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Review

Development of hydration strategies to optimize performance for athletes in high-intensity sports and in sports with repeated intense efforts

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Hypohydration – if sufficiently severe – adversely affects athletic performance and poses a risk to health. Strength and power events are generally less affected than endurance events, but performance in team sports that involve repeated intense efforts will be impaired. Mild hypohydration is not harmful, but many athletes begin exercise already hypohydrated. Athletes are encouraged to begin exercise well hydrated and – where opportunities exist – to consume fluid during exercise to limit water and salt deficits. In high-intensity efforts, there is no need, and may be no opportunity, to drink during competition. Most team sports players do not drink enough to match sweat losses, but some drink too much and a few may develop hyponatremia because of excessive fluid intake. Athletes should assess their hydration status and develop a personalized hydration strategy that takes account of exercise, environment and individual needs. Pre-exercise hydration status can be assessed from urine markers. Short-term changes in hydration can be estimated from the change in body mass. Sweat salt losses can be determined by collection and analysis of sweat samples. An appropriate drinking strategy will take account of pre-exercise hydration status and of fluid, electrolyte and substrate needs before, during and after exercise.

The body at rest is normally in thermal balance, and adjusting room temperature or the amount of clothing allows the individual to remain at a comfortable temperature. All forms of exercise, however, are accompanied by an increased rate of metabolic heat production, and body temperature will rise if heat loss is not increased correspondingly. Muscle temperature rises rapidly at the onset of intense exercise (Saltin & Hermansen, 1966) and a rise in core temperature generally follows. When hard exercise is combined with high ambient temperatures or restricted heat loss, core temperature may rise by >2–3 °C (Nadel, 1988) and exertional heat illness, which can be fatal, may result (Sutton, 1990; Sawka et al., 2007). Hyperthermia is observed most often in hot and humid environments, but it can occur even in cool weather. It is most commonly observed in athletes, military personnel and industrial workers, but may affect anyone exposed to prolonged heat stress. Endurance exercise has been more extensively studied than has high-intensity exercise, perhaps because there are greater opportunities to incur dehydration because of sweat loss during the exercise, but perhaps also because performance impairments are likely to be greater and therefore easier to measure. Even when it is only warm (about 20 °C), endurance cycling capacity, measured as time to fatigue at a fixed power output, is less than at 10 °C and performance is further reduced at higher temperatures (Galloway & Maughan, 1997). In exercise that causes fatigue in less than about 10 min, however, local muscle fatigue causes exercise to stop long before significant sweat losses have occurred. Elevations of local muscle temperature may be a factor in this fatigue, but there is unlikely to be a substantial elevation of body temperature at the point of fatigue. The higher the exercise intensity, however, the higher is the rate of metabolic heat production and the faster is the rate of rise in body temperature. Severe hyperthermia may be more likely in high-intensity exercise lasting 20–30 min than in very prolonged exercise where thermal equilibrium is more likely to be achieved (Sutton, 1990). There have been few measures of changes in core temperature in intensive exercise of shorter duration.

The evidence base relating to the effects of hydration on repeated-sprint sports is limited, but athletes competing in these sports demand advice on appropriate hydration strategies. Extrapolations must therefore be made from data collected in other exercise models: this requires some understanding of the similarities and differences among the different experimental models. Development of practical advice also requires an understanding of the constraints within which athletes must operate. The use of strategies such as pre-competition hyperhydration using plasma volume expanding agents such as glycerol or intravenous hydration during breaks in the game is prohibited by the World Anti-Doping Agency; hence, even though they may be effective, they may not be used in sporting competition.

Hydration and performance

Long before there is a risk to health as a result of disturbances of thermal and fluid balance homeostasis, exercise performance may be reduced in the heat, and athletes are therefore concerned to reduce this performance loss. Performance has most often been assessed in simple tasks such as running or cycling, and a wide range of different laboratory-based performance models have been used. The limitations to the application of these laboratory measures to the field have to be taken into account when considering the implications for sporting competition (Hopkins et al., 1999; Hopkins, 2001). A fluid deficit incurred before exercise can increase physiological strain and reduce performance, and this effect has been reported in some, but not all, studies of short-duration, high-intensity exercise: the large number of studies in this area have been reviewed by Sawka and Pandolf (1990) and Judelson et al. (2007b). The influence of hydration status on sprint performance has been investigated in many studies using a number of different exercise modes, and the results are rather inconsistent. It is possible that hypohydration may influence exercise performance differently depending upon whether the sprinting being investigated is running, where body mass must be supported and moved, or whether it is sprinting on a cycle or rowing ergometer, where this is not the case. If body mass is reduced, it changes the work required for running so the decreased body mass that is typically used to define the magnitude of hypohydration may compensate for any reduced muscular strength and/or power that it causes. There are some data to suggest that vertical jump performance may be improved by dehydration equivalent to about 3% of body mass (Viitasalo et al., 1987), but other studies do not confirm this (Hoffman et al., 1995; Judelson et al., 2007a). Systematic studies of the effects on performance of progressive levels of dehydration in events of different intensities and involving skills of varying complexity are urgently needed.

In a comprehensive assessment of the older literature, Sawka and Pandolf (1990) reviewed a large number of studies that measured the effects of varying degrees of hypohydration induced by various methods on measures of strength and power. Not all studies showed a significant decrement in strength performance, measured using isometric and dynamic models, even with relatively high levels of hypohydration (up to 7% of initial body mass). However, in none of the studies reviewed was there a beneficial effect of hypohydration on performance. Anaerobic exercise performance was generally found to be reduced, but again, some of the studies reviewed found no reduction in anaerobic exercise capacity. These authors also identified seven publications representing 10 studies in which the effects of hypohydration of 1–8% of body mass on maximum oxygen uptake or peak aerobic power were measured: in four of these studies, there was no statistically significant effect of hypohydration, but in six of the 10 there was a reduction of 4–27% in peak aerobic power. Interpretation of all of these studies, however, is complicated by the different methods used to induce hypohydration.

In one laboratory study, where dehydration equivalent to 2.5% of body weight was induced before exercise by sauna exposure, a 30% reduction in power output occurred in a test (which was carried out in cool conditions) lasting about 7 min (Nielsen et al., 1982). Another carefully controlled experiment, carried out under simulated race conditions, showed that 1500 m runners ran 3.7% slower when they were dehydrated by about 1.5–2% of body mass before exercise: 3.7% represents 6 s at world-class 1500 m pace (Armstrong et al., 1985). In shorter duration exercise involving greater power outputs (50, 200 and 400 m sprints and vertical jump) diuretic administration had no effect on performance even though the diuretic caused a body mass loss of $>2\%$ (Watson et al., 2005). In contrast to these findings, however, the same research group studied the effects on strength and power of a similar level of hypohydration induced by exercise in the heat and fluid restriction; although they found no effects on vertical jump height or on strength and power measures, performance was reduced in a series of six sets of back squat exercise (Judelson et al., 2007a). Taken together, the results of these studies suggest that body mass reductions of 2–3% have no significant effect on sprint performance. It is possible that sprinting would have been "easier" with the lower body mass, due to less mass for the runner to move. Thus, it is feasible that a reduction in physiological demand may promote improved performance, which may counteract any effects of hypohydration on sprinting. This is in agreement with the conclusions of a review by Judelson et al. (2007b) of the more limited data which suggested that some loss of performance may be observed in strength, power and in high-intensity exercise lasting <2 min, but responses appear to be rather variable (Judelson et al., 2007b). This is essentially the same as the conclusion reached almost 20 years earlier by Sawka and Pandolf (1990).

Performance of repeated sprint tasks appears to be adversely affected by hypohydration. Maxwell et al. (1999) had subjects perform intermittent walking/jogging in the heat, with and without drinking followed by a 2-h recovery period. On the euhydrated trial, there was a loss of 0.07 kg (0.1% of body mass), while on the hypohydrated trial body mass loss was 1.5 kg (2.0% of body mass). They then performed repeated 20 s sprints of increasing intensity at a 10.5% gradient, with 100 s recovery between successive sprints. Sprint capacity, assessed as the total sprinting time completed, was significantly longer when drinks were given during the preceding exercise/heat exposure. In an earlier study, Fogelholm and colleagues (1993) tried to simulate the practices of athletes who make weight before high-intensity sports competition. They used a combination of fluid and energy restriction over a period of 59 h, followed by a 5-h *ad libitum* eating and drinking phase and an overnight fast, to reduce body mass by 2.0 kg (equivalent to 2.7%), and then assessed the effects on 3 × 30 m sprint performance. The participants in this study were wrestlers and judokas, accustomed to this rapid body mass reduction, and the results indicated that this had no significant effect on 30 m sprint performance, averaging 4.16 s after the body mass loss compared with 4.14 s in a control trial. In this and other studies that have looked at athletes making weight, the effects of 1 or more days of severe restriction of energy intake cannot be separated from the effects of hypohydration. It must also be remembered that performance effects that are highly meaningful to the athlete are often far below the sensitivity of the laboratory tests of performance that are used (Hopkins, 2001).

Assessment of complex tasks is even more difficult than the measurement of simple locomotor performance. In complex tasks involving a mixture of intermittent high-intensity, endurance and skill, such as in many team sports, performance is also likely to be impaired at relatively low levels of fluid deficit. McGregor et al. (1999) showed that performance of a soccer skill test, which involved dribbling a ball between a line of seven cones each 3 m apart, deteriorated by about 5% when it was undertaken after simulated soccer activity when no drinking was allowed; in contrast, performance was maintained when drinks were given. The mean body mass loss of their subjects was 2.4% when no fluid was given and 1.4% when fluids were given. Similarly, in a study investigating the motor skill performance of cricket bowling (Devlin et al., 2001), subjects were dehydrated by 2.8% of their body mass and their performance was compared with that in a trial they had drunk flavored water and limited their dehydration to 0.5% of body mass. There was no influence of trial on bowling speed, but bowling accuracy, as determined by line and distance, was significantly worse when undertaken in the dehydrated state. Edwards et al. (2007) reported that the performance of a soccer-specific fitness test was worse after an exercise period without fluid intake, where body mass loss was 2.4% of initial body mass, than when sufficient fluid was given to limit mass loss to 0.7%. The effects of hypohydration on performance are apparent at rather small levels of water deficit, but, as highlighted above, the relative insensitivity of many of the tests of performance used and the potentially confounding effects of the methods used to induce a fluid deficit, mean that the literature is far from clear. There are undoubtedly also effects of mild dehydration on cognitive function and on mood and subjective feelings (Shirreffs et al., 2004; Petri et al., 2006). What is clear is that hypohydration – if sufficiently severe – will impair both physical and mental performance, but depending on the aspect of performance measured, this may be apparent after a very small (1%) loss of body mass or may not occur until substantial (5% or more) losses have occurred.

Although the outcome of team sports is usually determined by the short-term high-intensity efforts that characterize these sports, these sprints occurs in the context of an endurance event. The demands will vary greatly between sports, however; the football player will normally be on the field for the whole 90 min game, but the frequent substitutions and stoppages in most American team sports will change the demands on the individual player. Team sports players do not exercise to exhaustion, and hence the relevance of data from laboratory tests of running or cycling at constant pace to other types of exercise requires clarification. Sunderland and Neville (2005), however, showed that field hockey skill performance is decreased following intermittent high-intensity shuttle running and that this decrease is greater in hot (30 °C) than in temperate (19 °C) environmental conditions. Cheuvront et al. (2003) have undertaken an extensive review of published studies examining the effects of dehydration on endurance exercise performance, including studies of constant power output and those that include intermittent sprints. The conclusion drawn from these reviews is that in situations of exercise in a warm environment (defined as an ambient temperature >30 °C), dehydration to the extent of 2–7% of body mass consistently decreased endurance exercise performance. However, the extent of the performance decrements was highly variable, ranging from a reduction of only 7% to a 60% decline in performance. This suggests that the impairment may be task-specific, that it may be influenced by environmental factors and that there may be a large individual variability in the sensitivity to the effects of dehydration. When the endurance exercise was undertaken in temperate conditions, dehydration by 1–2% of body mass appeared to have no effect on endurance exercise performance when the exercise duration was <90 min, though performance was impaired at levels of dehydration $>2\%$ of body mass and when the exercise duration was longer than 90 min. A water loss equivalent to 2% or more of body mass appears to reduce endurance exercise performance in both temperate and hot environments, especially when the duration of exercise is in the order of 90 min or more.

When exercise intensity is very high, exercise duration will be too short for significant sweat losses to occur of for any ingested fluids to be absorbed in the small intestine (Schedl et al., 1994). Even sprinters, however, may undertake daily training sessions lasting 1–2 h or even more and these will be associated with substantial water and electrolyte losses when the ambient temperature is high. In exercise of longer duration, the general consensus is that it is better to drink water than to drink nothing during prolonged exercise in a warm environment, but drinks with CHO and electrolytes may promote better performance (Sawka et al., 2007). This has been shown using various exercise modes, intensities and durations in differing environmental conditions and with both male and female subjects of varying levels of fitness. In a test of cycling performance to fatigue, Maughan et al. (1989) showed that exercise time to fatigue was about 70 min when no drink was given, 76 min when 100 mL of water was given every 10 min during exercise, 79 min when a concentrated carbohydrate drink was given at the same rate and 91 min when a dilute carbohydrate–electrolyte drink was given. It has long been known that very prolonged exposures to hard physical work in hot environments can lead to muscle cramps in susceptible individuals and that ingestion of water and salt (sodium chloride) can reduce the frequency and intensity of muscle cramps (Moss, 1923; Talbott & Michelsen, 1933; Talbott, 1935). More recent data, mostly from team sports involving intermittent exercise, such as tennis (Bergeron, 2003) and American football (Stofan et al., 2005; Eichner, 2007), have suggested that similar cramps may occur in athletes and that they are more likely to occur in players who sweat profusely and especially in those with a high sweat sodium concentration.

This means that athletes, soldiers, industrial workers and others exposed to exercise and thermal stress should consider their hydration status before beginning exercise, the need for fluid, electrolyte and substrate replacement during exercise and the need for restoration of water and electrolyte balance after exercise. This requires a consideration of what to drink, when to drink and how much to drink. For athletes in events lasting less than a few minutes, intake during competition is neither necessary nor possible, but they should consider whether their precompetition hydration status is adequate and also whether they need fluids during training.

Most athletes drink less than they sweat, and some loss of body mass is therefore the normal response to exercise: this is commonly referred to as involuntary dehydration. Although practical advice to athletes may suggest that loss of 1 kg of body mass equates to loss of 1 liters of sweat, this is not quite true and some body mass loss may be incurred without hypohydration (Maughan et al., 2007). Many of the early studies in this area investigated *ad libitum* fluid intake during prolonged exposures to desert environments. Pitts et al. (1944) showed that even when water was readily available during prolonged walking, intake did not match sweat loss and a progressive dehydration occurred. They wrote that "during work men never voluntarily drink as much water as they sweat, even though this is advantageous for maintaining heat balance, but usually drink at a rate approximating about two-thirds of the water loss in sweat." Hubbard et al. (1984) showed that intake was increased when cool flavored water was provided, but intake did not match loss and some body mass loss still ensued. Noakes (2007) has argued that the only advice that should be given to athletes is that they should drink according to the dictates of thirst, but there is ample evidence of inappropriate drinking behaviors in many sports situations. Dawson et al. (1985) showed that *ad libitum* water intake during tennis practice match conditions amounted to only 27% of the total fluid lost. Again, the studies of Pitts et al. (1944) showed that men forced to drink at a rate equal to sweat loss performed better that when they were allowed to drink *ad libitum*. These results have been confirmed by subsequent laboratory studies. Recent studies suggest that cooling of ingested drinks may lead to better performance in the heat by slowing the rate of rise of body temperature (Lee et al., 2008a, b).

A few participants in endurance events drink more than they lose, and at its most serious, excessive fluid intakes can lead to hyponatremia with potentially fatal consequences (Almond et al., 2005). These cases, however, almost invariably relate to those walking or jogging at the back end of mass participation events, and over-drinking appears not to occur in trained athletes. Some of the problems of excessive fluid intake are perhaps due to inappropriate advice directed at inexperienced athletes, who then ignore the normal physiological signals that provide an impetus to fluid intake, but problems may also result from the prescription of fixed drinking schedules that athletes are encouraged to follow. Sweat rates and sweat composition depend on the ambient temperature and humidity and on exercise intensity, but they also vary greatly between individuals (Shirreffs et al., 2006). This calls into question any advice that prescribes a fixed drinking regimen, and the most recent Position Stand from the American College of Sports Medicine (Sawka et al., 2007) has suggested that fluid intake during exercise should be sufficient to limit any body mass loss to <2% of the pre-exercise mass and that athletes should never drink so much that they gain body mass during exercise. Even this latter caution may, however, not hold true if an athlete begins exercise in a severely dehydrated state. Maughan and Noakes (1991) had already argued that no single prescription of a fixed drinking schedule can be best for all individuals in every situation, and development of an individualized hydration strategy is essential for the protection of health and preservation of performance.

Assessment of pre-exercise hydration status

It is generally agreed that athletes should not begin competition in a state of fluid deficit (Sawka et al., 2007). There may be many reasons why an athlete has not fully replaced prior fluid losses, but it does not seem wise to begin exercise in a state of fluid deficit, especially when substantial sweat losses may be anticipated and opportunities for rehydration may be limited. A simple, convenient method for the assessment of hydration status is therefore desirable, but there is no universal agreement on the optimum pre-exercise hydration status, nor is there a good index of euhydration that can be applied. Some of the various options that can be used to assess hydration status have been described in detail by many authors over many years including Armstrong et al (1994), Shirreffs (2000), Armstrong (2005), Kavouras (2002) and Cheuvront and Sawka (2005). The primary variables that are homeostatically regulated are blood volume and plasma osmolality, but both are subject to short-term variation in response to posture change, exercise, food and fluid intake and a number of other factors, and hence neither is a good index of hydration status (Armstrong et al, 1994; Popowski et al., 2001). Changes in plasma osmolality track well with progressive changes in body mass during exercise in the heat up to a 5% loss of body mass (Popowski et al., 2001). Under well-controlled conditions, plasma osmolality increased by about 5 mOsmol/kg for every 2% loss of body mass by sweating, and during post-exercise water ingestion, values returned toward baseline. Kovacs et al. (1999), however, showed that urinary markers, including osmolality, color and electrical conductance, did not correlate well with hydration status after exercise. This finding is not surprising during periods of rapidly changing body water content, and it should be recognized that such measurements have no value. These findings, however, cannot be generalized to other situations, such as thermal sweating without exercise, and it must also be recognized that the distribution of water losses between the vascular space, the extracellular space and the intracellular space will be affected by both the rate of sweating and degree of sweat loss (Costill, 1977). Urine osmolality and specific gravity were less sensitive than plasma osmolality and showed delayed responses, but blood sampling is impractical in many field situations. Armstrong et al (1994) showed that urine indices may more sensitive to small changes in hydration status than are blood-derived indices when measures are made over a period of days rather than minutes or hours, and have suggested the use of urine color in field settings when urine osmolality or specific gravity measures are not possible. An alternative measure that is simple and inexpensive is urine conductivity, which is closely related to osmolality (Shirreffs & Maughan, 1998); although conductivity is easy and very inexpensive to measure, the lack of published data on normal values restricts its usefulness. Urine color is determined primarily by the amount of urochrome, a breakdown product of hemoglobin, present in the sample (Diem, 1962). When large volumes of urine are excreted, the urine is dilute and solutes are excreted in a large volume of urine, which is very pale in color. When small volumes of urine are excreted, the urine is concentrated and the solutes are excreted in a small volume. This generally gives the urine a dark color. Armstrong et al. (1998) have investigated the relationship between urine color and specific gravity and conductivity. Using a scale of eight colors (Armstrong, 2000), it was concluded that a linear relationship existed between urine color and both specific gravity and osmolality of the urine and that urine color can therefore be used in field settings to estimate hydration status when a high precision may not be needed. A few dietary factors may confound urine color, but these can normally be accounted for.

The acute changes in blood and urine markers in response to changes in posture, food intake and changes in body water content mean that none of the proposed markers of hydration status is reliable when the stability of these factors is not assured. Because of this, the first sample passed in the morning on rising is frequently selected as the criterion sample (Cheuvront & Sawka, 2005), but hydration status may change markedly between waking and the first training session of the day, especially if this occurs later in the day. These markers have been used to assess the hydration status of football players and other athletes reporting for training, where the sample collected is not the first passed that day (Maughan et al., 2004; 2005). The athlete who ingests a substantial volume of fluid between rising and the beginning of training may be well hydrated at the start of training even though the morning urine sample suggests otherwise. If more than a few hours elapse between rising and the beginning of training, fluid losses that are not replaced during that period may result in hypohydration at the start of training. The longer the interval between waking and training, the greater is the probability that the waking urine sample will not reflect hydration status at the beginning of training. Ballauff et al. (1991) have reported that, at least in children aged 6–11 years, there is no circadian rhythm in the urine osmolality, providing some further support for the suggestion that measurements may be made on samples collected at different times of day provided that there is some appreciation of the potential confounding factors.

Collection of urine samples from football players reporting for training (Shirreffs et al., 2005) or match play (Maughan et al., 2007) suggests that many players arrive for training or competition already dehydrated. Similar observations have been reported for professional basketball players (Osterberg et al., 2009) and for collegiate athletes across a range of sports (Volpe et al., 2009). Urine measurements of hydration status will always be rather imprecise, and single values may be of limited usefulness, but an individual who has a consistently high urine osmolality when about to begin a training session or competition is likely to he hypohydrated to some degree. For this reason, regular monitoring of playing squads has become routine in some sports. There is some evidence of a positive correlation between pre-training urine osmolality and the volume of fluid ingested during a training session where fluids are freely available (Maughan et al., 2005). This appears logical, as athletes who begin training with a higher urine osmolality may experience a greater sensation of thirst and therefore drink more, but this relationship has not been seen in all populations studied. A urine osmolality of more than about 900 mOsmol/kg is consistent with a body water deficit of about 2% of body mass (Shirreffs & Maughan, 1998). The American College of Sports Medicine position stand suggests that a urine osmolality $\leq$ 700 mOsmol/kg is indicative of euhydration (Sawka et al., 2007).

Bioimpedance methods can be used to estimate total body water content, and have attracted much attention, as the equipment required is relatively inexpensive, and the technique is straightforward and minimally invasive. However, acute changes in body water content are not reliably detected by the method, and it is sensitive to posture (Shirreffs & Maughan, 1994), skin temperature (Gudivaka et al., 1996) and other factors unrelated to body water content (O'Brien et al., 2002). The lack of precision and accuracy inherent in the methodology, together with the various confounding factors that influence results, limit its use for hydration monitoring (Institute of Medicine, 2005).

The choice of timing of sample collection will be affected by several factors and interpretation of the results must take account of this. There is no published evidence of a significant effect, but it seems wise to collect a urine sample in mid-stream or to collect and mix the whole void before retaining a sample. Only a few microliters are required for measurement of osmolality, but it is probably convenient to collect between 5 and 30 mL in an appropriate clear specimen tube. In view of the sensitivity of athletes about analysis of samples for WADA-prohibited substances, numerical identifiers rather than names should be used on all samples where athletes are liable to drug testing. Specific gravity measurement by refractometry or reagent-impregnated strips for urinalysis (e.g. Bayer Multistix, Bayer Diagnostics, Bridgend, UK) has the advantage of using apparatus that is inexpensive to purchase and to operate, requires little operator skill, is portable and can be used in the field. It should be noted, however, that the published evidence on the reliability of commercial reagent strips for the measurement of urine specific gravity is somewhat mixed; not all studies report good agreement with standard methods (de Buys Roessingh et al., 2001). Measurement of osmolality requires the use of a relatively expensive instrument that is not easily transported, requires an electricity supply and requires some technical competence on the part of the operator. Osmolality is now most commonly measured by freezing point depression, but equipment using vapor pressure analysis is also used. Samples for osmolality analysis are generally stable for some days at room temperature or on refrigeration. Some precipitation of calcium salts is likely after a short period of storage. This will not affect the osmolality or specific gravity to any significant degree, but the turbidity that ensues will preclude a reliable measure of color. The precision of the method will depend on the equipment used and on the individual operator, but highly reproducible results should be obtainable.

Water loss and sweat loss during exercise

An approximation of the amount of sweat lost during training or competition can be obtained from changes in body mass, with corrections applied for any fluid intake and any urine passed. Fluid intake can be assessed easily by change in mass of drinks bottles. When sweat rates are high, each kg of mass loss approximates 1 liter of sweat loss, but the relationship is not good at low sweat rates. In addition, not all of the body water loss is in the form of sweat; some is lost from the respiratory tract, and this route of water loss can be substantial when breathing hard in dry environments. Unlike sweat, respiratory water loss is electrolyte free but it will still result in a loss of body water, and hence differentiation between these routes of loss is probably unimportant. Water is also lost by diffusion through the skin and this is also a loss of solute-free water: losses by this route depend on body surface area but are independent of temperature and sweating rate, and generally small enough to be ignored (typically about 17 mL/h for a man with a body surface area of $2\,m^2$ (Dill et al., 1966)). Some body mass loss also results from the substrate used for energy metabolism; these losses are also generally small – typically 200–300 g/h in hard exercise – relative to the sweat rates encountered during such exercise. Substrate oxidation also generates water of oxidation, which is added to the body water pool; each gram of CHO oxidized results in the formation of 0.6 g of water, which is added to the body water pool. Oxidation of 1 g of fat results in the formation of slightly >1 g of water, depending on the degree of saturation of the fatty acids being oxidized. The effects of these factors on the interpretation of body mass changes have been discussed in detail by Maughan et al. (2007); they can generally be ignored when sweat rates are high, but are significant at low sweat rates. Some examples of these calculations are shown in Table 1.

Elite male football players sustain an average intensity of about 75% of VO_{2max} for the duration of the game, and total substrate oxidation is typically about 300 g, mostly in the form of carbohydrate (Bangsbo et al., 2006). This will generate about 200 g of water of oxidation, meaning that a loss of body mass of about 500 g is possible with no effective loss of body water. This is generally ignored when estimating sweat losses because it is small relative to the sweat losses of many athletes in training, but many athletes will not lose more than about 1 kg over the course of a game or a training session lasting 90 min (Maughan et al., 2005). For these individuals, therefore, the body water deficit cannot simply be assumed to correspond to the mass loss. The decision on whether or not to correct body mass changes for factors other than sweat loss will depend on how reliably these other components can be estimated and on how precise an estimate is required. In most applied sports science settings, a categorization as a heavy or light sweater is sufficient. Interpretation of changes in hydration status is complicated by changes in the storage of water in association with glycogen and by changes in the tonicity of body fluids as a result of loss of hypotonic sweat. As much as 3 g of water may be stored in skeletal muscle in association with each gram of glycogen (Olsson & Saltin, 1970), and the progressive utilization of the muscle glycogen store during prolonged exercise might be expected to release some of this water into the body water pool. There is some debate as to the fate of this water when the body glycogen stores are changing (Maughan et al., 2007). Pastene et al. (1996) estimated that about 1300 mL of water would be made available to the body water pool because of the depletion of muscle glycogen during the course of a marathon race, but this may well be an overestimate.

Accurate measurement of body mass change requires a balance readable to 10 or 20 g, but balances with this level of sensitivity are now readily available at a reasonable cost. Greater precision is difficult to achieve, and is probably not necessary for routine use provided that the sweat loss is sufficient for the mass change to be recorded with a reasonable degree of precision – mass change should probably be at least 10 times the readability of the balance. Measurements should ideally be made with subjects nude, as clothing will absorb an unknown and variable amount of sweat. Where an accurate result is required, subjects should shower and towel dry before the first measurement of mass and repeat this process

Table 1. Examples of change in hydration status calculations

	Pre-exercise body mass (kg)[*]	Post-exercise body mass (kg)[*]	Total body mass loss or gain (kg)[†]	Drinks consumed during exercise (g or mL)[‡]	Urine excreted during exercise (g or mL)[§]	Sweat volume (mL)	Body mass change (%)[†]
60 min football training	70.00	68.00	−2000	0	200	1800	−2.9
3 h golf	70.00	70.00	0	500	400	100	0.0
2 h tennis	70.00	70.20	+200	1000	0	800	+0.3

[*] Body mass measured nude with dry skin.

[†] + = mass (water) gain; − = mass (water) loss; 0 = no change in mass (water balance).

[‡] Drinks consumed any time between the two body mass measurements.

[§] Urine emptied from the bladder any time between the two body mass measurements.

before the post-exercise measurement to ensure the same degree of wettedness of skin and hair. Where nude measurements are not possible, subjects should wear minimal clothing and should change into identical dry clothing for the post-exercise measurement. It may be convenient to ask subjects to urinate and defecate if necessary before the first measurement as any urine or feces passed during the measurement period should be collected and weighed. Removing the need to collect these simplifies the whole process.

Electrolyte balance

Sweat contains a variety of electrolytes, especially sodium and chloride, which are the major ions of the extracellular space. Smaller amounts of potassium, and smaller still amounts of calcium, magnesium, iron and other minerals as well as a range of organic compounds are also present in sweat. Of all these components, it seems to be the sodium loss that is most significant for the athlete. The composition of sweat is influenced by many factors, including sweating rate, diet and acclimation status, but there is also a large inter-individual variability even in a homogeneous subject population (Robinson & Robinson, 1954). Given the potential link between sodium loss and muscle cramps (Talbott, 1935), those athletes with large salt losses through sweating may be predisposed to exercise-related cramp (Bergeron, 2003; Stofan et al., 2005). This may arise from large volume losses or from loss of a smaller volume if the sodium content of sweat is high. Salt losses cannot therefore be predicted from volume loss alone. When sweat electrolyte losses are high, they must be replaced, if not during exercise, then certainly between exercise sessions. A high dietary salt intake, however, may adversely affect blood pressure and cardiovascular risk in salt-sensitive individuals, and hence not all athletes should consume a high salt diet or consume drinks with a high sodium content during exercise.

There are different ways of assessing the composition of sweat, and the method of choice will depend on several factors. The whole body washdown technique will give the most precise result if properly applied (Shirreffs & Maughan, 1997), but for most practical purposes regional collection methods are the only realistic option. In essence, these consist of the application of an absorbent swab to an area of skin that has been cleaned and dried. The swab is covered with an adhesive non-porous film to prevent evaporation of sweat. After a suitable time interval, the patch is removed and the sweat is extracted for analysis. Regardless of the method used, care must be taken to ensure that no evaporation of sweat can occur from the patch after removal from the skin. Samples may be collected from different body sites, and it has long been known that there are regional differences in the sweat electrolyte content: Johnson et al. (1944) ascribed the first report of this to Kittsteiner in 1911. Collections can be made at several sites and the results combined as an arithmetic mean; alternatively, a weighting factor can be used to account for regional differences in composition. Sites that are commonly used include the forehead, forearm, chest, back, thigh and calf. Lemon et al. (1986) derived several equations for the estimation of whole body urea loss in sweat based on regional sampling at the upper back, lower back, chest, stomach and thigh. Patterson et al. (2000) compared sweat samples obtained from eleven regional collection sites with the whole body washdown method, and found that the sodium concentration at the calf and thigh was more highly correlated with the washdown values than was the case for composite data from 4 or 8 regional sites. The use of a single sampling site may increase the potential for error but may be sufficient to identify individuals with very high salt losses. The use of enclosed patches or capsules for collection of sweat samples will overestimate sweat sodium content, perhaps because preventing the sweat from evaporating under the patch leads to very high local sweat rates and to waterlogging of the skin.

Athlete feedback

The information provided to athletes and coaches, and to medical and other support staff, must be presented in such a way as to offer both a record of the data collected and some constructive suggestions on any modifications required to current hydration practice. Information must be present in a way that is easily understood and any recommendations must be amenable to implementation. Athletes often look to support staff to inform them of what they should do, but there are several simple steps that they can take themselves to identify whether their current hydration practice is appropriate to their needs.

1. Athletes should be encouraged to weigh themselves before and after training sessions of different durations and intensities and in different weather conditions. After some experience, they will learn to make reasonable estimates of their sweat losses under different conditions. It is recommended that weight loss should generally not exceed about 1–2% of body mass. If more than this has been lost, then they probably did not drink enough and should drink more next time, especially in warm weather. Except in the situation where the athlete began exercise in a hypohydrated state, there should never be a need to drink so much that weight gain occurs.

2. Any athlete who is passing urine less often than normal may be dehydrated. If urine volume is small and urine color becomes darker than normal, fluid intake should be increased. The aim should NOT be for urine to be as pale as possible.

3. High salt losses appear to be a contributing factor in some cases of muscle cramp. "Salty sweaters" who are prone to muscle cramps may benefit from drinks with more salt and may need more salt in food when sweat losses are high. The use of salt tablets is seldom, if ever, warranted. A crude self-assessment of salt losses can be performed by wearing a black T-shirt and looking for salt stains where the sweat has evaporated.

Weight category events

Participation in weight category events can pose a particular challenge for athletes. Most athletes in such events – which involve high-intensity exercise lasting no more than a few minutes – use various strategies to achieve their target body mass at weigh-in. For some, this requires only a small reduction in the last few hours and days, but many athletes will lose $>5\%$ of body mass in the last 24 h. Inevitably, a substantial part of this loss must be achieved by loss of body water. There is then a variable period before competition, depending on the sport. The demands vary greatly between sports: jockeys typically race on 2–4 days per week over a long season, with several races at each meeting, whereas the professional boxer may have only one to two fights per year.

Strategies for the recovery between weigh-in and competition will depend on the severity of the weight loss, the strategies used to achieve that loss, and the time available before competition. The main priorities for competitors in single events of short duration are to ensure that muscle glycogen stores are adequate and that rehydration is achieved. The strategy will also be influenced by other factors: in some sports, such as lightweight rowing, restoration of physiological function is crucial, but, because body mass is supported by the boat, any gain in body mass per se is of less importance. In sports such as wrestling, however, an absolute increase in body mass will be an advantage as the opponent has to contend with this greater mass. In sports with many events over the course of the day and with repeated weigh-ins, such as horse racing, maintenance of blood glucose levels throughout the day becomes important.

There are clearly practical issues that will depend on the sport, but making the target weight as early as possible in the weigh-in period will allow the longest possible time for recovery before competition. Rapid rehydration and restoration of circulating blood volume are best achieved by the ingestion of hypotonic carbohydrate–electrolyte solutions (Maughan & Shirreffs, 1997). The carbohydrate will contribute to blood glucose, helping to reduce the risk of hypoglycemic and will, if time allows, promote restoration of liver and muscle glycogen stores. Increasing the carbohydrate content of ingested fluids above about 4–6% will slow the rate of gastric emptying, and concentrations of 10% or more may also cause a transient net secretion of water into the small intestine that will further exacerbate the effects of hypohydration on plasma volume (Evans et al., 2009).

Summary

Dehydration impairs both physical and mental performance, and hence fluid replacement strategies are necessary when large sweat losses occur. Water and salt losses vary greatly, and hence individual prescription is required. Athletes should take responsibility for identifying their own rehydration strategy, which means assessing their own hydration status before exercise, assessing sweat rates and the adequacy of current drinking behavior and estimating the need for water, salt and carbohydrate replacement.

Key words: hydration, fluid loss, sweat, sodium, fatigue, performance.

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