Fluid-Electrolyte Balance During Labor and Exercise: Concepts and Misconceptions

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Body water and electrolyte balance are essential to optimal physiological function and health. During exercise, work, or high temperatures, a significant level of dehydration can develop, and the ratio of extracellular to intracellular fluid can change, despite ample supply of water. Physical and cognitive performance are impaired at 1–2% dehydration, and the body can collapse when water loss approaches 7%. Because fluid needs and intakes vary, formulating one general guideline for fluid replacement is difficult. Knowing the amount of water lost in sweat may enable predicting fluid needs via mathematical models for industrial, athletic, and military scenarios. Sodium imbalance might result from excessive Na⁺ loss or from gross overhydration. In most work or exercise lasting < 3–4 hr, the major concern is that fluid be available to prevent heat-related illnesses, which can be prevented if fluid and electrolyte losses are balanced with intake, using the recommendations presented.

Key Words: sodium, body water, heat illness, performance, hypohydration, body temperature, thirst, gastric emptying, hyponatremia, extracellular fluid

In 1855, the French physiologist Claude Bernard concluded that the primary condition for independence of existence is the stability of the “inner environment” (“la fixité du milieu intérieur est la condition de la vie libre”). He also argued that water and temperature are among the basic factors that must be constantly controlled (11). This early statement, which is the theoretical basis of homeostasis, indicates that the function of cells and the body as a whole are very much dependent on the constancy of their intra- and extracellular environments. Therefore, body water depletion will not only adversely influence performance, it will also, when severe, threaten life.

The total amount of water in the average adult human body (70 kg) is approximately 42 L, averaging 60% of total weight. About 28 L comprise the intracellular fluid (ICF), and the other 14 L the extracellular fluid (ECF). Most of the ECF contains interstitial fluid, which accounts for about 15% of body weight, and plasma (5% of body weight). Water content of women is lower than men of similar body weight because females have a higher ratio of adipose tissue to lean body mass.

Euhydration (i.e., normal daily water content) is represented by a horizontal sinusoidal wave on a graph of Body Mass (y axis) over Time (x axis). This wave

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indicates that body water expands and contracts within narrow limits in a repeatable fashion. Steady-state conditions of increased and decreased body water are defined as hyperhydration and hypohydration, respectively. Dehydration refers to water loss leading to hypohydration, and rehydration is the process of adding water from a state of hypohydration toward euhydration. Fluid intake that exceeds euhydration, thus leading to hyperhydration, is referred to as overhydration.

The volume of total body water is regulated daily within ±0.22% of body weight, and plasma volume within ±0.7% (30). Body fluids are regulated and maintained at an optimal level by the nervous and endocrine systems. Several factors can cause the ECF-to-ICF ratio to change, among them an imbalance between water intake and loss. During exercise, work, or high temperatures, a body weight deficit of 1–4.5% can occur, even with an ample supply of water (2, 32). These losses adversely affect physical and cognitive performance. Therefore, dehydration, rehydration, and voluntary hyperhydration—facts and misconceptions about each—during work and exercise-heat stress are the subjects of this review.

Hypohydration and Performance

Many pioneering studies have demonstrated the effect of dehydration on human performance. Adolph and associates reported that 16% of dehydrated soldiers but only 2% of euhydrated ones suffered exhaustion from heat strain during a desert march (2). Ladell reported that exhaustion from heat strain occurred in 75% of the cases when water was not supplied, but in only 7% of those when it was available (38). Sohar et al., in their classic 1959 study on soldiers marching in the desert, also showed that dehydration caused exhaustion, whereas euhydration allowed individuals to continue the mission (65). In a very early paper, Eichna et al. described dehydrated participants’ inability to perform in the heat: “Total incapacitation... acclimatized subjects who had performed a given task easily... Reduced to apathetic, listless, plodding men straining to finish the same task” (18). Performance impairment is already noticed at 1% dehydration (600–800 ml water loss), and collapse is evident in some individuals at about 7% loss of body water (27, 32). Cognitive performance is also adversely influenced by body water deficits (28, 38).

Effect of Hypohydration on Performance

The adverse effects of hypohydration on performance occur via impairment of the thermoregulatory and cardiovascular systems (46, 57). Depending on work intensity, total metabolism increases 5–20 times over the resting metabolic rate to provide energy for the working muscles. This high metabolic rate requires a marked increase in cardiac output. During intense exercise, which is further accentuated by heat stress, cardiac output can increase to 5 times (~25 L/min) the resting output. Most of the blood volume under exercise-heat stress is transferred to the working muscle and skin at the expense of blood flow to the viscera (i.e., kidney, liver, and gastrointestinal tract) (57).

Increased blood flow to the peripheral vascular bed acutely reduces the volume of blood filling the heart (“isotonic hypovolemia”) and decreases venous return, the end diastolic volume, and stroke volume. Further, the ability to maintain adequate cardiac output is compromised by progressive dehydration, which reduces blood volume (“hypertonic hypovolemia”). This decreased blood volume stimulates
an increase in heart rate, which subsequently limits exercise performance, because it
is the last means of maintaining cardiac output. In the latter situation, skin blood
flow is reduced, and the body’s ability to convect heat to the periphery is impaired.

During intense exercise, the heat generated by muscle metabolism must be
adequately dissipated so that body temperature does not rise to levels that will cause
exertional heatstroke. About 80% of the metabolic energy produced in contracting
muscles results in heat, which must be dissipated to maintain body heat balance. In
response to the elevated body temperature, cutaneous blood flow is increased,
transporting heat from the core to the periphery, and sweating is initiated. In hot
environments, a considerable amount of body water can be lost through sweat
secretion to enable the evaporative cooling of the body. Sweat secretion varies
considerably, depending on environmental conditions, work intensity, clothing,
state of acclimatization, and fitness level (59, 71). On average, sweat rates of 1–1.5
L/hr during exercise in the heat are common (53). Perhaps the highest sweat rate
reported was 3.7 L/hr, measured for Alberto Salazar during the 1984 Olympic
marathon (7). Sweating means the loss of vital body fluids and electrolytes, which, if
not replaced, can cause circulatory and thermal impairments (59).

Compared to euhydration, hypohydration results in an increased core tem-
perature during exercise, regardless of environmental conditions. As the water
deficit increases, there is a concomitant graded elevation of core temperature during
exercise (for review see Reference 61). In addition, the thermoregulatory advan-
tages conferred by high aerobic fitness and heat acclimatization are compromised,
but not eliminated, by hypohydration during exercise in the heat (61).

Cumulative results suggest that plasma hypertonicity exerts a powerful influ-
ence on thermoregulatory sweating and body temperature responses during exercise in the heat (59). Animal data suggest that this result may be due to a central
effect (37, 47, 64). Human research indicates that toxicity also may exert a periph-
eral effect via a high interstitial osmotic pressure, inhibiting the fluid availability to
the eccrine sweat gland (29, 49).

According to Fortney et al. and Sawka et al., toxicity has a consistent influ-
ence on sweating threshold values (body temperature at which the response is
initiated) but does not affect sweat sensitivity (sweating response per degree in-
crease in body temperature) (22, 60). Conversely, hypovolemia (e.g., a steady-state
blood volume that is less than normal) reduces sweat sensitivity but does not influ-
ence sweating threshold (21). Hypovolemia also increases skin blood flow thresh-
old values to some extent and has a profound effect on sensitivity (36). Thus,
hypovolemia alone can mediate an increase in core temperature and reduced heat
loss during exercise-heat exposure. As mentioned above, hypovolemia reduces
cardiac preload, alters atrial baroreceptor activity, and might result in syncope. The
reduced atrial filling pressure might modify neural information to the hypothalamic
thermoregulatory centers (21).

**Rehydration**

Under resting conditions, thirst—as a fluid intake drive—is an adequate stimulus
for total fluid replacement (31). Much of daily fluid replacement occurs during
regular meals (2). However, thirst does not appear to be a sufficient stimulus for
maintaining body water during exercise-heat stress, and spontaneous drinking oc-
curs only after considerable water loss (>2% of body weight). As early as 1932,
Vernon and Warner observed that voluntary consumption of water (served at 37 °C) replaced only 56% of sweat losses during exercise in a climatic chamber (70). These findings were confirmed by Adolph and Dill, who studied men working in desert heat (1), and were repeatedly confirmed by others (2, 32, 55, 67). This syndrome, the lag in voluntary fluid intake with dehydration, was termed "voluntary dehydration." That is, humans drink to temporary satiety, but a water debt remains (2). Later, Greenleaf termed this condition "involuntary dehydration" (31). Both terms are used interchangeably. Voluntary dehydration is considered the major cause for dehydration.

When water is not readily available or if it is unpalatable, salty, or warm, drinking is reduced, and voluntary dehydration increases (2, 34, 67). Physical activity accentuates voluntary dehydration, whereas leisure reduces it (2, 67). Therefore, a water deficit accumulated between meals is usually restored during a repast (2, 67).

Learning the need for fluid replenishment increases voluntary intake of water and reduces voluntary dehydration. This observation, first noted by Eichna et al. in a study during WWII (18), was later verified by Seidman et al., who observed no differences between the expected and ad libitum amounts of water (or a carbohydrate-electrolyte solution) that soldiers consumed during exercise in the heat (62). This suggested that awareness of one’s need for water can greatly enhance water consumption. In fact, during prolonged, intermittent exercise, physiological cues and behavioral factors may both affect drinking behavior at different times (32, 46, 51).

Rehydration depends on gastric emptying and intestinal absorption; the former is currently considered the primary factor limiting rehydration during exercise (16, 27, 39, 40, 45), because the maximal rate of intestinal absorption exceeds that of gastric emptying (16, 27). Fluid volume plays a major role in regulating the rate of gastric emptying (41). Up to at least 600 ml, the larger the volume consumed the greater the rate of emptying from the stomach (15, 58). Tonicity also affects gastric emptying. Hypotonic fluids are emptied from the stomach and absorbed from the intestinal lumen more readily than isotonic solutions (20, 42). Plain water is probably absorbed slightly faster than a carbohydrate solution (14, 42, 44, 48). Other factors that influence the gastric emptying rate include fluid characteristics (i.e., pH, temperature, electrolyte content, and caloric density) and environmental factors (i.e., heat stress and mode of exercise) (15).

Gastric emptying of liquids follows an exponential time course. In most cases up to 80% of water is emptied within 15–30 min (26). Exercise does not delay gastric emptying rate if work intensity is <70–75% of the maximal aerobic capacity (VO₂ max) (12, 15). However, in exercise lasting <1 hr in which intensity ranges from 75% to >100% VO₂ max, gastric emptying may be reduced, compromising fluid absorption and affecting performance (16).

Among the precautions cited in a 1909 monograph, Marathon Running, is the following: "Don’t get in the habit of drinking... Some prominent runners do, but it is not beneficial" (69). Until the late 1960s, running a marathon without any fluid replacement was considered the ultimate aim of most runners and a test of their fitness (53). Military personnel were the first to recognize the importance of water replacement to adequately perform labor in the heat (2, 55, 61, 67). Research from this perspective changed the general attitude toward water from its former negative interpretation ("withhold water to toughen the troops") to the current positive one ("supply enough water and encourage drinking") (67). Fluid ingestion during prolonged low-to-moderate-
intensity exercise (< 75% VO₂max) improves exercise performance (2, 10, 18, 43, 55). Moreover, there is sufficient rationale for replacing fluids during events lasting <1 hr to attenuate the rise in core temperature (26, 51). For example, Costill et al. reported that ingesting 100 ml after every 10 min of exercise significantly attenuated the increase in rectal temperature among trained marathon runners (38.5 °C and 39.2 °C after 2 hr of running, with and without water replacement, respectively) (44).

Endurance athletes often have difficulty ingesting the optimal volume of fluid to prolong exercise performance without drinking too much or too little. Wyndham and Strydom previously suggested that complete fluid replacement of body water loss during prolonged, strenuous exercise may not be necessary and that the goal of fluid replacement should be to prevent a 3% water deficit (72). This hypothesis has never been directly tested. Today, the prevailing concept is that ideally, during prolonged low-to-moderate-intensity intermittent exercise, the optimal rate of fluid replacement should match the rate of sweating as closely as possible (3, 17).

Most people can empty no more than 1,000 ml of fluid from the stomach during each hour of exercise. For example, Ryan et al. showed that replacing 350 ml of fluid every 20 min during cycling in the heat resulted in a gastric emptying rate of 94–99% of the drink ingested (58). However, endurance athletes usually drink no more than 400–600 ml/hr (52, 51). It remains unclear whether dehydration can be completely offset when sweat rate is high (1,000–1,500 ml/hr). Such high rates of fluid ingestion will obviously require large gastric volumes, which may cause gastrointestinal discomfort under exercise- and heat-induced visceral vasoconstriction. This requires proper rehydration instructions, which will reduce the gastrointestinal discomfort, enhance absorption, and reduce the rate of voluntary dehydration without exposing the individual to the dangers of dehydration or overhydration.

The American College of Sports Medicine (ACSM) recommends that runners drink 100–200 ml of fluids after every 2–3 km of a road race (4). However, fluid needs and intake vary, depending on climatic conditions, exercise intensity, and body size. Therefore, formulating one single guideline for optimal fluid replacement in all circumstances is difficult, if not impossible. Consideration of race pace verifies this fact. Following the ACSM guideline would provide an elite marathon runner (moving at a 3.1-min km, or 5-min mile pace) with 600–1800 ml/hr. In contrast, a jogger would consume 320–960 ml/hr running at a 6.2-min km (10-min mile) pace, and 270–800 ml at a 7.5-min km (12-min mile) pace. Given that maximal gastric emptying rate is approximately 1,000 ml/hr (58) and that sweat loss during exercise in a hot environment is typically 1,000–1,500 ml/hr (53), this means that the elite runner might consume an inadequate-to-excessive volume of fluid, and the jogger might not drink enough.

Knowing how much fluid is lost in sweat may facilitate predicting fluid intake. Using only body weight and running speed, Barr and Costill suggested a simplified equation for predicting the water needs of an average marathon runner (9). For military personnel and laborers, Shapiro et al. developed a comprehensive mathematical predictive equation for sweat rate in various climates, at different exercise intensities, and with varied clothing (63). Table 1 presents fluid requirements, as calculated by their mathematical model. At the extremes of this table (i.e., lower right corner), because water requirements exceed the maximal gastric emptying rate of approximately 1,000 ml/hr (58), overdrinking could occur if fluid intake matched these requirements exactly. A proper recommendation for fluid intake
requires considering factors such as body size, previous experiences with consuming large fluid volumes, and interindividual differences in gastric emptying rates. Each recommendation also should be field tested before it is used in athletic competition or an industrial setting.

Voluntary Hyperhydration With Hypotonic Fluid

The need to drink before, during, and after exercise has been emphasized strongly in attempts to reduce the negative effects of dehydration on competitive events and fitness activities (3). Since 1985 the issue of exercise-related hyponatremia (serum sodium concentration <130 mmol/L) (23) also has been recognized. Hyponatremia and sodium (Na⁺) deficiency are not synonymous terms; many hyponatremic states are associated with normal or even excessive body Na⁺ stores. Hyponatremia has been reported among marathoners and ultraendurance competitors (exercise lasting 7–17 hr) and during military maneuvers (8, 33, 53, 56, 73). Hyponatremia has also been observed during intermittent walking and recreational hiking in adults and children (>4 hr) (8, 25, 54). Although such cases are relatively rare (<0.3% of all participants in ultraendurance events), the incidence may exceed 10% among runners and triathletes who collapse at races (23). It seems, however, that the incidence of subclinical hyponatremia (130–135 mmol Na⁺/L) is much higher (13, 24).

Theoretically, hyponatremia can result from excessive Na⁺ loss that is not compensated by proper salt intake while ECF is replenished by adequate water ingestion, or from overhydration with hypotonic fluids (i.e., water), as illustrated in Table 2. Some clinicians have implicated large Na⁺ losses as the primary cause of hyponatremia (53), but estimates of high sweat Na⁺ concentrations do not support the low sweat Na⁺ values (<25 mmol/L) reported in heat-acclimated and trained individuals (5, 68). Researchers who advocate salt supplementation also base their arguments mainly on theoretical calculations, indicating that serum Na⁺ concentrations are reduced due to excessive Na⁺ loss in sweat. However, very few control

Table 1  Predicted Water Requirements (ml/hr) for Military Personnel and Laborers, Based on a 70-Kg Person, With Respect to Work Intensity and Heat Load (from Shapiro et al., 1982, ref. 10)

<table>
<thead>
<tr>
<th>Work intensity²</th>
<th>Heat load¹</th>
<th>Mild</th>
<th>Moderate</th>
<th>Severe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rest</td>
<td>500/300³</td>
<td>100/450</td>
<td>200/500</td>
<td></td>
</tr>
<tr>
<td>Light</td>
<td>400/700</td>
<td>500/800</td>
<td>600/950</td>
<td></td>
</tr>
<tr>
<td>Moderate</td>
<td>500/850</td>
<td>700/1,000</td>
<td>800/1,200</td>
<td></td>
</tr>
<tr>
<td>Heavy</td>
<td>850/1,250</td>
<td>1,000/1,500</td>
<td>1,250/1,600</td>
<td></td>
</tr>
</tbody>
</table>

¹Discomfort index = 0.5 (dry bulb temperature) + 0.5 (wet bulb temperature).
²In terms of oxygen consumption: light work, up to 0.5 L/hr, moderate work, 0.5-1.0 L/hr, heavy work, 1.0-1.5 L/hr.
³All values are for low (night) and high (summer daylight) solar radiation.
studies or actual field observations support those calculations. In fact, it is extremely difficult, perhaps impossible, for healthy humans to develop a salt deficiency, regardless of environment and amount of exercise (26, 51, 66). Epstein and Sohar (19) named this "christening by conjecture." If sweat contains 30 mmol Na+/L, hyponatremia could develop after only 10 hr of exercise. If food is consumed during such long periods of activity, salt depletion should not occur.

Alternatively, overhydration and expansion of the ECF volume also may cause hyponatremia via dilution of a normal or slightly reduced total extracellular Na+ content (Table 2). This mechanism will cause ICF volume expansion, thus balancing the osmolalities between the ECF and ICF fluid compartments. Armstrong et al. reported this for a study participant who developed hyponatremia within 4 hr of exercise in the heat (6). This individual, who started mild exercise in the heat with a relatively low serum Na+ concentration (134 mmol/L) drank excessively—twice as much as he lost in sweat—causing ECF dilution. Similarly, Irving et al. demonstrated a linear relationship between the volume of excess fluid at the finish of an ultramarathon race and postrace serum Na+ concentrations among eight runners (35). These authors and others have concluded that exercise hyponatremia results from fluid retention in individuals who ingest abnormally large fluid volumes (e.g., >10 L) during prolonged exercise (8, 35).

The possibility that hyponatremia results from fluid retention in the gastrointestinal tract (a "third space") has also been hypothesized (50). In this case, Na+ that moves into the intestine enters the extracellular fluid only at a later time (33, 53). This hypothesis supports medical observations in that clinical symptoms of hyponatremia may increase in number and severity 0.1–6 hr postexercise (5, 25, 33, 56). There are several different causes of hyponatremia (5, 50), and fluid retention in the gastrointestinal tract may not be involved in all types.

Cumulative data suggest that symptomatic hyponatremia can develop only in the presence of gross fluid overload. Accordingly, to prevent this condition, athletes must moderate fluid intake during exercise, based on sweat rates. In most cases, salt supplementation is not needed. Seidman et al. investigated fluid and salt balance in

<table>
<thead>
<tr>
<th>Condition</th>
<th>Initial</th>
<th>Final</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ECFi (L)</td>
<td>Na+ (mmol/L)</td>
</tr>
<tr>
<td>Normal response to uncorrected</td>
<td>15</td>
<td>2,100</td>
</tr>
<tr>
<td>sodium loss during exercise</td>
<td></td>
<td>140</td>
</tr>
<tr>
<td>Large sweat and urine Na+ loss</td>
<td>15</td>
<td>2,100</td>
</tr>
<tr>
<td>Fluid overhydration</td>
<td>15</td>
<td>2,100</td>
</tr>
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</table>

Note. ECFi = initial extracellular fluid volume, Na+ = initial serum sodium, ECFi = final extracellular fluid volume, Na+ = final serum sodium.
soldiers marching in the desert, drinking either water or an isotonic replacement beverage. The investigators found no fluid or electrolyte differences between the two groups (62). Serum Na⁺ concentrations were about 137 mmol/L at the end of 15 km and 134 mmol/L at the end of a 30-km march. Galun et al. documented a decrease in serum Na⁺ during a 24-hr, 120-km march (24). Urine osmolalities were about 200 mOsm/L, indicating a water secretion and urine dilution, probably because of overhydration. Interestingly, although these two studies differed in duration and climate, serum Na⁺ concentrations were similar (134 ± 2 and 135 ± 2 mmol/L). Such levels are typical and have been repeatedly observed (5, 9). This may support the concept that the normal response to uncorrected Na⁺ losses during exercise is probably a regulated reduction in the ECF volume that is proportional to the Na⁺ deficit, thereby maintaining normonatremia or resulting in clinically insignificant, mild hypernatremia or hyponatremia, as with most endurance athletes or soldiers (Table 2) (24, 52). Armstrong concluded, therefore, that electrolyte supplementation may be needed only in rare cases, for exercising individuals who lose >8 L of sweat, are not heat acclimated, skip meals, experience a caloric deficit of >1,000 kcal/day, or have diarrheal disease (5).

Conclusions

In most exercise events lasting <3–4 hr, the major concern is that fluid be available to prevent heat-related illness. Illnesses related to dehydration and hyponatremia can be prevented during virtually all prolonged exercise bouts if athletes attempt to balance fluid loss with intake using the following suggestions:

1. Athletes and exercise enthusiasts should not assume that they can drink unlimited quantities of fluid during exercise.
2. Slower runners are on the race course longer, consume more liquid at aid stations, and have relatively low sweat rates due to lower exercise intensity. Thus, they have a greater risk of hyponatremia if they consume too much water.
3. A low-salt diet or ingesting large quantities of hypotonic fluid 24–76 hr before competition or labor may predispose humans to hyponatremia by establishing a low-normal serum Na⁺ concentration (130–135 mmol/L).
4. When served chilled during athletic events, beverages containing carbohydrates and electrolytes can offset body fluid losses. Seidman et al. reported that under field conditions, such beverages, when not served cold, are unpalatable and not consumed readily (62).

Rehydration is summarized in ACSM's current position stand regarding exercise and fluid replacement (3). This document recommends that athletes drink at regular intervals to replace the water lost through sweating as closely as possible. Fluids should be cooled (15–22 °C) and flavored to enhance palatability and promote fluid replacement. They should be readily available so that adequate volumes can be ingested with ease. ACSM also reiterates the weak physiological basis for including sodium in fluids as a means of enhancing intestinal absorption, assuming sodium is sufficiently available in the diet. However, sodium may enhance palatability and prevent hyponatremia in individuals who drink excessive quantities of fluid. Nature dictated involuntary dehydration; we defy nature at our peril.
References


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