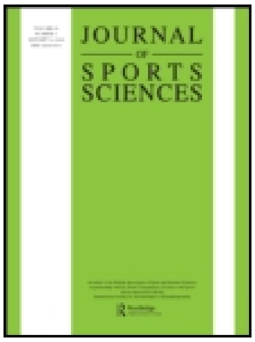

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Exercise in the heat: Strategies to minimize the adverse effects on performance

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Exercise in the heat is usually associated with reduced performance; both dehydration and hyperthermia adversely affect mental and physical performance. For athletes from temperate climates, the negative effects of heat and humidity can be attenuated by a period of acclimatization. This requires up to 10–14 days. Endurance-trained individuals already show some of the adaptations that accompany acclimatization, but further adaptation occurs with training in the heat. Prior dehydration has a negative effect even on exercise of short duration where sweat losses are small. The athlete must begin exercise fully hydrated and regular ingestion of fluids is beneficial where the exercise duration exceeds 40 min. Dilute carbohydrate-electrolyte (sodium) drinks are best for fluid replacement and also supply some substrate for the exercising muscles. Post-exercise rehydration requires electrolyte as well as volume replacement. In extreme conditions, neither acclimatization nor fluid replacement will allow hard exercise to be performed without some risk of heat illness.

Keywords: Dehydration, fluid replacement, heat, heat acclimatization.

Introduction

Although all athletes recognize the need for an adequate period of warming up before training and competition, it is equally clear that there is an optimum body temperature that should not be exceeded. It is easy to demonstrate that times in endurance events at major athletics championships are generally poor when ambient temperature and humidity are high: record performances are few, and races become more tactical. As the ambient temperature and humidity increase, so increased sweating rates and peripheral blood flow are necessary to limit the rise in body temperature that would otherwise occur. Both dehydration and hyperthermia can negatively affect exercise performance. In short-duration events, an elevated muscle temperature may improve muscle function, but performance is impaired if it is preceded by exercise which causes significant sweat loss. As the exercise duration increases, the effects of temperature become more apparent, and even mild dehydration will prevent the athlete from achieving optimum performance in endurance events; severe dehydration is potentially fatal. Even where competitive performance is not influenced, training for all track and field events may be adversely affected by the dehydration that commonly occurs in hot weather. Exercise in the dehydrated state leads to a more rapid elevation of body temperature and the onset of heat illness.

Where athletic competitions are scheduled for hot weather venues, there is therefore a need for the athlete to prepare for the conditions that will be encountered. There are two aspects of preparation for these conditions: first, the development of a suitable rehydration regimen; and second, the development of an acclimatization strategy. For athletes who habitually live and train in temperate climates, these preparations are essential if there is to be any chance of success.

Effects of temperature and dehydration on exercise performance

Several studies have shown that an elevated muscle temperature prior to high-intensity exercise results in improved exercise performance: these include studies on short-duration cycling (Asmussen and Bøje, 1945), running at distances of 100–800 m (Hogberg and

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Ljunggren, 1947, cited in Bergh and Ekblom, 1979) and tests of muscle strength, jumping performance and peak power output in cycling (Bergh and Ekblom, 1979). In these studies, however, elevated muscle temperatures were achieved by prior exercise, which has many effects on the muscle other than a simple increase in temperature. Where muscle temperature was elevated by immersion of the limb in warm water, performance in isometric contractions lasting a few seconds was consistently reduced (Edwards *et al.*, 1972; Petrofsky and Lind, 1975). Similarly, Craig and Froehlich (1968) used warm water immersion to elevate body temperature prior to exercise and showed that treadmill endurance time during an incremental exercise task carried out in the heat decreased progressively from 577 s when the pre-exercise rectal temperature was 37.6°C to 257 s when rectal temperature was 39.3°C.

Jacobs (1980) found that performance of a 30-s maximal exercise test on a cycle ergometer, using the procedures described in the Wingate test, was not influenced by dehydration equivalent to up to 5% of body weight; in this study, weight loss was induced by intermittent passive exposure to heat (air temperature of 56°C) over a period of up to 6 h. However, in a study where a 5% decrease in body weight was induced over a 36-h period, there was a significant decrease in both anaerobic power and anaerobic capacity in a 40-s cycle ergometer test (Webster *et al.*, 1988). In work of slightly longer duration, Saltin (1964) reported that endurance time in a high-intensity cycling test was reduced from 6.31 to 5.06 min by sauna dehydration (3.8% weight loss).

Nielsen *et al.* (1981) measured the total amount of work that could be performed at an exercise intensity corresponding to 105% of maximal oxygen uptake ($\dot{V}O_2$ max) after different dehydration procedures. Dehydration was induced by prolonged exercise, by sauna exposure or by diuretic administration to the extent of a loss of 2.5% of body weight; hot water immersion was also used to increase body temperature to the same extent as occurred during the exercise trial, and this treatment resulted in a 0.7% decrease in body weight. All treatments resulted in a decrement in performance relative to the control trial. Two exercise dehydration trials were carried out, and performance in the high-intensity exercise test was reduced to 53 and 55% of the control value in the two tests, respectively. After sauna exposure and diuretic administration, performance was 66 and 82% of the control value, respectively. Two trials involving passive heating by water immersion were carried out, and performance was reduced to 73 and 88% in these two trials, respectively. Thus, although the greatest decreases in performance were observed after exercise-induced dehydration, dehydration and hyperthermia without exercise, and dehydration alone, also resulted in an impaired exercise capacity.

Even at low levels (1.8%) of dehydration (Walsh *et al.*, 1994), high-intensity (90% $\dot{V}O_2$ max) exercise performance time is reduced. These results illustrate the difficulty in separating the effects of dehydration from the other changes which take place during the dehydration procedure. It seems certain that some of the decrement in performance which results from exercise-induced sweat loss is also an effect of an elevated body temperature. In the study of Craig and Froehlich (1968) referred to above, a maximal treadmill running test lasting about 12 min was used to assess the effects of an elevated body temperature, induced by hot water immersion. Their results showed that the decrease in exercise time was related to the pre-exercise rectal temperature.

In a study on the effects of diuretic-induced water loss (about 2% of body weight) on competitive middle-distance running performance, Armstrong *et al.* (1985) showed that, when comparisons were made with the normally hydrated state, dehydration resulted in performance in simulated races over distances of 1500–10,000 m being reduced by an average of about 3–7%. At 1500 m, a deficit of 3% in performance is worth more than 6 s at world class level. In a treadmill running test lasting about 12 min carried out to exhaustion, running time was significantly decreased in the dehydrated state. Despite these differences in running performance, these authors found no effect of dehydration on $\dot{V}O_2$ max. This finding is in agreement with the observation of Saltin (1964), who found a decreased exercise time during a maximal oxygen uptake test after exercise or sauna dehydration, but no effect on $\dot{V}O_2$ max itself. Other studies have shown that dehydration does reduce $\dot{V}O_2$ max, and it appears that a level of dehydration equivalent to at least 3% of body weight is necessary to produce an effect (see Sawka and Pandolf, 1990).

It would be surprising if dehydration and the consequent reduction of the circulating blood volume did not have a detrimental effect on $\dot{V}O_2$ max. There is ample evidence that $\dot{V}O_2$ max is increased when the total blood or plasma volume is increased by acute infusion of whole blood or of plasma volume expanders (see Maughan, 1992, for a review). Coyle *et al.* (1990) have manipulated the plasma volume, and suggested that the plasma volume which elicits the highest $\dot{V}O_2$ max value is about 200–300 ml above the normal level, in trained or untrained subjects.

Three groups are at special risk for heat intolerance: female athletes due to their lower sweat rates and higher body surface area (Kenney, 1985), master athletes because ageing decreases heat tolerance and thirst perception (Kenney, in press), and child athletes (see Bar-Or, this issue).

Effects of dehydration on endurance exercise

In short-term, high-intensity exercise, water and electrolyte losses during the exercise period itself are necessarily small, and dehydration is a concern only if it is induced prior to the onset of exercise. In prolonged exercise, especially at high environmental temperatures, sweat can be lost at rates in excess of 2 l h^{-1}. Studies on the effects of dehydration on the performance of prolonged exercise can therefore be divided into those in which a fluid deficit is induced prior to the beginning of exercise, and those in which fluid losses are not replaced during exercise and a progressive dehydration occurs during the exercise period itself.

The effects of dehydration on endurance capacity have been extensively studied by the military, and a decrease in exercise performance after dehydration is well documented (Adolph, 1947). The majority of more recent studies, especially those in which exercise was carried out in the heat, have confirmed this finding, and have also shown an increase in serum osmolality, heart rate and core temperature in dehydrated compared with euhydrated subjects (Gaebelein and Senay, 1980; Harrison, 1986).

In exercise, about 75–80% of the energy used by the muscles appears as heat: the total heat load is therefore closely related to exercise intensity. This causes particular problems in high-intensity exercise, where there is a high demand for blood flow to the exercising muscles to provide oxygen and to remove metabolic waste products. There is also a need for a high blood flow to the skin to promote heat loss. Where the cardiac output is insufficient to meet the demands of both muscle and skin blood flow, the latter will be compromised, leading to reduced heat loss and a rapid rise in body temperature.

In more prolonged exercise, sweat losses will occur during exercise, and sweat rates of 2–3 l h^{-1} are possible. The combined effects of progressive dehydration and a rising body temperature pose a considerable threat to the runner. During a marathon race at high ambient temperatures, runners may lose as much as 8% of body weight, corresponding to about 13% of total body water (Costill, 1972). Even in an event as short as 10 km, losses corresponding to more than 2% of body weight are possible. Many of the highest values of rectal temperature in distance runners have been observed after races at distances less than the marathon. Among competitors in a 14-km road race, Sutton (1990) reported more than 30 cases over a period of years where rectal temperature exceeded 42°C. In a single 10-km road race, England *et al.* (1982) reported 29 cases of heat illness, but their diagnostic criteria are unclear, and only 13 of these individuals recorded a rectal temperature of 39.7°C or greater. These data do, however, suggest that hyperthermia may be more common when the rate of heat production is very high, as in races of 10 km. At such high exercise intensities, skin blood flow is likely to be reduced, with a larger fraction of the cardiac output being directed to the working muscles, and so heat loss will be reduced.

The major electrolytes in sweat, as in the extracellular fluid, are sodium and chloride, although the concentrations of these ions in sweat are invariably lower than those in plasma (Costill, 1977). Other electrolytes present in significant concentrations in sweat include potassium and magnesium. Loss of substantial amounts of sweat will inevitably reduce the body reserve of these electrolytes, but except where losses are very high, replacement during exercise is not a priority, and even then sodium replacement alone should be considered during exercise (Maughan, 1994).

The factors influencing fluid loss during exercise, and the effects of dehydration on exercise performance, have been extensively reviewed elsewhere (Lamb and Brodowicz, 1986; Maughan, 1994).

Fluid replacement during exercise

The ability to sustain a high rate of work output in the heat requires replacement of water losses to prevent dehydration, but exercise performance may also be limited by the availability of carbohydrate as a fuel for the working muscles. Fluid ingestion during exercise therefore has the twin aims of providing a source of carbohydrate fuel to supplement the body's limited stores and of supplying water to replace the losses incurred by sweating (Coyle and Coggan, 1984; Lamb and Brodowicz, 1986; Murray, 1987; Maughan, 1994). The rates at which substrate and water can be supplied during exercise are limited by the rates of gastric emptying and intestinal absorption; although it is not clear which of these processes is limiting, it is commonly assumed that the rate of gastric emptying will determine the maximum rates of fluid and substrate availability (Lamb and Brodowicz, 1986; Murray, 1987).

Increasing the carbohydrate content of drinks slows the rate of gastric emptying (Costill and Saltin, 1974), decreasing the rate at which fluid can be supplied, but the presence of glucose and sodium in the lumen of the small intestine stimulates water absorption, provided that the osmolality of the solution is not too high (Leiper and Maughan, 1988). The optimum formulation for rehydration purposes during exercise will vary, depending on the relative requirements for fluid replacement and substrate provision, which in turn will depend on the environmental conditions and exercise intensity. Where water replacement is the first priority, however, an isotonic or moderately hypotonic solution containing glucose and sodium will be most effective (Farthing, 1988). Most commercial sports drinks contain 6–8% carbohydrate, about 20–25 mmol l^{-1} sodium and low (4–5 mmol l^{-1}) concentrations of potassium. These formulations represent a compromise between that which will give the highest rates of fluid replenishment, and that which can provide most carbohydrate. For most athletes in most situations, this will be optimal.

Despite the clear evidence demonstrating the negative effects of dehydration on exercise performance and the positive effects of fluid ingestion, it is equally clear that most athletes do not drink sufficient to match fluid losses during exercise (Noakes, 1992). This is in part at least due to the relative insensitivity of the thirst mechanism in humans, and some degree of dehydration – perhaps as much as 2% of body weight – is normally incurred before the stimulus to drink is initiated (Adolph, 1947). This level of dehydration is sufficient to impair exercise performance and thermoregulatory capacity. Drinking can be stimulated to some extent by improving beverage palatability (Hubbard *et al.*, 1990), but perhaps education of the athlete and an increased awareness of the need for a conscious effort to increase fluid intake in situations where dehydration is likely to occur may be the most effective way to proceed.

Post-exercise rehydration

Replacement of water and electrolyte losses in the post-exercise period may be of crucial importance for maintenance of exercise capacity when repeated bouts of exercise have to be performed. The need for replacement will obviously depend on the extent of the losses incurred during exercise, but will also depend on non-exercise losses. Athletes living in hot environments will experience substantially increased fluid losses even when not exercising.

Excessive intake of fluids with a low sodium content has been reported to induce hyponatraemia during exercise of long duration (Noakes, 1992). Ingestion of plain water in the post-exercise period also results in a rapid fall in the plasma sodium concentration and in plasma osmolality (Nose *et al.*, 1988). These changes have the effect of reducing the stimulus to drink (thirst) and of stimulating urine output, both of which will delay the rehydration process. In one study, subjects exercised at low intensity in the heat for 90–110 min, inducing a mean dehydration of 2.3% of body weight, and then rested for 1 h before beginning to drink (Nose *et al.*, 1988). Plasma volume was not restored until after 60 min when plain water was ingested together with placebo (sucrose) capsules. In contrast, when sodium chloride capsules were ingested with water to give a saline solution with an effective concentration of 0.45% (77 mmol l^{-1}), plasma volume was restored within 20 min. In the sodium chloride trial, voluntary fluid intake was higher and urine output was less; 71% of the water loss was retained within 3 h, compared with 51% in the plain water trial. The delayed rehydration in the water trial appeared to be a result of a loss of sodium, accompanied by water, in the urine caused by increased plasma renin activity and aldosterone levels.

It is clear from the results of these studies that rehydration after exercise can only be achieved if the sodium lost in sweat is replaced as well as the water, and it might be suggested that rehydration drinks should have a sodium concentration similar to that of sweat. The sodium content of sweat varies widely, and no single formulation will meet this requirement for all individuals in all situations; the fraction of fluid ingested after dehydration that is lost in the urine within the first few hours is inversely related to the sodium content of drinks ingested at this time (Maughan and Leiper, in press). Potassium may also be helpful in promoting rehydration (Maughan *et al.*, 1994). Other factors also intervene, and increasing the sodium content will have a negative impact on taste, which will in turn reduce the volume of fluid consumed (Hubbard *et al.*, 1990). It is equally clear, however, that an effective rehydration fluid will contain sufficient sodium to maintain the thirst stimulus and to promote the retention of the ingested fluid.

Acclimatization strategies

Although athletes from temperate climates are at a disadvantage when major championship events are held in conditions of high temperature and humidity, the negative effect of these climatic factors can be greatly reduced by a period of acclimatization. There is no doubt that regular exposure to hot humid conditions results in a number of adaptations which together reduce the negative effects of these conditions on exercise performance. The magnitude of the adaptation to heat that occurs is closely related to the degree of heat stress to which the individual is exposed. The process of adaptation begins within a few days, and the major adaptive changes, including an expanded plasma volume, a reduced heart rate and body core temperature during exercise, redirection of a larger proportion of the cardiac output towards the skin capillary bed, and a decreased perceived exertion, are largely complete within the first 6–8 days of exposure (Armstrong and Maresh, 1991). Full adaptation may take 14 days or even more for some individuals. It is equally clear that regular endurance training in temperate conditions confers some protection: trained subjects are already partially adapted, but full adaptation is not seen unless a period of time is spent training in the heat. The beneficial effects of endurance training in a temperate climate on the ability to cope with heat stress appear to be related more closely to training volume than to aerobic capacity (Pandolf *et al.*, 1988).

Among the benefits of training is an expansion of the plasma volume (Hallberg and Magnusson, 1984; Convertino, 1991). Although this condition is recognized as a chronic state in the endurance-trained individual, an acute expansion of plasma volume occurs in response to a single bout of strenuous exercise; this effect is apparent within a few hours of completion of exercise and may persist for several days (Davidson *et al.*, 1987; Robertson *et al.*, 1988). This post-exercise hypervolaemia should be regarded as an acute response rather than an adaptation, although it may appear to be one of the first responses to occur when an individual embarks on a training regimen. Plasma electrolyte and total protein concentrations are normal in the endurance-trained individual despite the enlarged blood and plasma volumes, indicating an increased total circulating content (Convertino *et al.*, 1980).

The increased resting plasma volume in the trained state allows the endurance-trained individual to maintain a higher total blood volume during exercise (Convertino *et al.*, 1983), allowing for better maintenance of cardiac output, albeit at the cost of a lower circulating haemoglobin concentration. In addition, the increased plasma volume is associated with an increased sweating rate, which limits the rise in body temperature (Mitchell *et al.*, 1976). These adaptive responses appear to occur within a few days of exposure to exercise in the heat, although, as pointed out above, this may not necessarily be a true adaptation. In a series of papers reporting the same study, Mitchell *et al.* (1976), Wyndham *et al.* (1976) and Senay *et al.* (1976) followed the time-course of changes in men exposed to exercise (40–50% $\dot{V}O_2$ max for 4 h) in the heat (45°C) for 10 days. Although there were marked differences between individuals in their responses, resting plasma volume increased progressively over the first 6 days, reaching a value about 23% greater than the control, with little change thereafter. The main adaptation in terms of an increased sweating rate and an improved thermoregulatory response (with body temperature lower by 1°C and heart rate lower by 30 beats min^{-1} in the later stages of exercise) occurred slightly later than the plasma volume expansion, with little change in the first 4 days.

Although there is clear evidence that acclimatization by exercising in the heat over a period of several days will improve the thermoregulatory response during exercise, this does not reduce the need to replace fluids during the exercise period; rather, because of the enhanced sweating response, there is an increased requirement for fluid intake (Greenleaf *et al.*, 1983). Better maintenance of body temperature is achieved at the expense of an increased water (sweat) loss. Although this allows for a greater evaporative heat loss, the proportion of the sweat which is not evaporated and which therefore drips wastefully from the skin is also increased (Mitchell *et al.*, 1976). A high sweat rate may be necessary to ensure adequate evaporative heat loss, but it does seem that many individuals have an inefficient sweating mechanism; even in the unacclimatized state, their rate of sweat secretion appears to exceed the maximum evaporative capacity. The athlete who trains in a moderate climate for a competition to be held in the heat will, however, be at a disadvantage on account of his or her inability to sustain a high sweat rate.

Although athletes may be tempted to believe that the need for fluid replacement will decrease as they become adjusted to the heat, heat acclimatization will actually increase the requirement for fluid replacement because of the earlier onset of sweating and greater sweat rates. It appears that voluntary fluid intake is increased to meet this increased fluid requirement and homeostasis is maintained (Hubbard *et al.*, 1990), but it is not clear how long this process of adaptation takes. Greenleaf *et al.* (1983) also showed that heat-adapted individuals have an increased fluid intake during exercise, take more frequent drinks and also begin to drink earlier during exercise. Again, it is not clear to what extent this reflects an increased sensitivity of the thirst mechanism and how much of the observed response can be explained by a learning effect.

If dehydration is allowed to occur, the improved ability to tolerate heat which results from the acclimatization process will disappear; in other words, regular exposure to exercise in the heat does not result in an increased tolerance to dehydration or to hyperthermia (Sawka and Pandolf, 1990). It been demonstrated in a number of studies that there is no adaptation to dehydration (Adolph, 1947); therefore, there is no reason to restrict fluid intake during training. There is, however, a real need for athletes to practise drinking in training; this will allow them to develop personal fluid replenishment strategies as well as letting them become accustomed to the sensation of running with fluid in the stomach. This is important, especially for those athletes who live and train in cold climates so that they can cope with the increased fluid intake necessary in hot weather competitions.

Many of the physiological parameters that are increased with heat stress are reduced during exercise in the heat after 7 days of acclimatization, including heart rate, rectal temperature, blood lactate accumulation and blood glucose concentration. Furthermore, the greater reliance on carbohydrate as a fuel source during exercise in the heat appears to be partially reduced after acclimatization, perhaps due to the reduction in plasma catecholamine concentration during exercise in the heat after acclimatization (Febbraio *et al.*, 1994).

The first 5 days of heat acclimatization are the most important, because the greatest cardiovascular and plasma volume adaptations occur during this period. The response, however, is variable between individuals, and training must be reduced and individually adjusted at this time.

Daily monitoring of body weight is advisable, to assess and control the extent of fluid loss and to guide the amount of extra fluid intake needed. If the reduction in body weight exceeds 4%, the intensity and duration of the training sessions should be reduced. Salt tablets are seldom if ever necessary, but some extra salting of food at the table may be appropriate in the early stages of acclimatization if sweat losses are very large. In temperate climates, a large part of the daily fluid intake is consumed at meal times; one of the initial responses to unaccustomed heat exposure is a suppression of appetite and consequent reduction of food intake. As well as leading to an energy deficit, this will tend to reduce the fluid intake, and a conscious effort must be made to drink in excess of the intake dictated by thirst alone.

The training sessions during the period of acclimatization should be organized according to the local variations in air temperature and humidity. High-intensity training, including interval work, should be done during cooler hours, which usually means early in the morning or late in the evening. Some prolonged exercise at lower intensity can be done in the hotter part of the day.

Endurance-trained athletes will generally cope better with the heat, and already show many of the adaptations that occur with heat acclimatization. The extent of these adaptations seems to be more closely related to the previous training volume than to $\dot{V}O_2$ max (Pandolf *et al.*, 1988). Well-trained individuals can adapt well to the heat with more intense, shorter-duration exercise than is normally recommended for less well-trained individuals (Houmard *et al.*, 1990). Sprinters, strength athletes and those without a good background of endurance training (including team management and officials), will usually take longer to acclimatize.

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