

This article was downloaded by: [Loughborough University]

On: 17 January 2012, At: 03:22

Publisher: Routledge

Informa Ltd Registered in England and Wales Registered Number: 1072954 Registered office: Mortimer House, 37-41 Mortimer Street, London W1T 3JH, UK



Journal of Sports Sciences

Publication details, including instructions for authors and subscription information:

<http://www.tandfonline.com/loi/rjsp20>

Fluid and electrolyte needs for training, competition, and recovery

Susan M. Shirreffs^a & Michael N. Sawka^b

^a School of Sport, Exercise and Health Sciences, Loughborough University, Loughborough, UK

^b Thermal and Mountain Medicine Division, US Army Research Institute of Environmental Medicine, Natick, Massachusetts, USA

Available online: 09 Dec 2011

To cite this article: Susan M. Shirreffs & Michael N. Sawka (2011): Fluid and electrolyte needs for training, competition, and recovery, *Journal of Sports Sciences*, 29:sup1, S39-S46

To link to this article: <http://dx.doi.org/10.1080/02640414.2011.614269>

PLEASE SCROLL DOWN FOR ARTICLE

Full terms and conditions of use: <http://www.tandfonline.com/page/terms-and-conditions>

This article may be used for research, teaching, and private study purposes. Any substantial or systematic reproduction, redistribution, reselling, loan, sub-licensing, systematic supply, or distribution in any form to anyone is expressly forbidden.

The publisher does not give any warranty express or implied or make any representation that the contents will be complete or accurate or up to date. The accuracy of any instructions, formulae, and drug doses should be independently verified with primary sources. The publisher shall not be liable for any loss, actions, claims, proceedings, demand, or costs or damages whatsoever or howsoever caused arising directly or indirectly in connection with or arising out of the use of this material.

Fluid and electrolyte needs for training, competition, and recovery

SUSAN M. SHIRREFFS¹ & MICHAEL N. SAWKA²

¹School of Sport, Exercise and Health Sciences, Loughborough University, Loughborough, UK and ²Thermal and Mountain Medicine Division, US Army Research Institute of Environmental Medicine, Natick, Massachusetts, USA

(Accepted 10 August 2011)

Abstract

Fluids and electrolytes (sodium) are consumed by athletes, or recommended to athletes, for a number of reasons, before, during, and after exercise. These reasons are generally to sustain total body water, as deficits (hypohydration) will increase cardiovascular and thermal strain and degrade aerobic performance. Vigorous exercise and warm/hot weather induce sweat production, which contains both water and electrolytes. Daily water (4–10 L) and sodium (3500–7000 mg) losses in active athletes during hot weather exposure can induce water and electrolyte deficits. Both water and sodium need to be replaced to re-establish “normal” total body water (euhydration). This replacement can be by normal eating and drinking practices if there is no urgency for recovery. But if rapid recovery (<24 h) is desired or severe hypohydration (>5% body mass) is encountered, aggressive drinking of fluids and consuming electrolytes should be encouraged to facilitate recovery for subsequent competition.

Keywords: *Hydration, water balance, fluid replacement*

Fluids and electrolytes for hydration

Hypohydration can degrade aerobic exercise performance, and increase physiological strain and perceived exertion during exercise in temperate, warm/hot environments. Normally, total body water (TBW) is ~60% of weight, so a 72 kg athlete has a total body water of ~43 L (Institute of Medicine, IOM, 2005). Total body water per unit lean body mass is relatively constant (~74%) across age, sex, and race (IOM, 2005). Total body water is distributed between the intracellular fluid volume (65% TBW) and extracellular fluid volume (35% TBW), with the ~15 L extracellular fluid volume including ~3 L plasma volume (IOM, 2005). Therefore, it is important to remember that the easily assessed plasma volume provides a relatively small portion of the extracellular fluid volume. Given the normal day-to-day variation in body water content, hypohydration or hyperhydration probably starts once the body water content exceeds the normal euhydration window of approximately ± 0.2 – 0.5% of body mass (Adolph, 1943; Adolph & Dill, 1938). Water loss and intake can be episodic, so body water fluctuates (Sawka, Chevront, & Carter, 2005; Sawka et al.,

2007). Assessment of hydration status is not straightforward, although various measures are in common use and serial measures of body weight and urine specific gravity provide useful tools for athletes (Chevront et al., 2010a). Plasma osmolality provides the “best” physiological index of hydration status from sweat losses (Chevront et al., 2010a); other methods either require serial measures or are very invasive or very variable or invalid (Chevront et al., 2010a; IOM, 2005). It should be noted that plasma osmolality will not be a sensitive marker of hypohydration induced by diuretics, cold or high-altitude exposure, as they induce an iso-osmotic hypovolaemia, for which there is no valid biomarkers.

Daily water losses occur from respiration, urinary/faecal and sweat losses, but during physical exercise and exposure to heat stress, sweat loss is the largest potential source of water loss (IOM, 2005; Sawka et al., 2005). In exercise, hypohydration most commonly occurs when sweat loss is not replaced, but it can also occur as a result of fluid restriction that may be unintentional or be planned as part of a strategy to lose weight. With sweat loss, substantial quantities of electrolytes, in particular sodium can be lost. Sweat sodium is hypotonic relative to plasma, so

sweat-mediated hypohydration will act to increase plasma osmolality but decrease plasma volume (IOM, 2005). Since sodium is the primary cation for the intracellular fluid space, its replacement is critical for re-establishing total body water (Nose, Mack, Shi, & Nadel, 1988). Regardless of the mode of water loss responsible for inducing body water deficits, fluid loss will occur both in the intracellular and extracellular fluid compartments (Costill, Coté, & Fink, 1976) and reduce plasma (blood) volume. Figure 1 provides the relationship of plasma volume reductions (from euhydration) relative to hypohydration level from sweat dehydration and diuretic administration (Cheuvront et al., 2010c). It should be noted, however, that since diuretics induce solute loss, the loss of extracellular fluid and plasma is greater. In addition, as mentioned above, diuretics induce an iso-osmotic hypovolaemia rather than the hypertonic hypovolaemia associated with sweat-induced hypohydration.

Hypohydration may occur prior to exercise or may result from fluid loss during exercise. The former may be deliberate in an aim to reduce body mass in weight category sports, or may be inadvertent due to failure to ingest sufficient fluid to match ongoing losses. This is likely to be of concern to athletes competing in weight category sports. There are, however, some indications that many athletes may begin both training and competition in a state of fluid deficit. Analysis of samples collected from elite football (soccer) players before training revealed that a significant number had urine osmolality values that were consistent with hypohydration (Shirreffs, Sawka, & Stone, 2006). Perhaps more surprisingly, samples collected from players before a competitive game revealed that 8 of the 20 outfield players had a urine osmolality in excess of $900 \text{ mOsmol} \cdot \text{kg}^{-1}$ when they arrived for the game (Maughan, Watson,

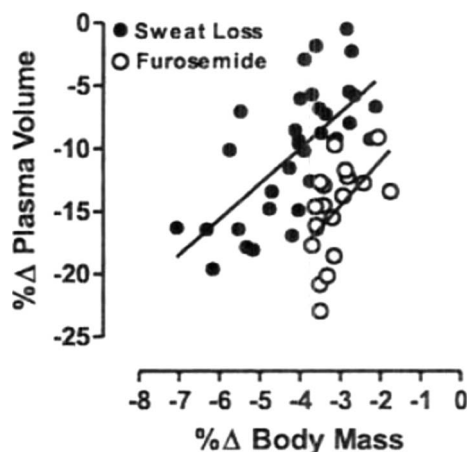


Figure 1. Plasma volume loss with hypohydration. Reprinted from Cheuvront et al. (2010) with the permission of the American Physiological Society.

Evans, Broad, & Shirreffs, 2007b). This evidence is mostly in the form of measures of urine osmolality or specific gravity made on athletes in these situations. Only when exercise duration exceeds ~ 60 min and when the ambient temperature is high, is it likely that fluid deficits during exercise will reach levels that are likely to have an effect on performance.

Hydration and performance

The influence of hydration status on aerobic performance and to a lesser extent cognitive performance has been studied widely, and consensus statements have been published in recent years (IOM, 2005; Sawka et al., 2007). It is agreed that hypohydration will degrade aerobic performance (IOM, 2005; Sawka et al., 2007), but there is active debate regarding the mechanisms responsible (Cheuvront et al., 2010c; Sawka & Noakes, 2007).

Hypohydration increases heat storage and reduces one's ability to tolerate exercise-induced heat strain (IOM, 2005; Sawka et al., 2007). The increased heat storage is mediated by reduced sweating rate and reduced skin blood flow for a given core temperature (Sawka et al., 2007). The reduced ability to tolerate exercise-heat strain is likely due to an inability to sustain the required cardiac output and a reduction in maximal aerobic power thus increasing the relative exercise intensity (Cheuvront, Carter, Castellani, & Sawka, 2005). Hypohydration that exceeds 2% of body mass loss ($\sim 3\%$ TBW) consistently degrades aerobic performance in temperate and warm/hot environments. Kenefick and colleagues demonstrated that hypohydration degrades time-trial performance to a greater extent with increasing heat stress (Kenefick, Cheuvront, Palombo, Ely, & Sawka, 2010). Their participants performed cycle ergometer exercise for 30 min at a constant intensity ($50\% \dot{V}O_{2\max}$) followed by a time-trial (total work completed in 15 min). Four groups of participants completed euhydration and hypohydration (-4% body mass) trials during compensable heat stress in 10°C , 20°C , 30°C , and 40°C environments. Therefore, the environments had a modest effect on core temperature ($38.4\text{--}38.9^\circ\text{C}$) but induced step-wise increments (by $\sim 3^\circ\text{C}$ from 25°C to 36°C) in skin temperature. Figure 2 presents the percent decrement time-trial performance from euhydration at each skin temperature. When skin temperature was $>29^\circ\text{C}$, time-trial performance was degraded by $\sim 1.6\%$ for each additional 1°C increase in skin temperature. Kenefick and colleagues' (2010) physiological data showed that a combination of high skin blood flow with plasma (blood) volume reductions via cardiovascular strain appeared to mediate the performance degradations. In addition, Castellani et al. (2010) recently demonstrated that

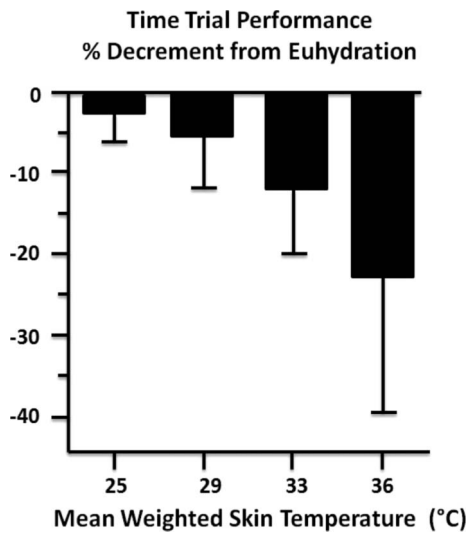


Figure 2. The percent decrement in time-trial performance from euhydration at each skin temperature. Reprinted from Sawka et al. (In Press); data from Kenefick et al. (2010). Reprinted with the permission of the American Physiological Society.

hypohydration markedly degrades aerobic performance at high altitude, and suggested that the systemic vasodilation from hypoxia and plasma (blood) volume from hypohydration act together to accentuate performance decrements.

The general conclusions that have been drawn for sweating-induced dehydration are that:

- Body water reductions in excess of 2% of body mass consistently degrade aerobic performance (IOM, 2005; Sawka et al., 2007), particularly in environments that are warmer (thus increasing skin temperature and skin blood flow requirements) (Cheuvront, Carter, Haymes, & Sawka, 2006; Kenefick et al., 2010): the warmer the environment, the greater the aerobic performance degradation (Kenefick et al., 2010), and the greater the water deficit, the greater the aerobic performance degradation (Sawka, Francesconi, Young, & Pandolf, 1984). Gigou and colleagues performed a meta-analytic review on studies of pre-exercise hypohydration, and concluded that hypohydration induced prior to exercise reduces mean power output by 3.2% relative to control trials where hydration was maintained (Gigou, Lamontagne-Lacasse, & Goulet, 2010). They further concluded that pre-exercise hypohydration of 3% or more of body mass impairs endurance performance.
- Reductions in body mass in the order of 1–2% appear generally not to degrade aerobic performance when the exercise duration is less than 90 min and the environment is temperate (20–21°C) (Cheuvront, Carter, & Sawka, 2003).
- Reductions in body mass in the order of 3–4% do not degrade muscular strength (Greive et al., 1998), jumping ability (Cheuvront et al., 2010b) or anaerobic performance (Cheuvront et al., 2006) but can degrade high-intensity endurance (Judelson et al., 2007). Reductions of 2–3% are associated with a deterioration in the ability to execute sport-specific skills (Baker, Dougherty, Chow, & Kenney, 2007; Devlin, Fraser, Barras, & Hawley, 2001; Dougherty, Baker, Chow, & Kenney, 2006). Baker et al. (2007) reported that basketball players attempted fewer shots and were less able to make shots linked with movement (e.g. lay-up) when dehydration had risen to 3% of normal body mass, and shooting was further impaired at a 4% deficit.
- Reductions in body mass in the order of 2–3% appear to have no significant effect on sprint running performance – that is, when body mass is “carried” (Judelson et al., 2007).
- Mild to moderate dehydration (up to 3% body mass loss), without heat stress, is unlikely to be associated with reductions in cognitive function, psychomotor function, mood, and mental readiness (Adams et al., 2008; Leibowitz, Abernethy, Buskirk, Bar-Or, & Hennessy, 1972; Szinnai, Schachinger, Arnaud, Linder, & Keller, 2005)
- High levels of hypohydration (more than 3% body mass loss), or more moderate levels combined with heat stress, may influence cognitive function, mood, and mental readiness (Cian et al., 2000; Cian, Barraud, Melin, & Raphel, 2001; Sharma, Sridharan, Pichan, & Panwar, 1986).

As discussed, body mass is related to total body water because lean body mass is consistently about 74% water. Therefore, fatter individuals will have a smaller total body water and a given weight reduction (body mass) from water loss will incur a greater reduction in total body water or represent a more severe hypohydration. In addition, as discussed above, aerobic performance will be more likely to be degraded at higher skin temperatures, and aerobic tasks are affected more than strength and power tasks. Therefore, since athletes vary in body composition, heat acclimation state (influencing skin temperature), and events vary in aerobic/non-aerobic components, it is likely that considerable variability will be observed for hypohydration-mediated sports performance degradation in real-life situations. However, these are general conclusions and some individuals may find their performance is influenced more or less than that suggested here for a given water deficit. In addition, the smallest performance changes that can currently be identified in research

studies are greater than what might be a meaningful impact in a competitive event.

It is also important to recognize that the artificial environment of some laboratory studies may introduce confounding factors. In a study by Robinson et al. (1995), for example, the conclusion was that fluid ingestion during exercise did not sustain performance in a cycling time-trial. However, the participants in this study were required to drink very large volumes: 629 ml cool flavoured water 5 min before the start of exercise and a further 215 ml every 10 min for the first 40 min of exercise. Perhaps unsurprisingly, the participants reported extreme abdominal discomfort, which may well have accounted for the lack of a beneficial effect of fluid intake.

Comparisons of studies on fluid provision are complicated by differences in the composition of drinks provided, and few studies include both water control and no-drink control treatments. Other variables include differences in the exercise test, participant training status, heat acclimation status, environmental conditions, nutritional status, the drinking schedule, and the temperature of drinks. Many studies, perhaps especially those in which relatively untrained individuals are required to perform in time-trials where pace judgement is of critical importance, are compromised by the absence of appropriate familiarization trials.

Taking all of the available information together would suggest that where performance is crucial, the scientific data can be used as a guide but each individual will need to establish their own individual response to changes in hydration status.

Hydration and perceived exertion and subjective feelings

The impact of hypohydration on cognitive performance has been reviewed extensively (IOM, 2005) and the impact is not clear-cut.

The subjective sensation of effort is increased during exercise if hypohydration is allowed to develop. Moran and colleagues reported that perception of effort, as assessed using the Borg scale, was closely related to the degree of hypohydration (Moran, Montain, & Pandolf, 1988). An exercise intensity that was rated at 13.4 ± 0.5 ("somewhat hard") when participants were dehydrated by 1.1% of body mass was rated at 17.6 ± 0.3 ("very hard") when dehydration reached 4.2%, thus there is clearly an association between the development of hyperthermia and the subjective sensation of effort. Galloway and Maughan (1997) reported a progressively higher subjective sensation of effort as ambient temperature increased from 4°C to 31°C. This effect was apparent early in exercise and may account at

least in part for the slower pace adopted by experienced runners when required to exercise in hot environments (Tucker, Rauch, Harley, & Noakes, 2004). In addition, hypohydration might increase thermal discomfort during exercise heat stress (Cheuvront et al., 2010c).

The increased sensation of effort when exercising in a dehydrated state is clearly important for the athlete, as it is likely to lead to a reduction in performance (Cheuvront et al., 2010c). It may, however, be of greater relevance in those who exercise for health reasons: an increased sensation of effort may be a factor in the early termination of an exercise session and is also likely to discourage long-term adherence to an exercise programme.

Consumption of fluids and electrolytes for hydration

In 2003, the International Olympic Committee held its second Consensus Conference on nutrition for sport. When considering the recommendations for drinking for hydration reasons, the following statement was included (Consensus Statement, 2004):

Sufficient fluid should be consumed during exercise to limit dehydration to less than about 2% of body mass ... Sodium should be included when sweat losses are high, especially if exercise lasts more than about 2 h. Athletes should not drink so much that they gain weight during exercise. During recovery from exercise, rehydration should include replacement of both water and salts lost in sweat.

In addition, and specifically from the two key papers that covered the topic of hydration (Coyle, 2004; Shirreffs, Armstrong, & Cheuvront, 2004a), the following conclusions were drawn:

Sodium should be included in fluids consumed during exercise if the exercise lasts more than 2 h. It should also be included in fluids consumed by individuals in any event who lose more than 3–4 g of sodium in their sweat. (Coyle, 2004)

After exercise that has resulted in body mass loss due to sweat loss, water and sodium should be consumed in a quantity greater than those in the losses to optimize recovery of water and electrolyte balance. (Shirreffs et al., 2004a)

The evidence on which these comments were based can be found within the cited papers and will not be discussed further here. And now, some 7–8 years later, these conclusions remain sound and more

recent reviews of the topic have arrived at similar conclusions (e.g. Sawka et al., 2007).

In addition, Montain and colleagues (Montain, Chevront, & Sawka, 2006) performed a mathematical model of sodium consumption and drinking behaviour on plasma sodium, and demonstrated that overdrinking (relative to sweating) is the primary factor mediating hyponatraemia and that consumption of "sports beverages" containing sodium can delay its development. There has been no new emerging evidence to suggest that any electrolyte other than the already identified sodium has a significant role in hydration before, during or after exercise. *Before exercise*, sodium containing fluids, or foods containing sodium, can help retain any water consumed to establish euhydration prior to the start of exercise when this is desired (Sawka et al., 2007). *During exercise*, sodium consumption along with water is recommended when exercise duration is more than 2 h or when significant amounts of sodium losses (3–4 g) are likely to occur (Coyle, 2004), or when the volume of drink consumed is large enough that it may cause a significant reduction in plasma sodium concentration (Vrijens & Rehrer, 1999). *After exercise*, replacement of sodium and restoration of sodium balance is a prerequisite for an effective restoration and maintenance of euhydration (Shirreffs, Taylor, Leiper, & Maughan, 1996), and no other electrolytes have been shown to play a significant role in this. However, research in the last few years has re-emphasized the importance of not having too rapid a rehydration after exercise if a diuresis is to be avoided and euhydration is to be achieved and maintained. The slowing of the appearance into the circulation of the rehydration fluid can be achieved by the drinking pattern (Kovacs, Schmahl, Denden, & Brouns, 2002) or by delaying the gastric emptying of the drink from the stomach into the intestine by, for example, increasing the carbohydrate content of the drink (Evans, Shirreffs, & Maughan, 2009a, 2009b).

Fluids and electrolytes for thermoregulation

An increase in body core temperature is a common response to exercise, unless the intensity is low and/or the exercise is taking place in a cool environment. An elevated body temperature may be related to early fatigue or a reduction in the intensity at which exercise is performed (Gonzalez-Alonso et al., 1999; Nielsen et al., 1993; Tatterson, Hahn, Martin, & Febbraio, 2000); however, no study has independently examined the role of core temperature as skin temperature has covaried (Chevront et al., 2010c). As demonstrated by Ely et al. (Ely, Chevront, Kenefick, & Sawka, 2009) for euhydrated individuals and by Kenefick et al. (2010) for hypohydrated

individuals, a high skin temperature (with a modest rise in core temperature) will markedly degrade aerobic performance. It is likely that both a high skin temperature and high core temperature will increase skin blood flow requirements to displace blood from the central circulation and therefore reduce cardiac filling, and thus stroke volume and possibly cardiac output. The hypovolaemia (reduced plasma/blood volume) further contributes to decreased cardiac filling and an inability to achieve a high maximal cardiac output.

The effect of the ingested fluid temperature on the rise in core temperature during 2 h of recumbent cycling at 51% peak in a temperate environment of 26°C with relative humidity of 40% was investigated by Wimer et al. (Wimer, Lamb, Sherman, & Swanson, 1997). Compared with ingesting 1350 ml of water at 38°C, the ingestion of 1350 ml of drinks at 0.5°C attenuated the rise in rectal temperature. This observation was subsequently confirmed by Lee and Shirreffs (2007), who found that, compared with ingesting a litre of flavoured water at 50°C, the acute ingestion of the same volume of the same drink at 10°C during 90 min of cycling at 53% peak in a moderate environment (25°C, relative humidity 61%) attenuated the rise in rectal temperature. However, when drinks at 10°C and 50°C were consumed in four smaller aliquots of 400 ml each at intervals during 90 min cycling at 50% peak in a similar moderate environment (25°C, relative humidity 60%), the absolute rise in core temperature by the end of exercise was similar with both drinks (Lee, Shirreffs, & Maughan, 2008a).

A recent review of the literature (Burdon, O'Connor, Gifford, & Shirreffs, 2010a) concluded that ingestion of cold drinks may attenuate an exercise-induced rise in core temperature and improve exercise performance in the heat (by 10%), but this was based on only four studies (Lee & Shirreffs, 2007; Lee, Shirreffs, & Maughan, 2008a, 2008b; Mundel, Bunn, Hooper, & Jones, 2007) and the findings of these studies were mixed. Since this review, further research into exercise performance has been conducted (Burdon et al., 2010b; Ross et al., 2011; Siegel et al., 2010; Stanley, Leveritt, & Peake, 2010). Siegel and colleagues (2010) investigated the effect of ice slurry ingestion (at -1°C) on thermoregulatory responses and submaximal running time in the heat. Approximately 600 ml of the ice slurry or cold water (at 4°C) was consumed before running to exhaustion in a hot environment. Running time was longer after consuming ice slurry (50.2 min) compared with cold water (40.7 min). Ross and colleagues (2011) investigated the efficacy of combining external and internal cooling techniques on performance of a cycling time-trial in a hot and humid environment. The internal and external

cooling was achieved by combining ingestion of a sports drink ice slurry (approximately 1 L) with cold towel application to the torso and legs. The combined internal/external cooling was associated with a 3% increase in power (~ 8 W) and 1.3% improvement in performance time ($\sim 1:06$ min) compared to a control trial when ad libitum ingestion of cold water (4°C) was allowed. Burdon and colleagues (2010b) investigated the effects of consuming approximately 1.7 L of a cold (4°C) compared with an approximately thermoneutral sports drink on performance in the heat. The drinks were consumed during 90 min of steady-state exercise prior to a 15 min performance test. Significant improvements (4.9%) in performance were observed with cold drink ingestion. Finally, Stanley and colleagues (2010) found no difference in cycling exercise performance in hot, humid conditions when either an ice-slush drink (at -0.8°C) or a drink at 18.4°C was consumed in the rest period between 75 min of steady-state cycling and a performance trial. These recent studies provide additional weight and validity to the previous conclusions drawn from research in this area.

Consumption of fluids and electrolytes for thermoregulation

Hypohydration reduces sweating and skin blood flow responses, thus increasing both core and skin temperature. The mechanisms responsible for this are increased plasma osmolality and reduced plasma (blood volume), both of which are related to the magnitude of hypohydration (IOM, 2005; Sawka et al., 2005, Fortney et al., 1984). Since sodium is the primary cation for extracellular fluid, the sodium deficits need to be replaced to re-establish extracellular fluid and total body water.

It might be expected, therefore, that ingestion of sufficient fluid to prevent a marked rise in serum osmolality or minimize plasma volume reduction will sustain thermoregulatory and thus cardiovascular support for exercise. Therefore, the replacement of both water and electrolytes is essential to sustain performance.

Heat, hydration, and the brain

It has long been known that the brain plays an important role in the sensation of effort during exercise (Bainbridge, 1919). The mechanisms that underpin this, however, have remained elusive and are generally relegated to a “black box” phenomenon that might be related to a high central (brain) temperature degrading brain function and reducing the drive to exercise (Nielsen et al., 1993). However, there is some evidence to suggest that the mechanism by which this might operate may be related to

changes in the permeability of the blood–brain barrier induced by hyperthermia and/or dehydration (Maughan, Shirreffs, & Watson, 2007a). A fixed period of exercise results in elevation of the serum concentration of a brain-specific protein, S100 β , if the exercise takes place in the heat but not when the same exercise is performed in a temperate environment (Watson, Shirreffs, & Maughan, 2005). However, two recent studies have not supported the concept that heat stress (Cheuvront et al., 2008) or hypohydration (Castellani et al., 2010) increase S100 β during exercise. Therefore, it is unclear if there is an increase in the permeability of the blood–brain barrier to relatively large protein molecules with exercise-heat stress. In a further study, Watson and colleagues showed that the provision of sufficient fluid during prolonged exercise in a warm environment to limit the rise in plasma osmolality that was observed in a trial where no fluid was given was effective in preventing a rise in serum S100 β (Watson, Black, Clark, & Maughan, 2006).

Conclusions

Hypohydration and hyperthermia can negatively influence the physiological responses to exercise and aerobic exercise performance. These effects can, however, be reduced by consumption of appropriate fluids and electrolytes (sodium).

Note

The opinions or assertions contained herein are the private views of the authors and are not to be construed as official or as reflecting the views of the US Army or the US Department of Defense. Any citations of commercial organizations and trade names in this report do not constitute an official Department of the Army endorsement or approval of the products or services of these organizations.

References

- Adams, G. E., Carter, R., III, Cheuvront, S. N., Merullo, D. J., Castellani, J. W., Lieberman, H. R. et al. (2008). Hydration effects on cognitive performance during military tasks in temperate and cold environments. *Physiology and Behavior*, 93, 748–756.
- Adolph, E. F. (1943). *Physiological regulations*. Lancaster, PA: Jacques Cattell Press.
- Adolph, E. F., & Dill, D. B. (1938). Observations on water metabolism in the desert. *American Journal of Physiology*, 123, 369–378.
- Baker, L. B., Dougherty, K. A., Chow, M., & Kenney, W. L. (2007). Progressive dehydration causes a progressive decline in basketball skill performance. *Medicine and Science in Sports and Exercise*, 39, 1114–1123.
- Bainbridge, F. A. (1919). *The physiology of muscular exercise*. London: Longmans.

- Burdon, C., O'Connor, H., Gifford, J., & Shirreffs, S. M. (2010a). Influence of beverage temperature on exercise performance in the heat: A systematic review. *International Journal of Sports Nutrition and Exercise Metabolism*, *20*, 166–174.
- Burdon, C., O'Connor, H., Gifford, J., Shirreffs, S., Chapman, P., & Johnson, N. (2010b). Effect of drink temperature on core temperature and endurance cycling performance in warm, humid conditions. *Journal of Sports Sciences*, *28*, 1147–1156.
- Castellani, J. W., Muza, S. R., Chevront, S. N., Sils, I. V., Fulco, C. S., Kenefick, R. W. et al. (2010). Effect of hypohydration and altitude exposure on aerobic exercise performance and altitude sickness. *Journal of Applied Physiology*, *109*, 1792–1800.
- Chevront, S. N., Carter, R., III, Castellani, J. W., & Sawka, M. N. (2005). Hypohydration impairs endurance exercise performance in temperate but not cold air. *Journal of Applied Physiology*, *99*, 1972–1976.
- Chevront, S. N., Carter, R., III, Haymes, E. M., & Sawka, M. N. (2006). Moderate hypohydration and hyperthermia do not affect anaerobic exercise performance. *Medicine and Science in Sports and Exercise*, *38*, 1093–1097.
- Chevront, S. N., Carter, R., III, & Sawka, M. N. (2003). Fluid balance and endurance exercise performance. *Current Sports Medicine Reports*, *2*, 202–208.
- Chevront, S. N., Chinevere, T. D., Ely, B. R., Kenefick, R. W., Goodman, D. A., McClung, S. P. et al. (2008). Serum S-100 β response to exercise-heat strain before and after acclimation. *Medicine and Science in Sports and Exercise*, *40*, 1477–1482.
- Chevront, S. N., Ely, B. R., Kenefick, R. W., & Sawka, M. N. (2010a). Biological variation and diagnostic accuracy of dehydration assessment markers. *American Journal of Clinical Nutrition*, *92*, 565–573.
- Chevront, S. N., Kenefick, R. W., Ely, B. R., Harman, E. A., Castellani, J. W., Frykman, P. N. et al. (2010b). Hypohydration reduces vertical ground reaction impulse but not jump performance. *European Journal of Applied Physiology*, *109*, 1163–1170.
- Chevront, S. N., Kenefick, R. W., Montain, S. J., & Sawka, M. N. (2010c). Mechanisms of aerobic performance impairment with heat stress and dehydration. *Journal of Applied Physiology*, *109*, 1989–1995.
- Cian, C., Barraud, P. A., Melin, B., & Raphel, C. (2001). Effects of fluid ingestion on cognitive function after heat stress or exercise-induced dehydration. *International Journal of Psychophysiology*, *42*, 243–251.
- Cian, C., Koulmann, N., Barraud, P. A., Raphel, C., Jimenez, C., & Melin, B. (2000). Influence of variation in body hydration on cognitive function: Effect of hyperhydration, heat stress and exercise-induced dehydration. *Journal of Psychophysiology*, *14*, 29–36.
- Consensus Statement (2004). IOC consensus statement on sports nutrition 2003. *Journal of Sports Sciences*, *22*, x.
- Costill, D. L., Coté, R., & Fink, W. (1976). Muscle water and electrolytes following varied levels of dehydration in man. *Journal of Applied Physiology*, *40*, 6–11.
- Coyle, E. F. (2004). Fluid and fuel intake during exercise. *Journal of Sports Sciences*, *22*, 39–55.
- Devlin, L. H., Fraser, S. F., Barras, N. S., & Hawley, J. A. (2001). Moderate levels of hypohydration impair bowling accuracy but not bowling velocity in skilled cricket players. *Journal of Science and Medicine in Sport*, *4*, 179–187.
- Dougherty, K. A., Baker, L. B., Chow, M., & Kenney, W. L. (2006). Two percent dehydration impairs and six percent carbohydrate drink improves boys' basketball skills. *Medicine and Science in Sports and Exercise*, *38*, 1650–1658.
- Ely, B., Chevront, S. N., Kenefick, R. W., & Sawka, M. N. (2009). Aerobic performance is degraded, despite mild hyperthermia, in hot environments. *Medicine and Science in Sports and Exercise*, *42*, 135–141.
- Evans, G. H., Shirreffs, S. M., & Maughan, R. J. (2009a). Post-exercise rehydration in man: The effects of osmolality and carbohydrate content of ingested drinks. *Nutrition*, *25*, 905–913.
- Evans, G. H., Shirreffs, S. M., & Maughan, R. J. (2009b). Post-exercise rehydration in man: The effects of carbohydrate content and osmolality of drinks ingested *ad libitum*. *Applied Physiology, Nutrition and Metabolism*, *34*, 785–793.
- Fortney, S. M., Wenger, C. B., Bove, J. R., & Nadel, E. R. (1984). Effect of hyperosmolality on control of blood flow and sweating. *Journal of Applied Physiology*, *57*, 1688–1695.
- Galloway, S. D. R., & Maughan, R. J. (1997). Effects of ambient temperature on the capacity to perform prolonged cycle exercise in man. *Medicine and Science in Sports and Exercise*, *29*, 1240–1249.
- Gigou, P.-Y., Lamontagne-Lacasse, M., & Goulet, E. D. B. (2010). Meta-analysis of the effects of pre-exercise hypohydration on endurance performance, lactate threshold and $\dot{V}O_{2max}$. *Medicine and Science in Sports and Exercise*, *42* (suppl.), 361–362.
- Gonzalez-Alonso, J., Teller, C., Andersen, S. L., Jensen, F. B., Hyldig, T. M., & Nielsen, B. (1999). Influence of body temperature on the development of fatigue during prolonged exercise in the heat. *Journal of Applied Physiology*, *86*, 1032–1039.
- Greive, J. S., Staffey, K. S., Melrose, D. R., Narve, M. D., & Knowlton, R. G. (1998). Effects of dehydration on isometric muscular strength and endurance. *Medicine and Science in Sports and Exercise*, *30*, 284–288.
- Institute of Medicine (IOM) (2005). Water. In *Dietary reference intakes for water, potassium, sodium, chloride, and sulfate* (pp. 73–185). Washington, DC: National Academies Press.
- Judelson, D. A., Maresh, C. M., Anderson, J. M., Armstrong, L. E., Casa, D. J., Kraemer, W. J. et al. (2007). Hydration and muscular performance: Does fluid balance affect strength, power and high-intensity endurance? *Sports Medicine*, *37*, 907–921.
- Kenefick, R. W., Chevront, S. N., Palombo, L. J., Ely, B. R. & Sawka, M. N. (2010). Skin temperature modifies impact of hypohydration on aerobic performance. *Journal of Applied Physiology*, *109*, 79–86.
- Kovacs, E. M., Schmahl, R. M., Denden, J. M., & Brouns, F. (2002). Effect of high and low rates of fluid intake on post-exercise rehydration. *International Journal of Sport Nutrition and Exercise Metabolism*, *12*, 14–23.
- Leibowitz, H. W., Abernethy, C. N., Buskirk, E. R., Bar-Or, O., & Hennessy, R. T. (1972). The effect of heat stress on reaction time centrally and peripherally presented stimuli. *Human Factors*, *14*, 155–160.
- Lee, J. K. W., & Shirreffs, S. M. (2007). The influence of drink temperature on thermoregulatory responses during prolonged exercise in a moderate environment. *Journal of Sport Sciences*, *25*, 975–985.
- Lee, J. K. W., Shirreffs, S. M., & Maughan, R. J. (2008a). The influence of serial feeding of drinks at different temperatures on thermoregulatory responses during prolonged exercise. *Journal of Sports Sciences*, *26*, 583–590.
- Lee, J. K. W., Shirreffs, S. M., & Maughan, R. J. (2008b). Cold drink ingestion improves exercise endurance capacity in the heat. *Medicine and Science in Sports and Exercise*, *40*, 1637–1644.
- Maughan, R. J., Shirreffs, S. M., & Watson, P. (2007a). Exercise, heat, hydration and the brain. *Journal of the American College of Nutrition*, *26*, 604S–612S.
- Maughan, R. J., Watson, P., Evans, G. H., Broad, N., & Shirreffs, S. M. (2007b). Water balance and salt losses in competitive football. *International Journal of Sport Nutrition and Exercise Metabolism*, *17*, 583–594.

- Montain, S. J., Chevront, S. N., & Sawka, M. N. (2006). Exercise associated hyponatremia: Quantitative analysis to understand the aetiology. *British Journal of Sports Medicine*, *40*, 98–106.
- Moran, D. S., Montain, S. J., & Pandolf, K. B. (1998). Evaluation of different levels of hydration using a new physiological strain index. *American Journal of Physiology: Regulatory, Integrative and Comparative Physiology*, *275*, R854–R860.
- Mundel, T., Bunn, S. J., Hooper, P. L., & Jones, D. A. (2007). The effects of face cooling during hyperthermic exercise in man: Evidence for an integrated thermal, neuroendocrine and behavioural response. *Experimental Physiology*, *92*, 187–195.
- Nielsen, B., Hales, J. R., Strange, S., Christensen, N. J., Warberg, J., & Saltin, B. (1993). Human circulatory and thermoregulatory adaptations with heat acclimation and exercise in a hot, dry environment. *Journal of Physiology*, *460*, 467–485.
- Nose, H., Mack, G. W., Shi, X. R., & Nadel, E. R. (1988). Involvement of sodium retention hormones during rehydration in humans. *Journal of Applied Physiology*, *65*, 332–336.
- Robinson, T. A., Hawley, J. A., Palmer, G. S., Wilson, G. R., Gray, D. A., Noakes, T. D. et al. (1995). Water ingestion does not improve 1-h cycling performance in moderate ambient temperatures. *European Journal of Applied Physiology and Occupational Physiology*, *71*, 153–160.
- Ross, M. L., Garvican, L. A., Jeacocke, N. A., Laursen, P. B., Abbiss, C. R., Martin, D. T. et al. (2011). Novel pre-cooling strategy enhances time trial cycling in the heat. *Medicine and Science in Sports and Exercise*, *43*, 123–133.
- Sawka, M. N., Burke, L. M., Eichner, E. R., Maughan, R. J., Montain, S. J., & Stachenfeld, N. S. (2007). American College of Sports Medicine position stand: Exercise and fluid replacement. *Medicine and Science in Sports and Exercise*, *39*, 377–390.
- Sawka, M. N., Chevront, S. N. & Carter, R. (2005). Human water needs. *Nutrition Reviews*, *63*, S30–S39.
- Sawka, M. N., Francesconi, R. P., Young, A. J., & Pandolf, K. B. (1984). Influence of hydration level and body fluids on exercise performance in the heat. *Journal of the American Medical Association*, *252*, 1165–1169.
- Sawka, M. N., Leon, L. R., Montain, S. J., & Sanna, L. A. (in press). Integrated physiological mechanisms of exercise performance, adaptation, and maladaptation to heat stress. *Comprehensive Physiology*.
- Sawka, M. N., & Noakes, T. D. (2007). Contrasting perspectives in exercise science and sports medicine: Does dehydration impair exercise performance? *Medicine and Science in Sports and Exercise*, *39*, 1209–1217.
- Sharma, V. M., Sridharan, K., Pichan, G., & Panwar, M. R. (1986). Influence of heat stress-induced dehydration on mental functions. *Ergonomics*, *29*, 791–799.
- Shirreffs, S. M., Armstrong, L. E., & Chevront, S. N. (2004a). Fluid and electrolyte needs for preparation and recovery from training and competition. *Journal of Sports Sciences*, *22*, 57–63.
- Shirreffs, S. M., Sawka, M. N., & Stone, M. (2006). Water and electrolyte needs for football training and match-play. *Journal of Sports Sciences*, *24*, 699–707.
- Shirreffs, S. M., Taylor, A. J., Leiper, J. B., & Maughan, R. J. (1996). Post-exercise rehydration in man: Effects of volume consumed and sodium content of ingested fluids. *Medicine and Science in Sports and Exercise*, *28*, 1260–1271.
- Siegel, R., Mate, J., Brearley, M. B., Watson, G., Nosaka, K., & Laursen, P. B. (2010). Ice slurry ingestion increases core temperature capacity and running time in the heat. *Medicine and Science in Sports and Exercise*, *42*, 717–725.
- Stanley, J., Leveritt, M., & Peake, J. M. (2010). Thermoregulatory responses to ice-slush beverage ingestion and exercise in the heat. *European Journal of Applied Physiology*, *110*, 1163–1173.
- Szinnai, G., Schachinger, H., Arnaud, M. J., Linder, L., & Keller, U. (2005). Effect of water deprivation on cognitive-motor performance in healthy men and women. *American Journal of Physiology: Regulatory, Integrative and Comparative Physiology*, *289*, R275–R280.
- Tatterson, A. J., Hahn, A. G., Martin, D. T., & Febbraio, M. A. (2000). Effects of heat stress on physiological responses and exercise performance in elite cyclists. *Science and Medicine of Sport*, *3*, 186–193.
- Tucker, R., Rauch, L., Harley, Y. X. R., & Noakes, T. D. (2004). Impaired exercise performance in the heat is associated with an anticipatory reduction in skeletal muscle recruitment. *Pflügers Archives*, *448*, 422–430.
- Vrijens, D. M., & Rehrer, N. J. (1999). Sodium-free fluid ingestion decreases plasma sodium during exercise in the heat. *Journal of Applied Physiology*, *86*, 1847–1851.
- Watson, P., Black, K. E., Clark, S. C., & Maughan, R. J. (2006). Exercise in the heat: Effect of fluid ingestion on blood-brain barrier permeability. *Medicine and Science in Sports and Exercise*, *38*, 2118–2124.
- Watson, P., Shirreffs, S. M., & Maughan, R. J. (2005). Blood-brain barrier integrity may be threatened by exercise in a warm environment. *American Journal of Physiology: Regulatory, Integrative and Comparative Physiology*, *288*, R1689–R1694.
- Wimer, G. S., Lamb, D. R., Sherman, W. M., & Swanson, S. C. (1997). Temperature of ingested water and thermoregulation during moderate-intensity exercise. *Canadian Journal of Applied Physiology*, *22*, 479–493.