHO-electrolyte solution was administered (approx. fluid deficit of 350 ml). Maughan et al. concluded that the higher electrolyte content of the meal, which had identical water content to the fluid replacement solution, allowed for better retention of fluid.

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