



# ASSESSING HYDRATION IN THE LABORATORY AND FIELD

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## KEY POINTS

- In the United States, “the loss of human life due to overheating during hot spells in summer exceeds that caused by all other weather events combined, including lightning, rain, floods, hurricanes and tornadoes” (Klinenberg, 2002).
- Evaporative sweating is necessary to dissipate heat during exercise or any condition in which core temperature increases. Sweating depends on adequate blood volume.
- Dehydration (hypohydration) is the result of long-term sweating in the absence of fluid replacement and is usually associated with increased plasma sodium concentration and plasma osmolality (hyperosmotic, hypovolemia). Hypohydration can also occur concomitant with large sodium losses (hyposmotic, hypovolemia).
- Exercise-associated hyponatremia is usually associated with ingestion of hypotonic fluids in greater excess than excretion (hypervolemic hyponatremia). Hyponatremia can also be associated with high sweat sodium concentrations concomitant with large sweat volume losses (hypovolemic hyponatremia—dehydration), which is more common in ultra-endurance events.
- Field studies provide the actual settings during the athletic competition and can be immediately applied to the athlete. However, the environment for data collection is less controlled.
- Laboratory studies require the extra step of translating findings to the field. However, these studies provide information on physiological effects, responses or mechanisms.

## INTRODUCTION

According to Eric Klinenberg's book *Heat Wave: A Social Autopsy of Disaster in Chicago*, “the loss of human life in hot spells in summer exceeds that caused by all other weather events combined, including lightning, rain, floods, hurricanes and tornadoes” (Klinenberg, 2002). During exercise, especially during heat exposure, the working muscles increase core temperature. In order to avoid overheating, fluid moves from the blood stream to the skin, where it can be evaporated as sweat, thus cooling the body. Therefore, maintaining blood volume is essential for optimal thermoregulation during exercise. In humans, the primary method of maintaining body fluids, including blood volume, is through fluid intake, although a small (~10%) amount of water is generated by the cells during metabolism. Because maintenance of fluids is so important for survival, humans have a number of important mechanisms to sense changes in the overall amount of fluid in the body and its composition.

In this review, these mechanisms will be described, followed by how they function during exercise. We will then describe how dehydration and exercise-associated hyponatremia (EAH) occur when the body is pushed to extremes and unable to employ the mechanisms designed to maintain the appropriate hydration and tonicity appropriate to support human function. Finally, the advantages and disadvantages of field and lab measurements will be discussed.

## REGULATION OF FLUID BALANCE

A completion of a marathon, or similar endurance event, typically results in a body water loss of ~2-3%, accompanied by increases in plasma sodium concentration of ~5-7 mmol/L (Sawka et al., 2007).

The brain controls body fluids and receives information on changes in body fluid status from three primary sources: central osmoreceptors, central angiotensin II and peripheral baroreceptors. This information is relayed to key areas in the brain responsible for triggering responses appropriate to the specific perturbation in body fluid status. The osmoreceptors are sensitive to very slight changes in osmolality, or tonicity (related to the amount of sodium in the blood), so only about a 2% change in osmolality is required to trigger increases in thirst and increases in the hormone arginine vasopressin (AVP). This is the hormone most responsible for inducing renal free water retention, so during periods of water loss AVP can be key to avoiding dehydration. AVP is also one of the most powerful vasoconstrictors in the body, so it will also contribute to the maintenance of blood pressure during periods of low blood volume.

Changes in body fluids are also sensed by peripheral baroreceptors. These baroreceptors are located in the atrium and sense changes in pressure as central blood volume is lost or gained. These receptors are important, but require an approximate 10% change in pressure before triggering responses by the brain and kidney to stimulate thirst receptors or increase fluid retention. We are adept at measuring changes in both the osmo- and volume receptors in the laboratory, as well as their fluid regulatory responses to them.

## DEHYDRATION

A number of variables can affect thermoregulation during exercise, including hydration status, duration and intensity of exercise, environmental conditions, acclimatization to exercise-heat stress, work capacity ( $\text{VO}_2\text{max}$ ), physical conditioning, and personal factors

like medications, supplements, sleep, and illness. Hyperthermia occurs during exercise when muscle-generated heat accumulates faster than heat dissipates via increased sweating and skin blood flow (Adolf, 1947). Depending on intensity and environmental factors, heat production can be as much as 15–20 times greater than at rest, and can raise core body temperature by 1°C every 5 min if no heat is dissipated (Nadel et al., 1977). Thus, significant water loss occurs due to sweating, which is necessary to dissipate heat during exercise or any condition in which core temperature increases. Hypohydration, or volume depletion, is usually associated with increased plasma sodium concentration and plasma osmolality, “hyperosmotic, hypovolemia.” Hypohydration that occurs concomitant with large sodium losses is called hypoosmotic, hypovolemia. Generally, an athlete can lose 2-3% of body weight during a long distance event without any negative health or performance effects (Sawka et al., 2007). In fact, such water loss is expected following long distance racing or training, especially in a hot environment.

Despite the information provided to athletes, and the increased number of water stops during races, the incidence of greater than 2% dehydration is reported as 50-70% in long races and greater than 4% dehydration is reported at ~30% of participants (Speedy et al., 1999; Noakes et al., 2005). Dehydration lowers physical and mental capacity for exercise, compromises cardiovascular and thermoregulatory function (i.e., attenuates sweating, so increases risk of heat-related disorders, e.g., heat exhaustion or heat stroke), reduces stroke volume, and increases heart rate, so it exaggerates strain on the cardiovascular system. Furthermore, the hypovolemia associated with dehydration can also reduce blood pressure, further exacerbating cardiovascular strain. Thus, dehydration can reduce exercise intensity or cause complete cessation of exercise. *The only way to avoid dehydration is through fluid intake.*

### EXERCISE-ASSOCIATED HYPONATREMIA (EAH)

Exercise-associated hyponatremia can occur when athletes reduce serum sodium concentration by  $\geq 5$  mmol/L during endurance exercise (Speedy et al., 2001; Almond et al., 2005). This condition can occur when athletes competing in long duration events ingest hypotonic fluids in greater excess than they are able to excrete (hypervolemic hyponatremia), or when athletes have unusually high sweat sodium concentrations concomitant with large sweat volume losses (hypovolemic hyponatremia). Most athletes tolerate a substantial fall in sodium concentration without symptoms (Speedy et al., 2001). However, in those athletes that cannot tolerate these losses, or when the EAH is extreme (serum sodium of 120-125 mmol/L), the consequences can be severe (cerebral edema and metabolic encephalopathy, permanent brain damage, death). Hypervolemic hyponatremia, the most common of the two types, has been attributed to excessive drinking concomitant with inappropriately elevated levels of AVP or an inadequate renal response to AVP (Verbalis, 2003) that leads to excessive free water retention (Sawka et al., 2007). Surely behavior (over drinking) can override the power of these physiological systems?

Women are at greater risk for EAH and this risk has been attributed to their lower body weight and size, excess water ingestion and longer racing times relative to men (Speedy et al., 2001; Almond et al., 2005). While these factors contribute to the greater incidence of EAH in women, it is likely that their greater levels of estradiol in plasma and/or tissues also play a role in increasing their greater risk. Estradiol is associated with greater free water fluid retention and alterations in fluid distribution independent of body size or fluid intake behavior (Ayus & Arieff, 1996; Stachenfeld et al., 2001; Stachenfeld & Taylor, 2005). Moreover, women of reproductive age are more likely to experience postoperative hyponatremia (Ayus & Arieff, 1996). More importantly, estradiol exposure may leave women more susceptible to the extreme consequences of EAH. In both men and women undergoing even minor surgery, a combination of anesthesia, postsurgical stress and nausea, can lead to dramatic increases in AVP, which is associated with brain swelling and damage primarily in women (Ayus & Arieff, 1996). Thus, estradiol may play a significant role in the greater risk of cerebral edema and encephalopathy found in women, indicating a more complex etiology than simply lower body size, longer running times and cultural norms of drinking behavior contribute to the sex differences in EAH (Almond et al., 2005).

### HOW TO ASSESS HYDRATION IN THE FIELD AND IN THE LABORATORY

One important dynamic that exists when studying the exercise fluid regulatory response is that between field and laboratory research.

#### FIELD RESEARCH

In field research, the scientist has the advantage of studying responses in conditions under which the athlete will face during competition. In addition, the athletes are performing their own specific activity with the equipment they use in competition. In the laboratory, with few exceptions like running, rowing or cycling, these conditions can only be modeled to be as close as possible to the actual sport. Thus, the information derived from a carefully conducted field study should be immediately valuable and can be easily applied to the individual athlete.

However, during field studies environmental conditions, such as the temperature and humidity cannot be controlled, and may be variable across research days, practice or training days and competition. Collecting sweat, urine or blood samples can be difficult during training or competition because either the equipment needed is not portable or the collection process interferes with the race or training session. In addition, performing intervention studies in the field is challenging because interventions for the purpose of research may impact performance. Thus, in the field, the information gathered is important but can be limited to observational studies.

A number of elegant systems are used to determine hydration in the field such as portable refractometers to determine urine specific

gravity. Urine duration can be counted in seconds to estimate volume if collection is not viable, the athletes can estimate their own fluid intake when bottles or cups are supplied to them, body weights can be measured before, during and after the event or training sessions to determine sweating volume, and simple sweat collection systems (e.g., patches) can measure sweat electrolyte composition. During races the investigator can determine and record environmental conditions on race day and track them over time. To measure physiological variables, minimally intrusive heart rate, temperature and blood gas monitors are also available.

## LABORATORY RESEARCH

Observational research in the field poses questions that can be explored in a more controlled setting in the laboratory. Interventions can be used in the laboratory in order to determine mechanisms that explain responses or performance in the field, or explore mechanisms that explain the impact of exercise or physical activity on physiological systems.

*Research in the laboratory* is necessary in order to carefully control conditions to study mechanisms involved in fluid and electrolyte regulation. The studies that demonstrated sodium ingestion during exercise maintained plasma volume without suppressing thirst and fluid-regulating hormones were performed in the laboratory (Nose et al., 1988a, 1988b, 1988c). With salt ingestion, the subjects were better able to maintain fluids within the compartments needed to support sweating (Nose et al., 1988a). Another example is the study of EAH. It has proved difficult to examine the mechanisms for EAH in the field because the studies are retrospective; that is, athletes are examined after they have become hyponatremic during a race, but are not placed into EAH groups before the race, and drinking behavior cannot be controlled to induce EAH in the field. Such prospective studies can only be performed in the laboratory, where a controlled environment provided the first prospective study to examine risk factors associated with EAH. Subjects with a history of hyponatremia were recruited into the laboratory, performed long-term exercise with excess fluid (water) intake precisely controlled (Stachenfeld & Taylor, 2009). These studies demonstrated that water retention, not sodium loss, was the primary contributor to the lower exercise  $[\text{Na}^{2+}]$  in women at risk for EAH. Moreover, sex hormone interventions suggested that sodium loss might be a more important factor in EAH in women during increased progesterone exposure.

## PRACTICAL APPLICATIONS

- There is large individual variability across athletes and/or active people in water and sodium losses through sweating, so athletes should practice their fluid replenishment regimen as they are training for the event. *The amount of sodium and fluids needed differ across athletes and is very much dependent on conditions:*
  1. Determine sweat rate from body weight changes during training. (1 kg (2.2 lb) body mass  $\approx$  1 L (34 oz) of body water loss);

2. Monitor fluid intake;
  3. Determine the best way to maintain electrolytes during racing.
- Sodium ingestion during long-term exercise can:
    1. Improve total body and compartmental fluid volume retention;
    2. Increase plasma sodium content;
    3. Maintain thirst;
    4. Stimulate the kidneys to retain water.
  - Assess body mass and plasma and urine sodium/osmolality before and after training sessions and racing when possible.
  - One liter (34 oz) of a sports drink containing 20 mEq/L of sodium will provide 460 mg of sodium.
  - Although the body fluid status related to dehydration and EAH is completely different, some of the symptoms, such as malaise, nausea, light-headedness, dizziness, and fatigue, can overlap. Therefore, if changes in body weight or a blood sample cannot be attained, assessment of fluid intake and urination during the exercise bout is important before deciding on treatment.
  - Athletes who lose large volumes of sweat should consider ingesting additional sodium in the form of sports drinks with greater sodium content, or in bars, gels, or electrolyte powders or tablets that provide extra sodium.
  - Sports drinks are hypotonic to plasma, so athletes who use sports drinks should not assume that they are immune to EAH.

## SUMMARY

Both dehydration and EAH can be dangerous during long-term exercise so all athletes competing or training for long distance events must learn how to regulate their body fluids and electrolytes. There is large variability across individuals, so there is not one protocol for drinking or eating during training or racing that will work for all athletes. It is for this reason that athletes must monitor their sweat loss and fluid intake during training, and they should do this under as many environmental conditions as possible. Field studies are integral for determining challenges that athletes face, and are primarily observational in nature so as to not interfere with the athlete's training or competition. These observational studies form the basis for the mechanistic questions that can be studied in the laboratory. In the laboratory, environmental conditions can be tightly controlled, and fluids and electrolyte intake and output can be measured precisely. It is in the laboratory studies that physiological mechanisms can be determined, with the ultimate goal of improving health and performance in the field. Endurance athletes should aim to maintain fluid losses at close to 2% body weight. Thus, during shorter exercise bouts (~1-2 h) ad libitum drinking water or sports drinks are recommended. However, during exercise bouts expected to be greater than 2 h, the athlete should plan specific, practiced hydration and electrolyte replacement strategies to protect health and performance.

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