Heat stress and exercise increase water loss from the body, primarily in the form of sweat. For some occupational groups, including miners, construction workers in hot climates, soldiers, and some athletes, daily water losses can reach 10–12 L. These losses must be replaced on a daily basis to maintain functional capacity. Both hyperhydration and hypohydration will, if sufficiently severe, impair all aspects of physiological function. Tests of strength and power are largely unaffected by dehydration of up to about 2%–4% of body mass. However, decrements in the performance of endurance tests may occur at these levels, especially in warm environments. Body water deficits, if sufficiently severe, also have adverse effects on measures of mood and on some elements of cognitive function and result in an increased subjective rating of the perception of effort. Beverages consumed during exercise can provide carbohydrates and electrolytes that may be beneficial in some situations; however, drinking in volumes required to match sweat loss may cause gastrointestinal discomfort that will generally impair performance.

INTRODUCTION

Both hyperhydration and hypohydration will, if sufficiently severe, impair all aspects of physiological function and may ultimately prove fatal. Something approximating euhydration is, therefore, a prerequisite for optimum physical and mental performance. However, there is a range of values for body water content and tissue osmolality over which the body functions adequately, if not optimally. There is some debate 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 individual.

Water intake is episodic, while losses are continuous. Consequently, the body water balance fluctuates over the course of a normal day, though it generally returns to the same point over a 24-hour cycle. Effective homeostatic mechanisms mean that normal hydration status can be maintained on a daily basis at a wide range of water intakes. This is applicable only when there is an intake of water sufficient to replace the daily losses, as the body has no mechanism to compensate for an inadequate water intake. Endogenous water production is derived entirely from oxidative metabolism and is, thus, dictated by the metabolic rate and the fuels oxidized. For the average adult woman living in Europe, the adequate daily water intake from all sources including food is deemed to be 2.0 L, while the corresponding value for adult men is 2.5 L. Assuming that the data on which this conclusion is reached are normally distributed, this means that half of the population remains healthy on less than that amount, while half of healthy adults consume more. In the United States, the Institute of Medicine used data reported in the national dietary survey to assess habitual intake and set the adequate intake (AI) level for total water intake for young men and women (aged 19–30 years) at 3.7 L and 2.7 L/day.
respec
tively.2 Both reports recognized that body water deficits can occur due to reduced intake or increased water losses from physical activity and environmental exposure (e.g., heat). However, they also concluded that, on a day-to-day basis, fluid intake, driven by the combination of thirst and the habitual consumption of beverages at meals and on other occasions throughout the day, normally allows maintenance of hydration status and total body water at appropriate levels.

It is important to note that the AI level is not a recommendation of the amount that should be consumed by any individual but rather the average (or median) amount consumed by apparently healthy individuals. From the European data, it is apparent that the 95th percentile value for daily water intake is slightly more than 50% higher than the AI value, at 3.1 L/day for women and 4.0 L/day for men. It is not clear from the data collected that these values represent requirements and, in some cases, are likely to be far in excess of requirements, with losses in urine being the primary route for maintaining equilibrium. In some sense, the AI is rather arbitrary. One can say with some certainty that the lower the intake, the greater the risk of failing to achieve an AI. However, achieving the AI does not indicate that an individual is consuming sufficient water to meet his or her needs. This is particularly true of those with physically active lifestyles and those who live in hot climates.

Both US and European reports recognized that these 2 main factors, physical activity and environmental heat stress, can substantially increase water and salt (especially sodium) losses due to an increased sweating rate, but no specific guidelines for intake were given in either case. Several other factors may also become important in specific contexts, such as episodes of infectious diarrhea, where stool losses can exceed 1 L/hour. Those who work in an air-conditioned environment where the humidity is maintained at a low level will face increased losses in breath and through the skin. Losses will be similarly increased in dry air at altitude or in long-haul air travel. The insulation properties and permeability to water vapor of clothing worn and the amount of skin covered will also affect the local microclimate. The balance between these various avenues of water loss can be important, as respiratory and transcutaneous losses are not accompanied by any solute loss. Sweat is invariably hypotonic relative to plasma, while urine is generally hypertonic but may be hypertonic when flow rates are high.

PHYSICAL ACTIVITY AND WATER BALANCE

Few situations pose such a challenge to the body’s homeostatic mechanisms as prolonged strenuous exercise in a hot, humid environment. Only a small part (usually about 20% and seldom more than 25%) of the energy available from substrate catabolism is used to perform external work, with the remainder appearing as heat. At rest, the metabolic rate is low; oxygen consumption is about 200–250 mL/min, corresponding to a rate of metabolic heat production of about 60 W. Heat production increases in proportion to metabolic demand and reaches about 1 kW during strenuous activities such as marathon running (for a 70-kg runner at a speed that takes about 2½ hours to complete the race). To limit the rise in core temperature, heat loss must be increased correspondingly; in most environmental conditions, this is achieved primarily by an increased rate of evaporation of sweat from the skin surface.

Several factors determine the extent of the sweat loss that occurs during exercise. Although large interindividual variability is observed, the primary factors are exercise duration, intensity, and frequency and the environment, especially ambient temperature and humidity, but including also wind speed or air movement across the body. The effect of these factors may be substantially modified by the amount and thermal properties of the clothing worn.

The primary routes of water loss at rest are urine, feces, respiration, and transcutaneous loss. The approximate rates by these routes for the typical adult male living in a temperate environment are shown in Table 1. It should be noted that there is large variability among individuals even when factors such as body size, gender, environment, and activity levels are taken into account.

In hard exercise in hot conditions, sweat rates can reach 3 L/h, and some trained athletes can sustain sweat rates in excess of 2 L/h for many hours, though values of about 1–2 L/h are more commonly seen (see Table S1 in the Supporting Information for this article online). As with water loss at rest, there is large variability among individuals even when factors such as body size, gender, environment, and activity levels are taken into account. The individual variability in both sweat losses and fluid intake in athletes in training is shown in Table S2 in the Supporting Information online; all data in this table were collected from rather homogeneous populations of well-trained, young, male, professional football (soccer) players.

For active individuals, the fractional turnover rate of water is much higher than what can occur for most other body components. In the sedentary individual living in a temperate climate, about 5%–10% of total body water is typically lost and replaced on a daily basis.3 When prolonged exercise is performed in a hot environment, 20%–40% of total body water can be turned over in a single day, as described below. It is important to note that large increases in water intake require
substantial behavioral changes. In a recent analysis of diet and fluid intake in the general population in the United Kingdom, Gibson et al.4 found that, on average, total water intake among British adults was equivalent to the European AI (2 L/d for women, 2.5 L/d for men) and that 75% of this was derived from beverages. Large increases in the requirement for water mean that a much higher fraction must be derived from beverages, as there is not a corresponding increase in energy requirements.

In addition to water, a variety of minerals and organic components are lost in sweat. Sweat is often described as an ultrafiltrate of plasma, but it is invariably hypotonic and its composition is highly variable. Solute losses will depend on both the sweating rate and the sweat composition. The main electrolytes lost are sodium and chloride, at concentrations of about 15–80 mmol/L. A range of other minerals, including potassium and magnesium, are also lost, as are trace elements in small amounts. Some athletes may lose up to 10 g of salt (sodium chloride) in a single training session and may train in these conditions twice per day.2 These substantial salt losses must be replaced through foods and beverages, resulting in dietary salt intakes that are far in excess of those recommended for the general population, though the use of salt supplements is seldom necessary. In spite of large increases in water requirements, the body water content is tightly regulated, and regulation by the kidneys is closely related to osmotic balance.

For most physically active individuals, the intensity, duration, and frequency of training sessions and competitive outings are less than for the athletes represented in Tables S1 and S2 in the Supporting Information. Leiper et al.6 measured total body water and water turnover rates of 6 male cyclists (cycling group) who trained and competed on a recreational basis and 6 age-matched sedentary men (sedentary group) using deuterium oxide dilution and elimination. During the 7-day study, the cycling group cycled daily outside for an average distance of 50 km (range 12–146) at an average speed of 29 km/h, while the sedentary group did no regular exercise. During the study, the weather was cool (10°C [4°C–18°C]) and mainly cloudy but dry. Daily average (median [range]) nude body mass remained essentially the same in both groups, suggesting that water balance was maintained on a daily basis. Median total body water of the cycling group (70.1% [65.5%–73.9%] of total body mass) was greater than that of the sedentary group (63.5% [52.7–71.0%]). The average median water turnover rate (mL/kg/d) was faster in the cycling group (47 [42–58]) than in the sedentary group (36 [29–50]). The average median daily urinary loss (mL/kg/d) was similar in the cycling group (27 [22–33]) and the sedentary group (29 [24–31]). Calculated nonrenal daily water loss (mL/kg/d), presumably mostly in the form of sweat, was faster in the cycling group (19 [15–35]) than in the sedentary group (6 [5–22]), but there was no relationship between the average distance cycled daily and the water turnover rate. This study demonstrated that the water turnover rate was faster in individuals undertaking prolonged exercise than in sedentary men and that the difference was due to the almost 3 times greater nonrenal water losses that the exercising group incurred. This suggests that exercise-induced increases in respiratory water loss and sweat rate are major factors in water loss even when exercise is undertaken in cool environments.

In contrast, Leiper et al.7 assessed the effect of exercise on water turnover in endurance trained and sedentary middle-aged men living in a temperate environment. The exercising men ran, on average, 14.8 km/day, while those in the sedentary group did not take part in any regular physical activity. The average median (range) rate of water turnover (mL/kg/d) was higher in the exercising group (4673 [4320–9606]) than in the sedentary group (3256 [2055–4185]; \( P = 0.001 \)). There was a tendency for nonrenal water losses (mL/kg/d) to be greater in the exercising group (1746 [1241–5196]) than in the sedentary group (1223 [1021–1950]; \( P = 0.08 \)), but the major difference in water loss between the groups was the greater urine output (mL/d) in those who exercised (3021 [2484–4225]) compared to those who were sedentary (1483 [925–2266]; \( P = 0.001 \)). These results suggest that fluid intake in middle-aged men who exercise regularly is greater than that of sedentary individuals of the same age group. However, this difference is not driven by an increased sweat loss but rather by a conscious decision to increase intake because of a perceived need. The volume is in excess of that required to replace

Table 1 Approximate values for the main components of 24-hour water balance for a typical 70-kg sedentary individual living in a temperate environment and for the same individual who performs hard exercise in a warm environment

<table>
<thead>
<tr>
<th>Component</th>
<th>Sedentary, temperate (mL/d)</th>
<th>Active, warm (mL/d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intake</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fluids</td>
<td>1250</td>
<td>4600</td>
</tr>
<tr>
<td>Food</td>
<td>800</td>
<td>1200</td>
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<tr>
<td>Metabolism</td>
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<tr>
<td>Total</td>
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<td>5600</td>
</tr>
<tr>
<td>Loss</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Urine</td>
<td>1250</td>
<td>500</td>
</tr>
<tr>
<td>Feces</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
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<td>700</td>
</tr>
<tr>
<td>Transcutaneous</td>
<td>650</td>
<td>800</td>
</tr>
<tr>
<td>Sweat</td>
<td>0</td>
<td>3500</td>
</tr>
<tr>
<td>Total</td>
<td>2350</td>
<td>5600</td>
</tr>
</tbody>
</table>

Data from multiple sources.
exercise-induced sweat and respiratory water losses, and the excess is lost in urine.

**OCCUPATIONAL ACTIVITY AND WATER BALANCE**

Sports activities often involve relatively high intensities of exercise and can, therefore, provoke large sweat losses. However, exercise duration is generally rather short, thus limiting the total sweat loss. In contrast, many physically demanding occupational tasks must be sustained over shifts that may last for many hours with relatively short rest breaks and sometimes with limited opportunities for fluid intake. Studies examining hydration status in the workplace have generally focused on manual workers in hot, humid conditions who perform physical activity and those who wear personal protective equipment. Environmental monitoring regulations are in place to protect the health and safety of workers in many industrial settings, though no such protection is afforded in most developing countries.

Brake drew attention to the hydration issues in occupational settings by monitoring hydration status and drinking behaviors of mine workers in hot climates. He reported that about 60% of 64 underground workers began work in a state of hypohydration, based on measurement of preshift urine specific gravity. In contrast, in a larger cohort of 413 workers, only about 14% appeared to be dehydrated at the end of their shift, suggesting that the availability of fluids, the opportunities for drinking, and the workers’ drinking behaviors during the workday were adequate. Fluid consumption, sweat rates, and hydration state were reported for miners on 10-, 12-, and 12.5-hour shifts under conditions of thermal stress. Average environmental conditions were severe (Wet Bulb Globe Temperature 30.9°C; standard deviation [SD], 2.0°C; range, 25.7–35.2°C). Fluid intake averaged 0.8 L/h during exposure (SD, 0.3 L/h; range, 0.3–1.5 L/h), and the average fluid consumption per shift was 6.48 L (over this mix of different shift lengths) with an SD of 2.41 L and a range of 2.40–12.50 L. To this must be added the water content of foods consumed during the shift. The author concluded that, in spite of the extremely large sweat losses experienced by some individuals, intake was sufficient to prevent the development of hypohydration during the working shift.

Another study of outdoor workers in northwest Australia found that more than 70% of the 710 urine samples collected suggested that the workers were poorly hydrated; 51% of the samples showed levels of dehydration that put the worker at increased risk of heat-related illness and impaired work performance, with 16% of the values corresponding to a state of clinical dehydration. The researchers reported that this situation persisted in spite of efforts by employers to address hydration and to encourage better drinking behaviors. Bates et al. also investigated the hydration status of expatriate manual workers at various construction sites in the Middle East during the summer months. They found that the hydration status of workers was generally better than of those working in comparable conditions in Australia; however, a high proportion were still found to be inadequately hydrated on arrival at work and at the end of the shift. Water intake during the working shift was generally sufficient to match losses and maintain the preshift hydration status but not to correct any preexisting hypohydration. There were some differences in average hydration status between the sites, possibly reflecting the emphasis placed by staff and employers on hydration awareness.

To assess whether these findings were specific to the heat stress imposed by the working and living environment, Polkinghorne et al. made a similar series of measurements on miners working in temperate regions of Australia. Based on urine specific gravity measurements, they reported that nearly 60% of the workers were dehydrated both before and after their shift. They also observed that workers who were dehydrated for the entire shift were more likely to be obese than those workers who were adequately hydrated for their entire shift.

The findings cited above suggest that hypohydration is common in individuals who work in demanding physical occupations and that water intake during the shift is generally adequate to prevent development of further hypohydration. In a relatively large cohort of South African forestry workers studied in autumn and winter, 43% in autumn and 47% in winter were reported to be dehydrated (urine specific gravity >1.020 g/mL) on arrival at work. Perhaps because of the limited availability of beverages when working in the field, an increase in the prevalence of dehydration was seen at the end of the shift, with 64% in autumn and 63% in winter classified as being dehydrated at the end of their shift. This indicated a failure of water intake during the shift to match sweat losses. The authors also suggested that some individuals were overhydrated (urine specific gravity <1.013 g/mL), but this measure may be distorted by acute intake of a large bolus of water. Roberts and Donnelly also studied water balance in forestry workers doing hard manual labor in a temperate environment. They found that although a reduction in body mass provided evidence of dehydration during each day’s work shift, recovery was apparent by the following morning. This must be the case if a progressive hypohydration over the work week is to be avoided. Further evidence for an inadequate intake of water during the work shift came from a study of underground coal miners in Germany, where it was found
that average sweat losses during a shift amounted to about 3.4 L, and that the amount of water ingested during the shift was sufficient to replace only about 60% of this loss.\textsuperscript{19}

These studies have focused on extreme situations and environmental conditions that may not be applicable to those who work in temperate conditions performing less strenuous activity without protective equipment. In many work places, environmental conditions are controlled by air conditioning and heating systems, and many workers remain seated at a desk for a large portion of their workday. There is, however, little information on water balance in these more sedentary occupations. To address this, Mears and Shirreffs\textsuperscript{20} examined the hydration status of adults working in different occupations at the beginning and end of a shift and their reported water intake. A total of 156 workers (89 males, 67 females) were recruited from workplaces that included students, teachers, security staff, office workers, firefighters, and catering staff. A urine sample was obtained at the start and end of the shift and was analyzed for osmolality (Uosm), urine-specific gravity, and sodium and potassium concentrations. Euthydrated at the end. Median reported water intake from the 156 participants, 54% began the shift with a urine osmolality suggestive of hypohydration, with 35% ending the shift with urine osmolality values considered hypohydrated. More males (64%) than females (42%) were hypohydrated at the beginning of the shift. Fifty-two percent of individuals who were identified as being hypohydrated at the start of the shift were also hypohydrated at the end. Median reported water intake from all beverages over the assessment period was greater in males than in females (1.2 [range, 0.0–3.3] vs 0.7 [range, 0.0–2.0] L, respectively), though there was a striking variability among individuals. The authors concluded that, even for individuals engaged in largely sedentary tasks in cool or temperate environments, a large proportion of workers exhibited urine values indicating hypohydration, and many remained in a state of hypohydration at the end of the shift.

**OTHER FACTORS AFFECTING SWEAT LOSS**

It is well established that women tend to sweat less than men under standardized conditions, even after a period of acclimatization.\textsuperscript{21} It is likely, however, that a large part of the apparent sex difference can be accounted for by differences in training and acclimation status. There is a limited amount of information on the effects of age on the sweating response and, again, levels of fitness and acclimation are confounding factors, but the sweating response to a standardized challenge generally decreases with age.\textsuperscript{22} These observations should not, however, be interpreted as suggesting an inability to exercise in the heat, nor should they be taken to indicate a decreased need for women or older individuals to pay attention to fluid intake during exposure to heat stress. There are some differences between children and adults in the sweating response to exercise and in sweat composition. The sweating capacity of children is low, when expressed per unit surface area, and the sweat electrolyte content is low relative to that of adults.\textsuperscript{23} However, the need for fluid and electrolyte replacement is no less important than in adults. Indeed, in view of the evidence that core temperature increases to a greater extent in children than in adults at a given level of dehydration, the need for fluid replacement may well be greater in children.\textsuperscript{24}

**ENVIRONMENT AND WATER LOSS**

Data presented in Tables S1 and S2 in the Supporting Information show the influence of environmental temperature and humidity on sweat losses of football (soccer) players training and competing in different environments. Laboratory studies allow better control of environmental conditions, and Galloway and Maughan\textsuperscript{25} had participants cycle to exhaustion at ambient temperatures of 4, 11, 21, and 31°C with a relative humidity of 70 ± 2% and an air velocity of approximately 0.7 m/s. Mean sweat rate, calculated on the assumption that it was linear throughout the test, increased with an increase in ambient temperature, with sweat rates of 0.55, 0.65, 0.78, and 1.15 L/h for the 4 trials.

Maughan et al.\textsuperscript{26} examined the influence of relative humidity on endurance exercise performance in a warm environment. Athletes cycled at 70% of VO\textsubscript{2max} until volitional exhaustion in an environmental chamber maintained at 30°C and at 4 relative humidity conditions: 24, 40, 60, and 80%. The mean sweating rate was higher at higher humidity (22 ± 4 mL/min at 24%; 23 ± 6 mL/min at 40%; 27 ± 5 mL/min at 60%; 30 ± 6 mL/min at 80%). However, because of the progressive reduction in exercise time as humidity increased, the total sweat loss during the exercise period was not different between trials.

The effects of environmental conditions on body water losses and, therefore, on the requirement for water intake are not always what one might predict. Many individuals who live and work where the weather is hot and humid limit their exposure to the external
environment by living in an air-conditioned house, driving an air-conditioned car, and working in an air-conditioned office. Physically demanding occupations may be carried out at a slower pace than would be the case in a temperate environment and with longer and more frequent rest breaks in cool and shaded positions. Body water turnover may, therefore, be low in these situations.

Water loss via the lungs is increased substantially at high altitudes because of the dryness of the air and the increased rate of ventilation that occurs in an attempt to maintain tissue oxygenation. In 1954, Pugh reported that dehydration was common in high-altitude climbers, who often failed to recognize the importance of hydration. He reported water intakes of up to about 4 L/day in climbers at high altitude, and attention to hydration was cited as one factor that contributed to the first successful ascent of Mount Everest in 1953. As well as the increased insensible fluid losses due to low humidity and increased ventilation, urinary water loss is increased at altitude. In the artificial environment of a hypoxic chamber corresponding to 4500–8848 m altitude, Westerterp et al. found that insensible water loss was unchanged because the increase in respiratory evaporative water loss was counterbalanced by a decrease in metabolic rate. In combination with a reduced fluid intake due to decreased sensation of thirst and to loss of appetite, hypohydration is almost inevitable. There will be some increase in respiratory water losses at more moderate altitudes, such as those in the cabins of commercial airliners and in some air-conditioned environments.

**ELECTROLYTE LOSSES AND IMPLICATIONS FOR HYDRATION STATUS AND FUNCTIONAL OUTCOMES**

Sweat and urine losses from the body are accompanied by the loss of variable amounts of a number of electrolytes, though respiratory water loss is electrolyte free. Of the electrolytes found in sweat, sodium and chloride are quantitatively the most important (Table 2), and the concentrations of these electrolytes are important in determining the effects on the toxicity of the body water compartments and, thus, on hydration status. One might think of the kidneys as excreting sodium and potassium that are surplus to the body’s requirement. However, there is an obligatory loss of these electrolytes in sweat, and these losses must be replaced to maintain homeostasis. Sweat is invariably hypotonic with regard to body fluids, but the solute content is influenced by a number of factors and is also highly variable among individuals. Factors that have a major influence on the sodium concentration of sweat include sweating rate and acclimation status and, perhaps, the prior diet. There also seems to be a large individual variability that is not explained entirely by these factors.

Potassium is also lost in sweat, and this has been the basis for adding potassium to sport beverages, typically at a concentration of about 5 mmol/L. Whereas sodium plays a critical role in restoring fluid balance after exercise, there is no evidence that the addition of potassium to beverages improves the restoration of fluid balance following dehydration, though restoration of potassium balance may be important for the maintenance of the intracellular water space. General guidelines for promoting recovery after exercise have focused on replacing sodium, with potassium mainly consumed through food (e.g., fruit, vegetables) later during the recovery process. Cell volume may have important implications for both recovery from an intense exercise session and for adaptation to the training stimulus. The potential role of hydration status in modulating the response to training has been largely ignored. However, 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 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. showed a 13% increase in the intracellular water content of forearm muscle during intensive forearm wrist flexion exercise. In high-intensity running and 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; intense cycling exercise is accompanied by a decrease in plasma volume of 20%–25% or even more.

Major disturbances in cell volume have profound effects on cellular metabolism. 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. 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 declines with age, and this may be relevant to the generally observed reduction in the capacity of older individuals to respond to a training stimulus. At present, however,
understanding of the influence of cell volume changes on regulatory pathways does not allow practical recommendations to be made. Finally, it is important to understand that water intake per se does not equate to cell swelling, as these processes are much more complex. The loss and replacement of electrolytes in sweat and their redistribution among body water compartments is, therefore, of great significance for the metabolic sequelae of exercise.

**HYDRATION AND THE PHYSIOLOGICAL RESPONSES TO EXERCISE**

Hyphydration causes a reduction in the circulating blood volume and an increase in plasma osmolality; these changes are typically proportional to the magnitude of decrease in total body water. The fall in blood volume reduces venous return and ventricular filling and results in a reduction in the stroke volume, so heart rate is elevated to maintain an adequate cardiac output. Hypohydration also reduces muscle blood flow and is accompanied by an increase in muscle glycogen use during exercise, which may contribute to the earlier onset of fatigue. When exercise is performed in warm, humid environments, a marked increase in skin blood flow is necessary to facilitate heat loss from the body. In the face of a diminishing circulating blood volume and a high skin blood flow, maintenance of central venous pressure and cardiac output are further challenged. Consequently, hyphydration augments hyperthermia and cardiovascular strain at a given exercise intensity in proportion to the magnitude of body water deficit. While the precise mechanism responsible for the decrements in physical performance observed with hyphydration during prolonged exercise remains unclear, Sawka et al. have argued that this response is primarily brought about through a reduction in VO2max; this will effectively increase relative exercise intensity for any given task. While some maintain that dehydration-associated impairment of tasks with a large cognitive component are due only to changes in mood and the discomfort and distraction associated with the condition, there is evidence of direct effects of hyphydration on the central nervous system, including changes in blood–brain barrier permeability, cerebrospinal fluid volume, and a reduction in cerebral perfusion and oxygenation.

**HYDRATION AND PERFORMANCE**

As mentioned above, dyshydration, if sufficiently severe, will impair both mental and physical performance. While severe dehydration is undoubtedly harmful to performance and mild dehydration has no discernible effect, there must come a point somewhere in between at which a meaningful effect of performance begins to occur. Identification of that point has been challenging for several reasons including the following: there is difficulty in determining baseline hydration status and, therefore, in quantifying the degree of hyphydration elicited by any intervention; different tasks will be affected differently by changes in hydration status, and many tasks cannot be assessed with the precision necessary to detect small changes in performance; the effects of hyphydration will be influenced by environmental conditions; an interaction between hydration status and body core temperature seems likely; although personal factors such as aerobic fitness and acclimation status will affect responses, there seems to be an additional individual variability in susceptibility to the effects of hyphydration that is not explained by these factors; and the different methods used to induce hyphydration (e.g., fluid restriction, exercise, heat exposure, diuretic administration) seem likely to have different effects.

For these and other reasons, it is possible to draw different conclusions from an analysis of the available evidence. Early studies interested in quantifying possible decrements in operational effectiveness of military personnel fighting in hot climates were limited in aspects of methodology, including in particular small participant numbers. Nevertheless, these studies consistently reported reductions in aerobic exercise performance due to hyphydration. Later, a number of laboratory-based studies demonstrated that hyphydration of 2% body mass or more can result in impaired endurance performance in both temperate and warm environments compared to undertaking the same task when fluid balance was maintained. In addition, there is some evidence of a progressive reduction in performance with increasing levels of hyphydration. While there are studies reporting no clear effect of hyphydration on exercise performance, a recent review of the literature by Cheuvront and

<table>
<thead>
<tr>
<th>Electrolyte</th>
<th>Sweat, mmol/L</th>
<th>Plasma, mmol/L</th>
<th>Intracellular water, mmol/L</th>
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</thead>
<tbody>
<tr>
<td>Sodium</td>
<td>20–80</td>
<td>130–155</td>
<td>10</td>
</tr>
<tr>
<td>Potassium</td>
<td>4–8</td>
<td>3.2–5.5</td>
<td>150</td>
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<td>Sulfate</td>
<td>0.1–2.0</td>
<td>0.3–0.9</td>
<td>10</td>
</tr>
</tbody>
</table>

*The large variability in the composition of sweat and the relative constancy of the internal environment are striking.

Data from Maughan.
Recent meta-analyses have been undertaken to explore the effects of hypohydration on anaerobic or muscular strength activities. From the limited satisfactory data available, it appears that dehydration up to the equivalent of about 2%–4% of body mass does not degrade either anaerobic performance or muscular strength; however, around these levels of hypohydration, some performance decrements start to become apparent. Recent meta-analyses have been undertaken on the topic of hydration and performance. However, when based on a small number of articles, and when these are flawed in 1 or more ways, a meta-analysis is only as good as the selection criteria applied. In such cases, issues with the design of some of the studies invalidate the conclusions reached. For example, in one study, participants were forced to drink water to the extent that mean abdominal discomfort was rated at 4.1 on a scale of 1–5, with 5 representing “extreme discomfort.” Thus, it is no surprise that drinking did not improve performance. The participants were also in a situation in which they were aware that they were not complying with the demands of the study, which is also likely to have affected their performance.

In addition to the decrements in physical performance, several studies recorded a decline in aspects of cognitive function during hypohydration, with the available evidence suggesting that alertness, concentration, and performance of complex cognitive tasks can be impaired at relatively mild levels of dehydration. Understanding of this area would benefit from further, quality research.

ENVIRONMENT AND PERCEIVED EFFORT

Exercise in a warm environment generally feels harder than when work at the same power output is performed in a cool environment. Increasing the humidity of the environment has a similar effect to when exercise is performed in the heat. These effects are apparent even in the early stages of exercise, before substantial body water deficits have been incurred, and reflect the varied factors that determine the subjective rating of perceived exertion (RPE). The strongest physiological predictors of RPE appear to be an individual’s respiratory rate, sensations of strain in the working muscles, and perceptions of body temperature, joint strain, and limb movement speed. Measured changes in heart rate, oxygen uptake, and blood lactate concentrations typically do not correlate strongly with RPE, as these responses are typically not subjectively perceived, but may still be important. In warm, humid environments, there is a greater skin blood flow and, therefore, a requirement for a greater cardiac output than when the same metabolic demand is experienced in a more comfortable environment. This elevated cardiac output is met largely by a higher heart rate. In the later stages of exercise, if sweat losses are not replaced, the falling blood volume will also result in a higher heart rate to maintain central venous pressure and cardiac output, which will result in an increasing RPE.

HYDRATION AND RATING OF PERCEIVED EXERTION

It is clear that an individual’s perception of effort is a key regulator of self-selected effort during exercise, while also playing a significant role in the decision to continue or terminate exercise. With this in mind, any condition or intervention that alters RPE clearly has implications for not only athletic performance but also adherence to exercise programs prescribed to improve health (e.g., physician exercise referral schemes). While many studies report RPE data, this measure is rarely a primary outcome variable. Despite this, higher ratings of perceived exertion have been reported when exercise is undertaken in a hypohydrated state compared to exercise at the same intensity when fluid balance is maintained. A recent systematic review and meta-analysis of the available information has concluded that overall mean RPE is significantly higher when exercise is undertaken in the hypohydrated state compared to when participants are euhydrated (mean difference, 1.01; 95% confidence interval, 0.72–1.31; P < 0.001; F², 0%). Compared to exercise in a euhydrated state, overall mean RPE was higher in 5 trials (50%) with prior hypohydration and 6 trials (46%) in which exercise-induced hypohydration was allowed to develop over the course of exercise (Watson and Maughan, unpublished data). The difference in RPE score between the euhydrated and hypohydrated trials increased as total exercise time progressed, becoming significant for exercise durations of 60 minutes or more (P < 0.05).

DRINKING STRATEGIES

The drinking practices of athletes have changed greatly over the years. In the early days of organized athletics, much of the focus of training and dietary strategies was on sweating, purging, and making weight. Barclay Allardyce, the most successful pedestrian of the 19th century, said that “water is never given alone. It is an established rule to avoid liquids as much as possible. Milk is never allowed. Soups are never used.” Although this seems totally counter to what is now believed to be
appropriate, his athletic performances were outstanding and his advice prevailed for much of the next 100 years. In a classic text published in 1888, Shearman wrote that “it stands to reason that a man taking violent exercise and perspiring freely requires more liquid than he does during his ordinary life.” This is indisputably true, but he also wrote that “it is also a well-known fact that taking too much liquid does more to make the body fat and heavy than taking too much solid food.”

Over recent decades, there has been considerable controversy over the advice that should be given to active individuals. This controversy reveals different interpretations of the available evidence and it also illustrates the limitations of much of the available evidence. When interpreting data, authors and readers should be aware of the potential for confounding effects introduced by preventing drinking when individuals wish to do so, requiring them to drink when they do not wish to do so, asking them to ingest excessive volumes of fluid, providing beverages that they like or do not like the taste or temperature of, providing familiar or unfamiliar beverages, and controlling effects other than those of hydration itself (e.g., carbohydrate content, temperature). One view is that athletes should use assessments made during training to determine their sweat losses in different exercise and environmental conditions and use this information to prepare a planned drinking schedule during competition, with the aim of restricting body mass losses to not more than about 2%. This recommendation is based on laboratory studies suggesting it is unlikely that any negative effects on exercise performance would be seen until hypohydration reaches a level equivalent to about 2% loss of body mass and that perhaps even greater losses could be tolerated in cool environments. The alternative view is that athletes should simply drink according to the dictates of thirst and that this will automatically result in the ingestion of the amount of fluid necessary to optimize performance.

What does seem clear is that small body water deficits have no appreciable effect on physiological function, and it is not necessary, for various reasons, to drink sufficient fluid to match the rate of body water loss, or at least to prevent a loss of body mass. It is also important to note that the body water deficit incurred during intense exercise is usually assessed by measuring the change in body mass and assuming that all the loss of mass is caused by a loss of water. This assumption is not entirely valid, but the debate about the utility of body mass change as a marker of the change in body water content is largely irrelevant. Performance effects of acute dehydration are usually related to the extent of the body mass loss, so notwithstanding the assumptions and inaccuracies involved, it remains an appropriate measure of the point at which effects on performance may become apparent. Some degree of body mass loss can be tolerated with no apparent adverse effects, but the definition of the point at which an appreciable effect occurs is fraught with difficulty.

When sweat rates are high, it may be difficult to ingest fluid at a rate that matches the rate of loss because of the gastrointestinal discomfort that ensues. A study by Robinson et al. was published with the title “Water ingestion does not improve 1-h cycling performance in moderate ambient temperatures,” seeming to confirm the suggestion that water intake may not always benefit exercise performance. In this study, however, participants were required to cycle as far as possible in 60 min (~85% VO2max) while receiving either no fluid or attempting to ingest sufficient fluid to replace the volume lost in a familiarization trial (~1.7 L). During the trial, when fluid was given, the cyclists were able to drink a mean volume of 1.49 L, but this resulted in an uncomfortable feeling of stomach fullness and was accompanied by a reduced mean distance covered in 1 hour from 43.1 km to 42.3 km (P < 0.05). Given the high ratings of gastrointestinal discomfort reported by most of the cyclists, with mean ratings of abdominal fullness in excess of 4 on a scale from 1 (no discomfort) to 5 (extreme discomfort), the reduction in performance is unsurprising but should not be taken as evidence that drinking per se is harmful. Rather, this study shows that drinking in amounts that cause discomfort is harmful to performance. In addition, beverages consumed during exercise often contain carbohydrates that may be beneficial in some situations. However, ingesting these beverages in volumes required to match sweat loss may cause gastrointestinal discomfort due to a slowing of the gastric emptying rate in proportion to the energy content of the beverage.

There is some evidence that a reliance on thirst to dictate intake may not always be the best strategy when sweat losses are high and when performance is critical. Wong et al. 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 2 endurance exercise sessions. Even though the total fluid intake was the same in both trials, a greater volume was ingested in the early stages of recovery with the prescribed drinking schedule. However, the relative effects of the carbohydrate content of the beverage and the fluid replacement could not be separated with the study design used. There are studies in the literature reporting conflicting findings. For example, Dion et al. reported that half-marathon running performance is not improved by a rate of fluid intake above that dictated by thirst sensation in trained distance runners. However, in that study, a group of runners
completed a series of exercise tests in a hot environment during Canadian winters, likely ensuring that the runners were not heat acclimated and, thus, calling into question the ecological validity of the study.

It may also be important to note that cold beverages may be more beneficial than warm beverages in reducing the sensation of effort and in enhancing performance during exercise in a warm environment. The cold beverage acts as a heat sink, requiring the input of energy to raise the temperature of the ingested fluid to body temperature, and this attenuates the rise of core temperature. It might, therefore, be expected that there would be an additional benefit from increasing the volume consumed, though obviously gastrointestinal discomfort would intervene at some point.

CONCLUSION

Water loss from the body, primarily in the form of sweat, is greatly increased by exposure to a hot environment and by physical activity, with sweat rates reaching 2–3 L/h in some individuals when exercise is performed in a warm environment. For some populations, including miners, construction workers in hot climates, soldiers, and some athletes, water losses and, therefore, needs can reach 10–12 L/day. Though water from foods typically account for 20%–30% of total water needs for sedentary individuals, such high intakes inevitably require a large increase in the amount of fluid consumed. Both hyperhydration and hypohydration, if sufficiently severe, will impair all aspects of physiological function. The point at which dyshydration will have measurable effects on performance is much debated, in part because this will depend on the methods used to alter hydration status, the nature of the exercise task, the environment, and the physical and mental characteristics of the individual. Tests of strength and power are largely unaffected by dehydration of up to about 2%–4% of body mass, but decrements in the performance of endurance tests are often apparent at these levels, especially in warm environments. Body water deficits, if sufficiently severe, will also have adverse effects on measures of mood and on some elements of cognitive function and will also result in an increase in the subjective rating of the perception of effort. Beverages consumed during exercise can provide carbohydrates and electrolytes that may be beneficial in some situations, but drinking in volumes required to match sweat loss may cause gastrointestinal discomfort that will generally impair performance.

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