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HYDRATION CONSIDERATIONS FOR COLD AND ALTITUDE ENVIRONMENTS

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KEY POINTS

- Cold and altitude have unique mechanisms that contribute to dehydration in these environments.
- The impact of dehydration on health and performance in these environments depends on exercise intensity, severity of environmental conditions, and length of exposure.
- Dehydration can impair performance at altitude, but cold induced performance decrements depend on skin temperatures.
- Logistical constraints impact fluid consumption in both environments.
- Whether or not dehydration contributes to the development of cold injuries and high-altitude illnesses is currently unclear, and additional work is needed in this area.

INTRODUCTION

Hypohydration is defined as a >2% decrease in total body water and often occurs when individuals are exposed to extreme environments (Sawka et al., 2015). When considering the influence of the environment on hydration status and thermoregulation, individuals often think of heat stress, due to increased body water loss with sweating. However, exposure to cold and altitude environments also increases body water loss through several other physiological mechanisms which negatively impact hydration status if losses are not matched by fluid intake. The purpose of this Sports Science Exchange (SSE) article is to discuss the mechanisms that contribute to dehydration in both cold and altitude environments and examine the implications of dehydration in these environments on health and performance for those who may need to work or compete in the cold and/or at altitude.

HYDRATION IN COLD ENIVRONMENTS

Mechanisms for Cold-Induced Water Loss

Dehydration in a cold environment can result from numerous physiological factors including cold-induced diuresis (Knight & Horvath, 1985), increases in respiratory water loss due to decreased air humidity (Brebbia et al., 1957), blunted thirst (Kenefick et al., 2004), or increases in sweat loss depending on the clothing worn and exercise intensity (Marriott & Carlson, 1996) (TABLE 1).

Cold-Induced Diuresis

It is well established that there is a marked effect of cold exposure on urine production, a phenomenon known as cold-induced diuresis (CID). CID results from a cascade of physiological responses, starting with the sympathetically mediated peripheral cutaneous vasoconstriction, which redistributes blood to the core of the body to conserve body heat. This increases central blood volume which stimulates the cardiopulmonary baroreceptors located in the atria, ventricles, and pulmonary blood vessels, signaling an increase in blood pressure which results in increased urine production and output to reduce blood volume and pressure. The redistribution of blood and CID may be greater during cold-water immersion due to the influence of the hydrostatic pressure of the surrounding water on the vasculature.

Respiratory Water Loss

Respiratory water loss is increased in a cold environment and depends on two factors: water vapor pressure in the ambient air and ventilation or metabolic rate. Lower water vapor pressures in the ambient inhaled air will lead to greater water losses. The inhaled air is warmed to body temperature and fully saturated, leading to 100% relative humidity and a water vapor pressure of 47 mmHg by the time the air reaches the alveoli. The amount of water lost at each pressure depends on the water vapor pressure gradient between the ambient air and the fully saturated air in the lung. Therefore, respiratory water loss will increase as the water vapor pressure of the ambient air decreases.

While water vapor pressure gradients will determine the amount of fluid lost with each breath, the metabolic rate and associated ventilation have a far greater impact on overall respiratory water losses. Few studies have quantified the impact of cold air, associated lower water vapor pressure and changes in ventilation on respiratory water losses and its contribution to body water deficits in cold environments (Brebbia et al., 1957; Mitchell et al., 1972). Thus, this is an area in need of future work to be able to accurately recommend fluid replacement guidelines for cold weather activities of varying intensities and durations.

Blunted Thirst

Fluid intake has been shown to be decreased at rest and during exercise in cold environments. Cold environments appear to attenuate thirst sensations both at rest and during exercise (Kenefick et al., 2004). A reduction in thirst (~40%) in the cold appears to occur regardless of hydration status (i.e., still blunted even in dehydrated individuals with increased plasma osmolality). Interestingly, in the cold, even in

the presence of increased plasma osmolality, the arginine vasopressin (AVP) response is blunted. The decline in AVP release is likely related to the overloading of the cardiopulmonary baroreceptors that occur with the redistribution of blood flow from the periphery.

Impact of Clothing on the Microclimate

It is important to keep in mind that while air temperature may be cold, an individual may not actually be cold themselves depending on the amount of clothing worn. This influence of clothing thickness and insulation has important implications for both thermoregulatory responses and fluid losses during exercise in the cold. It is imperative to match clothing to metabolic rate to prevent excessive heat storage, rises in core temperature and subsequently increases in sweat loss, which can also contribute to wet clothing and increased risk of cold injury.

Dehydration and Performance in Cold Environments

Hypohydration has been shown not to impair aerobic exercise performance in a cold environment when compared to a thermoneutral environment (Cheuvront et al., 2005). Previous studies have shown that 3-4% body mass dehydration did not lead to decrements in cycling time trial performance when skin temperatures were decreased (Cheuvront et al., 2005; Kenefick et al., 2010). Unlike in hot environments where dehydration contributes to greater cardiovascular strain and competition for blood flow between contracting muscles and skin for thermoregulation, the peripheral vasoconstriction to maintain body temperature eliminates the increased cardiovascular demand and allows for adequate muscle blood flow (Sawka et al., 2012, 2015). As mentioned above, an important consideration for the impact of dehydration on performance in the cold is what the individual wears during exercise. In these studies, participants were wearing t-shirts and shorts, which may not be representative of what individuals would choose to wear during exercise in ~2-10°C weather. The combined effects of a cold environment and hypohydration on performance may be dependent on skin temperature and what the individual is wearing during exercise. In fact, another investigation demonstrated that the decrement in performance across a range of environmental temperatures (10, 20, 30, and 40°C) was related to the increase in skin temperature caused by the elevations in ambient temperatures (Kenefick et al., 2010; Sawka et al., 2012). From a performance perspective, it's important to match clothing with metabolic rate to prevent the creation of a warm/hot microclimate.

Cold Injuries

It is often suggested that dehydration can increase the risk of cold injuries. The influence of dehydration on cold injuries is less understood with the research reporting conflicting results that appear to be dependent on the level of dehydration reached, type of cooling (whole body or local), and severity of the cold stress. In two investigations, dehydration (~4.5%; ~3.5%) led to significantly lower finger/hand temperatures compared to when individuals were euhydrated (Roberts & Berberich, 1988; Roberts et al., 1984). The literature suggests that dehydration may blunt the cold-induced vasodilation response, leading to lower finger and hand temperatures, which would subsequently decrease dexterity and increase risk of cold injury. In another investigation, skin temperatures were higher with whole body cold stress (120 min at 7°C) and dehydration (~4%), suggesting that dehydration and hypertonicity impairs the vasoconstrictor response to cold stress, and increases peripheral blood flow (O'Brien et al., 1998). While there is evidence suggesting increases and decreases in peripheral blood flow when individuals are dehydrated in the cold, future studies are needed to determine the threshold for blunted cold-induced vasodilation and whether or not the differences in finger blood flow/temperature translates to decrements in dexterity and increases the risk of cold injury.

HYDRATION AT ALTITUDE

Water Loss at Altitude

Similar to the cold, altitude exposure leads to a series of physiological responses that decrease total body water (TABLE 1). The decrease in total body water is the result of a combination of increased fluid loss and decreases in fluid consumption which are both further influenced by the severity of hypoxic and hypobaric stress, ambient temperature, as well as physical activity (Institute of Medicine, 1996). Due to the altitude induced increase in ventilation, hypoxic ventilatory response and decrease in water vapor pressure in the ambient air, respiratory water loss is increased at altitude relative to a sea level environment (Marriott & Carlson, 1996). Altitude exposure is also associated with diuresis that results from respiratory alkalosis, influence of hypoxia on the ion channels within the kidneys, and alterations in fluid regulating hormones (Goldfarb-Rumyantzev & Alper, 2014). Unlike a cold environment, hypohydration has been shown to lead to further reductions in exercise performance at altitude and may contribute to increased development and severity of altitude mountain sickness (AMS) symptoms, which can have a cyclical effect and contribute to further dehydration (Castellani et al., 2010). While exposure to hypobaric hypoxia alters physiological responses affecting hydration status, it does not appear to alter thermoregulatory responses (i.e., skin blood flow and sweating) during exercise (Charkoudian et al., 2019). Factors including blunted thirst, nausea from AMS, and logistical concerns regarding access to drinkable water also affect fluid intake at altitude.

Decrease in Plasma Volume at Altitude

To facilitate an increase in oxygen carrying capacity of the arterial blood, plasma volume decreases upon ascent to altitude. While the decrease in plasma volume is well established, the physiological mechanisms contributing to the decrease in plasma volume are complex and appear to depend on several variables including exercise, water availability, altitude illnesses, and rate of ascent (Siebenmann et al., 2017).

Hypoxic Ventilatory Response

One of the most notable physiological responses to altitude exposure is the increase in ventilation, or hypoxic ventilatory response (HVR) that occurs upon ascent/exposure to the lower partial pressure of oxygen. This response, mediated primarily through the peripheral

chemoreceptors, acts to increase ventilation to increase systemic oxygen content in the hypoxic environment. This increase in ventilation, in combination with the decreased relative humidity often found in hypoxic environments, contributes to increases in respiratory water loss. Since expired air is fully saturated with water (i.e., almost 100% relative humidity), the lower the ambient humidity, the greater the water losses during breathing at altitude (Siebenmann et al., 2017). Interestingly, to date, no studies have quantified respiratory water losses at altitude. Whether or not this increase in water loss greatly contributes to, or exacerbates, the water loss through other avenues has yet to be determined.

The role of the HVR and the sensitivity of the peripheral chemoreceptors has been shown to be highly correlated with the diuretic responses, which led authors to hypothesize that the activation of the peripheral chemoreflex may contribute to the diuretic response seen at altitude (Siebenmann et al., 2017; Swenson et al., 1995).

Acute Diuresis at Altitude

The HVR also contributes to fluid loss by contributing to the acute diuretic response that occurs at altitude (Goldfarb-Rumyantzev & Alper, 2014). While the increase in ventilation acts to increase the arterial partial pressure of oxygen and arterial oxygen saturation, it also leads to respiratory alkalosis (increased pH) due to the increased "blowing off" of carbon dioxide. To return pH to normal levels, the kidneys compensate by increasing renal excretion of bicarbonate ions and water follows (Skalla et al., 2026). The initial reduction in fluid also leads to hemoconcentration and improves the oxygen carrying capacity of the arterial blood (Young et al., 2019).

Plasma Proteins and Influence on Intravascular Volume

While the decrease in plasma volume at altitude is well-established (Young et al., 2019), the original thought that the plasma volume contraction was solely the result of an altitude-induced diuresis has been challenged. Recent work demonstrated that the loss of plasma volume at altitude was strongly related to changes in total circulating proteins, as a 4-day sojourn to 3500 m led to a ~10% decrease in plasma volume which was not the result of an increase in urine production or decrease in total body water (Schlittler et al., 2021; Young et al., 2019). Interestingly, the reduction in plasma volume was accompanied by a reduction in plasma proteins, which was suggestive of a redistribution of fluid from the intra- to extravascular spaces, driven by changes in oncotic pressure. Similar findings have been shown during a 22-day acclimatization to 4300 m, where the change in plasma volume was primarily mediated by the changes in plasma proteins and associated oncotic pressure (Young et al., 2019).

Alterations in Fluid Regulating Hormones

The literature regarding high altitude diuresis and the contribution of fluid regulating hormones remains controversial (Goldfarb-Rumyantzev & Alper, 2014). Several studies have investigated the impact of fluid regulating hormones including adrenomedullin, the renin-angiotensin-aldosterone system, and arginine vasopressin or anti-diuretic hormone (ADH) during both acute and chronic exposure to altitude (Goldfarb-Rumyantzev & Alper, 2014; Haditsch et al., 2015). While several investigations have sought to determine the role these hormones play with regards to fluid balance at altitude, confounding factors including rate of ascent, elevation reached, ambient temperature, and level of physical activity all contribute to the variability in hormonal responses at altitude (Marriott & Carlson, 1996). ADH has been shown to be significantly increased after exercise in those who developed AMS, but not in those who do not develop AMS (Bärtsch et al., 1991), which suggests a role for fluid regulating hormones in the development of AMS. However, more research is needed to fully understand the impact of fluid regulatory hormones on AMS.

TABLE 1. Summary of the physiological responses and mechanisms contributing to fluid losses and dehydration in cold and altitude environments.

Physiological Response	Mechanism
Cold Environment	
Cold Induced Diuresis	• Peripheral vasoconstriction from decreased skin temperature (Tsk) leads to redistribution of blood to the core and overloads baroreceptors in the atria, leading to increased production of atrial natriuretic peptide (ANP). • Increased urine output.
Respiratory Water Loss	• Decreased water vapor pressure in ambient air requires the body to warm and moisten the air in the trachea prior to reaching the bronchioles. • Magnitude of decrement dependent on metabolic rate and ventilation.
Sweating	• Depending on the clothing worn and metabolic rate/heat production of the individual exercising in the cold, there may be considerable sweat losses which could lead to dehydration.
Blunted Thirst	• Results from blunted arginine vasopressin release and also prompted by peripheral vasoconstriction and subsequent physiological effects.
Altitude	
Respiratory Water Loss	• Decreased water vapor pressure in ambient air requires the body to warm and moisten the air in the trachea prior to reaching the bronchioles. • Hypoxic ventilatory response (HVR) leads to an increase in ventilation.
Diuretic Response	• The increased ventilation, related to the HVR, prompts increased CO2 loss, raising blood pH (respiratory alkalosis), leading kidneys to increase urine output due to a need to decrease bicarbonate (HCO3-) in the blood. • May be related to alterations in fluid regulating hormones.
Plasma Volume Shifts	• Shift of fluid from the intravascular to extravascular space due to alterations in oncotic pressure from decreased plasma proteins.
Sweating	• Sweating may be higher at altitude due to increased solar radiation and increased skin temperatures. The higher skin temperatures would promote higher sweating rates. • It is important to note that the decreased absolute humidity (and wider water vapor pressure gradient) would promote the evaporation of sweat.

Sweating at Altitude

High altitude environments have the potential to influence the sweating response to exercise due to the increase in solar radiation and decreased water vapor pressure, both of which contribute to increases in body water losses (Gagge & Gonzalez, 2011; Gonzalez et al., 2013). On one hand, the decreased absolute humidity and the wider water vapor pressure gradient promotes the evaporation of sweat off the skin (Gonzalez et al., 2013). On the other, the increase in solar radiation may lead to higher skin temperatures thus contributing to higher sweat rates.

Dehydration and Performance at Altitude

Dehydration at altitude appears to contribute to further performance decrements than the hypoxic stress alone. Work done by Castellani et al. (2010) examined the impact of 4% hypohydration on time trial performance at ~10,000 ft (3048 m). Hypoxia (euhydrated) and dehydration (normoxia, sea level) independently led to performance decrements of 11% and 19%, respectively. In the combined altitude and dehydration trial, exercise performance was impaired by a 34% decrement relative to the sea level, euhydrated trial. This study demonstrates that the body water losses and dehydration experienced at altitude have significant impacts on exercise performance with potential cumulative impacts of dehydration and altitude exposure (Castellani et al., 2010).

A Role for Hydration Status in the Development of AMS?

Currently, whether dehydration increases the prevalence and severity of AMS is unclear. In some (Mairer et al., 2009), but not all (Aoki & Robinson, 1971; Castellani et al., 2010) investigations, dehydration appeared to increase the prevalence and severity of AMS symptoms. However, AMS and dehydration share similar symptoms such as headache, fatigue, and altered cognitive function, therefore it is recommended that those ascending to altitude remain well hydrated (Marriott & Carlson, 1996) to prevent dehydration from exacerbating the symptoms of AMS.

Logistical Constraints for Water Consumption

In addition to physiological mechanisms contributing to decreases in total body water, logistical concerns also contribute to decreased water consumption. For example, individuals may choose to reduce fluid intake to avoid needing to use the bathroom or have decreased availability to water. Water is heavy and can add additional loads, which is especially important during prolonged excursions in the cold. Finally, depending on the ambient temperature, water can freeze, which can make it difficult to consume adequate fluid to maintain hydration.

Altitude also presents a series of logistical concerns that contribute to decreases in total body water during mountaineering or hiking expeditions. Water is heavy to carry, is difficult to replenish a water supply while hiking, and lack of access to bathrooms may all contribute to voluntary dehydration in hikers. Additionally, decreased thirst (Jones et al., 1981; Karpęcka-Gałka & Frączek, 2024; Sharma et al., 2023) or symptoms of AMS such as nausea may deter individuals from drinking enough fluid to maintain total body water.

PRACTICAL APPLICATIONS

- Both cold and altitude environments lead to decreases in total body water loss due to alterations in physiological responses and reductions in fluid intake.
- Water consumption is impacted by logistical considerations in both environments.
- Short duration of exercise performance in the cold is not impacted by hydration status – if the individual is cold (i.e., decreased skin and core temperature), but dehydration significantly impairs performance at altitude.
- Hydration status may play a role in the prevention of cold injuries and development of symptoms of AMS.

SUMMARY

It is well-established that in cold and altitude environments, several physiological mechanisms and logistical constraints contribute to decreases in total body water and dehydration. The current literature suggests that dehydration at altitude, but not in the cold, contributes to performance decrements. However, more work is needed in this area across a range of environmental conditions, exercise intensities, and levels of dehydration. Future work should also focus on quantifying the fluid losses from mechanisms such as respiratory water loss and diuresis across a range of conditions to aid in the development of fluid replacement guidelines in these environments for those who need to work and compete in these environmental extremes. A summary of the physiological responses and mechanisms that contribute to decreases in total body water and plasma volume in cold and altitude environments are presented in TABLE 1.

The views expressed are those of the authors and do not necessarily reflect the position or policy of PepsiCo, Inc.

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