Abstract
Hydration status has profound effects on both physical and mental performance, and sports performance is thus critically affected. Both overhydration and underhydration – if sufficiently severe – will impair performance and pose a risk to health. Athletes may begin exercise in a hypohydrated state as a result of incomplete recovery from water loss induced in order to achieve a specific body mass target or due to incomplete recovery from a previous competition or training session. Dehydration will also develop in endurance exercise where fluid intake does not match water loss. The focus has generally been on training rather than on competition, but sweat loss and fluid replacement in training may have important implications. Hypohydration may impair training quality and may also increase stress levels. It is unclear whether this will have negative effects (reduced training quality, impaired immunity) or whether it will promote a greater adaptive response. Hypohydration and the consequent hyperthermia, however, can enhance the effectiveness of a heat acclimation program, resulting in improved endurance performance in warm and temperate environments. Drinking in training may be important in enhancing tolerance of the gut when athletes plan to drink in competition. The distribution of water between body water compartments may also be important in the initiation and promotion of cellular adaptations to the training stimulus.

Introduction
It is generally recognized that failure to maintain an adequate hydration status will impair both physical and mental performance in a wide range of laboratory tasks. There is some debate, though, as to the level of dehydration or
overhydration at which effects on performance become apparent, both in statistical terms and in terms of impairments that are meaningful for the athlete. This lack of consensus is hardly surprising, given the nature of the different exercise challenges used, the effects of varying environmental conditions, the different methods used to induce hypohydration, the varying characteristics of the subjects studied, and the individual variability in responses. There are also likely to be differences in the response depending on whether exercise begins with a pre-existing body water imbalance or whether dehydration develops as exercise progresses. Fluid replacement strategies during competition are also a matter of considerable controversy, with some advocating a planned strategy designed to limit the development of a water deficit or overload [1], while others insist that a simple reliance on thirst will ensure that the amount of fluid ingested is optimal [2, 3].

The focus of much of the available research has been on the consequences of a water deficit rather than water excess: the latter condition is uncommon and has generally been noted in very slow participants in marathon events or in other very prolonged activities. The focus of scientific interest has also been on the potential influence of hydration status on performance in sports competitions or on laboratory tasks intended to simulate the component physical and cognitive functions, but most athletes spend far more time in training than in competition. Elite rowers, for example, typically train for 4–6 h per day, but the event itself lasts a little over 6 min. Swimmers may train for 3–5 h per day for an event lasting less than 60 s. Hydration should therefore not be an issue in competition for these athletes unless they begin the event in a severely hypohydrated state, but substantial losses of water and electrolytes may be incurred in training. Even when the training duration is too short to cause major sweat losses, it is likely to be correspondingly more intense, and there will then be fluid redistribution between body water compartments: high-intensity exercise causes a substantial increase in the osmolality of the intracellular space of the active muscles and this will result in a corresponding decrease of the extracellular compartments, including the vascular space.

Notwithstanding the debate about the optimum hydration status and the most appropriate drinking strategy for athletes in competition, several considerations apply in relation to appropriate drinking behaviors in training. On the basis of the available information, it could be suggested that ensuring adequate hydration status would allow the athlete to maintain a high training load, in terms of intensity and volume, and thus maximize the training stimulus. Drinking in training would also allow the athlete to rehearse drinking strategies for competition, to practice the physical actions of drinking while engaging in the actions that characterize their sport, and to become accustomed to the sensation
of exercising with fluids in the stomach. On the other hand, it could equally be suggested that training with a less than optimum hydration status would increase the physiological strain experienced by the athlete: this could have the effect of augmenting the training response, but also has the potential to increase the risk of illness or overtraining syndromes. With only limited evidence available, this analysis will attempt to evaluate which of these options might be more effective.

Water and Salt Balance in Training

The net fluid balance over a training session is determined by the rate of water loss and the amount of fluid ingested in training, and both loss and intake are influenced by many factors. Sweat losses are influenced by training intensity and duration, and by weather conditions, including temperature, humidity and wind speed, as well as by the practical considerations that dictate fluid availability. Drinks can be made available in essentially unlimited amounts in training for indoor sports and for some outdoor activities such as tennis or football training. Cyclists can carry some fluid with them without undue inconvenience or weight penalty. In running, however, it is unrealistic to carry significant amounts of fluid and few elite distance runners would ever expect to drink in training. Intake is also influenced by the preferences of the individual and the culture of the sport. The subjective response to the absence of fluid intake is likely to depend to a great extent on whether the athlete voluntarily chooses not to drink or whether this is imposed, either by the coach or by external circumstances.

Leiper et al. [4] used a deuterium tracer method to measure water turnover in a group of cyclists who covered an average of 50 (range 12–146) km/day in training at an average speed of 29 km/h in a cool (10°C) environment and in a sedentary group. Daily body mass remained essentially the same in both groups over the study period. Average median water turnover rate was faster (p < 0.05) in the cyclists (47 ml/kg per day, range 42–58) than the sedentary subjects (36 ml/kg per day, range 29–50; fig. 1). The average median daily urinary loss was similar in both groups, so the calculated non-renal daily water loss (comprising mostly sweat but also including respiratory, transcutaneous and fecal losses) was faster (p < 0.05) in the cyclists (19 ml/kg per day, range 13–35) than in the sedentary subjects (6 ml/kg per day, range 5–22), but there was no relationship between the average distance cycled daily and the water turnover rate. A report of fluid intake of elite Kenyan distance runners in training suggested that in spite of the absence of any fluid intake during the
one or two daily training sessions carried out, hydration status was well main-
tained over the 5-day study period [5]. Experience suggests that similar results
would be obtained in other groups of athletes who choose not to drink in
training: in spite of substantial fluid deficits incurred in each training session,
there is not a progressive negative fluid balance over a period of days or weeks.
This may imply that athletes make up for lost fluids after exercise and at meal
times rather than during the actual training sessions, perhaps for reasons of
convenience.

Even within a single group of athletes carrying out the same training session
and with the same access to fluids, there can be a large difference in both sweat-
ing rate and drinking behavior. To illustrate the variability in response that is
normally observed, some of the available data on sweat losses and fluid intake in
elite male football players in training are summarized in table 1. All players in
these studies were members of the first team squads at leading European clubs,
and training was generally similar for each of the training sessions. Even though
these players represent a rather homogeneous group, large individual differ-
ences in both sweating rates and drinking behaviors are apparent. Figure 2
shows the volume of fluid consumed in relation to the estimated sweat loss in
elite football players in training: the response is highly variable, but, in this co-
hort of players, none drank so much that they gained weight. In a few players,
the fluid intake was not sufficient to maintain body mass within 2% of the initial

Fig. 1. Calculated average median daily water turnover rate, urine output and non-renal
water loss for a group of cyclists in training and a sedentary group of subjects. Adapted
from Leiper et al. [4].
Hydration during Intense Exercise Training

The sweat electrolyte concentration also varies greatly between individuals, and those who have high sweat rates, and high sweat sodium concentrations can lose substantial amounts of salt (sodium chloride) in training [6]. For some individuals, the losses in a single training session may far exceed the recommended daily salt intake.

Potassium is also lost in sweat. Sweat potassium concentration ranges from 5 to 10 mM [7], and this has been the basis for adding potassium to a sport beverage, typically at a concentration of about 5 mM. Sodium plays a critical role in

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**Fig. 2.** The volume of fluid consumed and the sweat volume lost in training in several groups of football players. None of these players drank so much that they gained weight, but most drank sufficiently to limit body mass loss to less than 2% of the initial body mass. Data from various sources, including unpublished data. The line of balance would be where intake exactly matched loss so as to maintain the pre-training body mass.

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**Table 1.** Sweat losses and fluid intake in elite professional football players

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Humidity, %</th>
<th>Players</th>
<th>Sweat loss, ml</th>
<th>Fluid intake, ml</th>
<th>Dehydration, %</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>32°C</td>
<td>20</td>
<td>26</td>
<td>2,193 (1,670–3,140)</td>
<td>972 (239–1,724)</td>
<td>1.59 (0.71–3.16)</td>
<td>[46]</td>
</tr>
<tr>
<td>27°C</td>
<td>55</td>
<td>24</td>
<td>2,033 (1,385–2,382)</td>
<td>971 (265–1,661)</td>
<td>1.37 (0.45–2.58)</td>
<td>[47]</td>
</tr>
<tr>
<td>28°C</td>
<td>56</td>
<td>20</td>
<td>2,221 (1,515–2,895)</td>
<td>1,401 (721–2,278)</td>
<td>1.15 (–0.24 to 2.30)</td>
<td>unpubl. data</td>
</tr>
<tr>
<td>25°C</td>
<td>60</td>
<td>24</td>
<td>1,827 (884–3,100)</td>
<td>834 (243–2,057)</td>
<td>1.22 (–0.24 to 2.60)</td>
<td>unpubl. data</td>
</tr>
<tr>
<td>5°C</td>
<td>81</td>
<td>16</td>
<td>1,690 (1,060–2,650)</td>
<td>423 (44–951)</td>
<td>1.62 (1.06–2.65)</td>
<td>[48]</td>
</tr>
</tbody>
</table>

All training sessions lasted about 90 min.
restoring fluid balance after exercise; however, there is no evidence that the addition of potassium to drinks improves the restoration of fluid balance following dehydration, though restoration of potassium balance may be important for the maintenance of the intracellular water space [8, 9]. General guidelines for promoting recovery after exercise have focused on replacing sodium [1], with potassium mainly consumed through food (e.g. fruit, vegetables) later during the recovery process. As discussed later, though, cell volume may have important implications for both recovery from training and adaptation to the training stimulus.

**Hydration Status and Stress Responses**

Restriction of fluid intake during prolonged exercise results in increased core temperature, increased heart rate and increased perception of effort: there is also an increased plasma cortisol concentration during exercise when no fluid is ingested compared with trials where fluid is consumed [10]. These responses are likely to be amplified in warm environments. It might be argued that stress is an important element of the stimulus to adaptation, but because of the general suppression of immune function that usually accompanies elevated circulating cortisol levels, these observations raise concerns about a possible increased risk of infectious illness if hard training is performed consistently in a hypohydrated state. Some evidence to support this comes from a study on rats where intravenous endotoxin injection induced a febrile response in dehydrated rats but no such response was seen when the same endotoxin was injected into euhydrated rats [11]. There are data to show that even relatively mild (3% body mass loss) levels of dehydration can result in a decrease in the secretion rates of some of the salivary antimicrobial proteins that play an important role in mucosal immunity. Fortes et al. [12] reported decreased saliva secretion rates of lysozyme and α-amylase during prolonged exercise in the heat when no fluid was allowed, though the secretion rate of saliva secretory IgA remained unchanged. In the control trial, where sufficient fluid was consumed to replace sweat losses, there were no changes in secretion rates of any of the measured parameters.

Although a change in intestinal barrier function, with consequent increase in the risk of invading pathogens, might be postulated in the presence of hypohydration, Smetanka et al. [13] did not find any association between markers of gut barrier function and fractional body mass loss after a marathon race. Such cross-sectional studies, however, can provide only very limited information. A more recent review of gastrointestinal (GI) problems in athletes concluded that
preventing dehydration might reduce the risk of GI complaints during intense exercise [14]. After the onset of exercise, splanchnic blood flow (SBF) decreases by about 20% at 10 min and by 80% after 1 h of exercise at 70% VO₂max [15]. This decrease in SBF is often cited as an important factor in the development of GI problems during exercise, especially in symptomatic athletes [16, 17]. Thus, the ingestion of fluid during exercise could have a protective effect on SBF and reduce the incidence of GI complaints during exercise. This may be important for those individuals who are especially prone to GI upset when training or competing.

**Rehydration and Recovery between Training Bouts**

The athlete’s priorities for recovery after a training session will depend on several factors, but key among these is intensity and duration of the first session. This will determine the extent of substrate depletion and sweat losses, though the latter will also depend on environmental conditions and on the sweating characteristics of the individual. Also of critical importance is the time available for recovery before the next training session begins. Key considerations after endurance or team sports training are the replacement of carbohydrate stores in muscle and liver and restoration of water and salt balance [18]. Ensuring an appropriate nutrient, metabolic and hormonal environment to stimulate and support the adaptive response to the training stimulus is also a major objective for all athletes, as discussed in detail below.

The volume of water consumed after training should be sufficient to replace any net fluid deficit (the difference between water losses and water ingested) incurred during the training period. In addition, sufficient fluid should be ingested to allow for ongoing losses in sweat, expired breath and urine, and it is often recommended that the volume of fluid consumed in the immediate post-exercise period should be about 1.5 times the net fluid deficit [6]. Wong et al. [19] showed that a prescribed fluid intake was more effective than an ad libitum drinking schedule in restoring exercise capacity when applied during the 4-hour recovery period between two endurance exercise bouts. Even though the total fluid intake was the same on both trials, a greater volume was ingested in the early stages of recovery with the prescribed drinking schedule. The relative effects of the carbohydrate content of the drink and the fluid replacement could not, however, be separated with the study design used. Sufficient salt should be consumed to match sweat electrolyte losses and thus prevent a rapid diuresis: without restoration of salt balance, effective restoration of water balance cannot be achieved [20]. Water may be consumed in the form of a variety of beverages.
Training the Gut

The availability of ingested fluid is determined by the rates of gastric emptying and intestinal absorption. Either of these processes can limit the availability of ingested food and fluids. It has long been known that a high energy intake (i.e. regular intake of a high volume of food) is associated with a rapid mouth-to-caecum transit time [22]. There is some evidence that the rate of gastric emptying of liquids is not affected by a few days of ingestion of large volumes of liquids, but subjective reports of gastric comfort show that tolerance develops rapidly [Leiper and Maughan, unpubl. data]. In addition, limited evidence shows that gastric emptying rates may be increased with endurance training [23].

The absorptive capacity of the gut is capable of rapid adaptation to periods of feeding and fasting, and is highly responsive to changes in the composition of the diet. The maximum rates of carbohydrate absorption that can be achieved may be enhanced by a short period of adaptation to a high carbohydrate diet [24]. In a study of highly trained athletes, a group who consumed glucose during each of their workouts over a 4-week training block increased their ability to oxidize this carbohydrate, while muscle oxidation of carbohydrate consumed during exercise remained constant in a matched group who did the same training with ingestion of water [25]. The design of this study could not distinguish whether the adaptation was achieved by a higher intake of carbohydrate or in response to the specific intake of the carbohydrate during exercise. An increased capacity to absorb carbohydrate may be important from a hydration perspective as carbohydrate uptake in the intestine can drive the movement of water from the intestinal lumen into the circulation [26].

These data suggest that athletes in endurance events may benefit from specific efforts to increase tolerance to large volumes of carbohydrate-containing fluid in the gut and to enhance the rate at which ingested water and substrate can be absorbed into the circulation. Further, higher amounts of carbohydrate may be tolerated during prolonged exercise if attention is given to the type of carbohydrate (e.g. glucose and fructose) [27].

Finally, the temperature of the drinks that are consumed during exercise is also important, especially when training in the heat. A recent meta-analysis
shows that beverages with a temperature <22°C significantly increase palatability of the fluid, with consequent effects on the volume of fluid consumed and on hydration status during exercise [28].

**Adaptation to Dehydration and Coping Strategies**

Some athletes and coaches deliberately restrict fluid intake in training in the belief that the body will adapt to a lack of fluid and will therefore cope better with dehydration in competition. Deliberate restriction of fluid intake has long been a common practice in sport [29] and added to this the use of purgatives, laxatives and ‘sweating liquors’ was also common among early athletes to promote weight loss [30]. Practices in many sports have changed substantially, but particularly in the weight category or weight-sensitive sports, where acute dehydration is a normal part of pre-competition preparation for the majority of competitors, chronic hypohydration is not uncommon [31]. Even when fluids are provided, it is common for athletes in weight category sports to drink little or nothing during training, perhaps in the belief that they will adapt to the dehydrated state [32]. There is no evidence that the body adapts to dehydration, although those who frequently restrict fluid intake may learn to complain less about the symptoms that accompany it. It is perhaps also likely that those who are resistant to the effects of dehydration are those who persist in participation in weight category sports. Those who cannot tolerate the weight-making process are likely to discontinue participation in the sport.

Dehydration during training may, however, enhance the effectiveness of a short-term heat acclimation program in both untrained individuals and in highly trained athletes [33]. This seems to be a consequence of the greater elevation of core temperature that occurs when exercising in the heat in a hypohydrated state and the consequently greater cardiovascular adaptations that ensue, including the extent of the increase in vascular volume [34, 35]. Emerging evidence suggests that the adaptations that occur in response to even a short period of heat acclimation may promote enhanced endurance performance in a temperate environment [36].

**Hydration and Adaptation to Training**

The aim of training is, or should be, to enhance performance in competition. To achieve this, the training stimulus must induce a selective expression of the genetic potential of the individual. There must be a selective stimulation of protein
synthesis and breakdown so that the tissue content of proteins that convey a performance advantage is increased. For the strength athlete, this may mean an increase in the muscle content of the contractile proteins, actin and myosin: for the marathon runner, an increase in muscle mass would be a disadvantage, so the aim is to increase the muscle content of mitochondrial protein and this an increase in oxidative capacity. These are examples only, and a complex pattern of tissue remodeling takes place in response to training. There has been considerable focus on the nutritional strategies that can promote these changes, especially on the provision of protein [37].

The potential role of hydration status in modulating the response to training has been largely ignored, but hard training can not only induce substantial fluid deficits, it can also result in large movements of fluid between body water compartments. Changes in the water content of cells can have a large effect on all aspects of cell function. In short-term high-intensity exercise, there is a large increase in intracellular osmolality in the active muscles as glycogen is broken down to lower molecular weight intermediates, and other complex molecules are degraded. In spite of the existence of compensatory mechanisms that attempt to prevent changes in cell volume, the high intracellular osmotic pressure causes water to move from the extracellular space into the active muscles, resulting in cell swelling. Raja et al. [38] showed a 13% increase in the intracellular water content of forearm muscle during intensive forearm wrist flexion exercise. In high-intensity running or cycling exercise, the increase in the water content of the active muscles is likely to be even higher because of the greater accumulation of metabolic intermediates, and intense cycling exercise is accompanied by a decrease in plasma volume of 20–25% or even more [39].

Major disturbances of cell volume have profound effects on cellular metabolism [40]. Cell swelling will favor anabolic reactions, including protein synthesis and glycogen synthesis, while cell shrinkage will encourage these reactions to proceed in the opposite direction [41]. The expansion of cell volume after intense exercise may therefore play an important role in the initiation and regulation of the changes in protein synthesis that must occur in order to produce the functional changes that accompany training. It may be worth noting that the ratio of intracellular to extracellular water also falls with age [42], and this may be relevant to the generally observed reduction in the capacity of the older individual to respond to a training stimulus. At present, however, our understanding of the influence of cell volume changes on regulatory pathways does not allow practical recommendations to be made [43]. Finally, it is important to understand that water intake per se does not equate to cell swelling, as these processes are much more complex [40].
In summary, training in the hydrated state and/or resuming euhydration as soon as possible after exercise seem to be more appropriate strategies to support training adaptation than training in a hypohydrated state, although insufficient data are available to permit firm conclusions.

**Practical Implications**

Optimizing hydration practices in athletes should be initiated via education and individual hydration status and sweat rate assessments. Sweat rates can be assessed fairly well using body mass changes, although some limitations exist. Respiratory water loss, substrate oxidation and mass loss, as well as changes in body water due to fluid intake and urinary or fecal loss all contribute to errors when estimating sweat rate from changes in body mass [44]. However, by measuring fluid intake, selecting critical exercise sessions, and repeating these measurements in various environments, estimates of sweat rates can be determined fairly well from body mass changes. It is worth remembering that most investigations into the effects of sweat loss on exercise performance have used body mass loss as the measure of sweat loss, so it is not inappropriate to advise athletes on the basis of body mass loss.

Athletes often begin training in the dehydrated state. Assessing urine osmolality or specific gravity can be helpful in establishing a baseline and initiate good drinking behavior in athletes. However, urinary measures are likely to be unreliable after exercise as changes lag behind the changes occurring in the plasma [46]. Sport nutrition practitioners may use these strategies to establish hydration status and sweat rates, and improve athletes’ knowledge and skills pertaining to the individualization of hydration strategies. Too often, however, these strategies can create an athlete dependency on such services.

While it may be useful to determine individual sweat rates, it appears equally important to teach the athlete to increase tolerance to greater fluid volumes and higher carbohydrate intakes, especially for prolonged exercise and exercise in the heat. If changes in fluid consumption should impact performance at competitions, practice to drink should be integrated into high-intensity training sessions. It is expected that the GI system adapts with repeated exposures to drinking in training.

**Disclosure Statement**

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References


29 Downer AR: Running Recollections and How to Train. London, Gale and Polden, 1902.