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PHYSIOLOGICAL IMPACT OF HYPOHYDRATION ON THERMOREGULATION, CARDIOVASCULAR FUNCTION, AND SUBSTRATE USAGE DURING EXERCISE

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Abstract

Water is an essential nutrient for life and the intake of fluid before and during prolonged exercise is key for optimal performance. Hypohydration, a condition of fluid deficit, can adversely affect the body's response to physical work. Hypohydration hinders both dry and evaporative heat loss, impairing the body's thermoregulatory processes during exercise. Associated with hypohydration is a decline in plasma volume which negatively affects cardiovascular function, resulting in a depressed stroke volume. Additionally, modifications in fuel usage may occur during exercise in a hypohydrated state with a shift toward a greater dependency on carbohydrate. These hypohydrated-induced impairments in thermoregulation and cardiovascular function, combined with modified fuel substrate utilization, result in decreased maximal oxygen consumption, exercise performance, and exercise capacity. This review discusses the basic concepts regarding hypohydration and the associated physiological impact it has on responses to exercise. Additionally, the review includes an introduction into the less explored area of hypohydration and the possible fuel substrate alterations that occur during exercise.

Key words: *dehydration, body temperature regulation, cardiovascular physiology, energy metabolism*

Introduction

Water serves many roles in the body, and thus is a nutrient that is essential for life. Water provides structure to cells and fills the space between them. It acts as a solvent for many nutrients and is involved in all biochemical reactions of the body. Water also has a vital role in the digestion, absorption, transportation, and utilization of nutrients (1). Additionally, water acts as a lubricant, a body temperature regulator, and a regulator of acid-base balance (2).

Approximately 60% of body mass is water, corresponding to 42 liters for the average adult male (70kg). In the body, water is distributed in the extracellular (20% body mass) and the intracellular fluids (40% body mass). The extracellular fluid is composed of interstitial fluid (15% of body mass) and plasma (5% of body mass) (3). Water constitutes 65 to 75% of muscle tissue (2) and approximately 10% of adipose tissue (4). Thus, the water content for men is typically higher than that for women of comparable weight, because men tend to have a lower ratio of fat tissue to lean tissue.

A person with a normal total body water is considered to be in a state of "euhydration", whereas a person with a total body water below normal (body fluid deficit) is described as being in a state of "hypohydration" (5). The process by which hypohydration occurs is called "dehydration" (5,6).

Fluid Balance

As mentioned, fluid within the human body exists in intracellular and extracellular compartments. Cell membranes are semi-permeable, providing easy passage for water molecules. This allows the body to redistribute water not only within, but also between fluid compartments and helps lessen the effects of water loss (4,7). The movement of water within the body is largely determined by hydrostatic and osmotic pressures (8). Blood volume, cardiac output, and peripheral resistance together determine hydrostatic pressure, while osmotic pressures are dependent upon the concentrations of solutes inside and outside of cells (7).

The nervous and endocrine systems are primarily responsible for the regulation and maintenance of optimal body fluid levels. A daily water intake of 3.7 liters for adult men and 2.7 liters for adult women will meet the needs of most individuals (9). However, if water intake does not equal or exceed water output, a water deficit will occur leading to a state of hypohydration. Hypohydration results in a hyperosmotic and hypovolemic body environment that causes several changes to the cardiovascular function and thermoregulatory processes of the body. During physical work or exercise, hypohydration of as little as one to two percent body mass can negatively affect thermoregulation and cardiovascular function (10). Furthermore, impairments in thermoregulation and cardiovascular function may affect fuel usage and exercise performance.

Effects of Hypohydration on Thermoregulation

During exercise, the control of body temperature (thermoregulation) is adversely affected by hypohydration. Compared with euhydration, hypohydration produces an increase in core temperature during exercise in temperate (11-14) and hot (11,15-18) environments, although the effects are intensified in hot environments. A study by Buono and Wall (11) demonstrated the effects of pre-exercise hypohydration (5% decrease in body mass) on core temperature in temperate and hot environments. Eight male subjects completed four exercise trials at 60 percent maximal oxygen uptake for 60 minutes. The four randomly assigned trials consisted of the following: temperate-euhydrated, temperate-hypohydrated, hot-euhydrated, and hot-hypohydrated. Compared to the euhydration trials, hypohydration resulted in a higher core temperature. Additionally the increased core temperature in the hot-hypohydrated trial was significantly higher than the three other trials. In fact, the increase in rectal temperature during the hot-hypohydrated trial was approximately twice that seen in the temperate-hypohydrated trial.

As noted by the authors, their results have been supported by previous research. In 1971, Greenleaf and Castle (19) reported that rectal temperature increases 0.10 degrees Celsius for each one percent decrease in body mass during exercise at 24 degrees Celsius. Comparatively, Sawka, et al. (18) observed rises in rectal temperature of 0.15 degrees Celsius per one percent declines in body weight during exercise at 49 degrees Celsius. Exercise intensities and durations were comparable in these two studies.

Buono and Wall (11) theorized that the greater increase in rectal temperature during the heat was due to either an increase in metabolic heat production or a decrease in heat dissipation from the body. Because oxygen uptake was similar between the four trials, they reasoned that the increased rectal temperature during the heat was due to a reduction in heat loss. Based on their results, a reduction in heat loss could be attributed to two mechanisms. Compared to the euhydrated trials, whole body sweat rates were lower during hypohydration. Also, hypohydration led to decreases in forearm blood flow, indicating a reduction in cutaneous blood flow.

Hypohydration impairs both dry and evaporative heat loss (20). Compared to interstitial fluid and plasma, perspiration is hypotonic (21). This creates a hyperosmotic, hypovolemic condition in the body (6). Studies have shown that under this condition, whole-body sweat rates decrease (20,22,23). Hyperosmolality increases the threshold for temperature for sweating (23), whereas the hypovolemia lowers sweating sensitivity (22). Thus, due to the hyperosmotic, hypovolemic body environment produced by hypohydration, evaporative heat loss suffers. Hypohydration during exercise also hinders dry heat exchange, especially in a hot environment. The decrease in forearm blood flow during exercise in a hypohydrated state as seen by Buono and Wall (11) has been observed by others (16,22,24). Fortney et al. (22) proposed a mechanism for the reduced skin blood flow. They theorized that hypovolemia due to hypohydration may reduce cardiac preload and modify the activity of atrial baroreceptors, which have afferent input to the hypothalamus. A decreased atrial filling pressure may alter the neural stimulation to the thermoregulatory centers of the hypothalamus, which control skin blood flow and sweating. Additionally, González-Alonso et al. (25) demonstrated that hypovolemia due to hypohydration increases plasma norepinephrine, which is associated with increases in cutaneous vasoconstriction.

Effects of Hypohydration on Cardiovascular Function

Studies have shown that during exercise, hypohydration causes an increase in heart rate (16,25,26) and decreases in stroke volume (16,26) and cardiac output (16,25,26). These hypohydrated-induced cardiovascular effects stem from a loss of blood volume, which is due to a loss of plasma volume. During hypohydration, a decreased blood volume causes a reduction in central venous pressure (27,28), attenuating venous return to the heart, lowering cardiac filling, end diastolic volume, and thus stroke volume (28).

Studies have indicated that during exercise in a hypohydrated state, heart rate increases, maintaining cardiac output values similar to those seen during euhydration (29-31). However, later studies demonstrated that increases in heart rate during hypohydration are not sufficient to maintain cardiac output equal to that seen during euhydration (16,25,26). Roy et al. (26) suggested that a different strategy to maintain cardiovascular function appears to be at work. These researchers referred to a study by Zappe et al. (32) that found no differences in mean blood pressure between euhydrated and hypohydrated conditions. Results from this study indicated that total peripheral resistance was higher during hypohydration. Roy et al. (26) observed higher norepinephrine levels during hypohydration which, as they suggested, appear to be associated with increased sympathetic drive which could be implicated with decreased cutaneous blood flow.

Data from González-Alonso et al. (25) seem to support the suggestions of Roy et al. (26). González-Alonso and associates (25) observed the cardiovascular changes associated with dehydration during exercise in the heat (35 degrees Celsius). Cardiac output decreased during hypohydration and this was associated with elevations in systemic vascular resistance, forearm vascular resistance, and cutaneous vascular resistance. Naturally, decreases in forearm and cutaneous blood flow occurred. However, mean arterial pressure was slightly, but significantly (p<0.05) reduced despite increases in systemic and cutaneous vascular resistance. González-Alonso et al. (25) concluded that increases in cutaneous and forearm vascular resistance with dehydration might have resulted from the independent or combined effects of: 1) imposition of cutaneous vasoconstriction overriding the thermally-induced active vasodilatory process and/or 2) withdrawal of cutaneous active vasodilation independent of vasoconstriction. The authors also suggested that either local release of norepinephrine in the skin or from plasma catecholamines (33) may have had a role in the dehydration-induced increase in cutaneous vascular resistance. González-Alonzo, et al. (25) did observe significant (p<0.05) increases in plasma norepinephrine during the dehydrated trial.

Hypohydration and Exercise Capacity

Several studies have examined the effects of hypohydration on maximal oxygen uptake (34-37) and exercise performance (38,39). Results from these studies indicate that impairments in performance are related to the cardiovascular and thermoregulatory modifications that occur during a hypohydrated state.

Research has demonstrated that maximal oxygen uptake significantly decreases during hypohydration by various means in temperate (34,35,37) and hot (36) environments. However, as the environment temperature increases, hypohydration becomes a greater influence on exercise performance (39).

The mechanism by which hypohydration causes a reduction in maximal aerobic capacity may be a reduced maximal cardiac output (4). As discussed previously, hypohydration results in a decreased plasma volume which lowers blood volume. Blood viscosity increases and central blood volume drops causing a decrease in venous return. During maximal exercise, cardiac filling suffers resulting in a lower end diastolic volume and thus a lower stroke volume and cardiac output. Several researchers have reported decreased cardiac outputs during exercise in a hypohydrated state (16,25,26). In a hot environment, the need to dissipate heat by increasing cutaneous blood flow could affect maximal aerobic power by 1) reducing cardiac output to contracting muscles and/or 2) decreasing central blood volume and venous pressure causing reductions in venous return and cardiac output (4).

The endurance performances of athletes are also impaired by hypohydration. Armstrong, et al., (38) had athletes (runners) perform races of 1,500, 5,000, and 10,000 meters on an outdoor track in both a euhydrated and hypohydrated state. Performances at all distances were adversely affected by hypohydration, but the longer distances (5,000 and 10,000) were affected to a greater extent. Athletes normally have a high aerobic fitness. High aerobic fitness and heat acclimation are two characteristics that offer core temperature advantages. However, studies have indicated that hypohydration negates these advantages (12,17,34). Thus, athletes and others with high aerobic fitness and who are heat acclimated are not immune to the effects of hypohydration. In fact, because heat-acclimated individuals have lower core temperatures during exercise while euhydrated, they experience a core temperature penalty during hypohydration that is greater than that seen in unacclimated persons (4).

Thermoregulatory impairments due to hypohydration may also influence physical performance. Sawka et al., (39) conducted a study to examine the effects of hypohydration on physiologic tolerance to heat strain. The researchers had subjects walk to exhaustion in a hot environment in both a euhydrated and hypohydrated state. During hypohydration, exercise time was reduced from 121 to 55 minutes and core temperature at exhaustion was also lowered. As concluded by the authors, hypohydration not only impairs exercise performance but also lowers physiologic tolerance to heat strain. A lower maximum core temperature during exercise in a hypohydrated state has been noted by others (40), and it has been suggested that the improved exercise performance and tolerance to an elevated core temperature observed in well-hydrated individuals may be related to their improved ability to store heat, not dissipate it (41).

Fuel Usage

Little research has examined the effects of hypohydration on substrate utilization. Turlejska et al. (42) demonstrated in dogs that hypohydration intensified the catecholamine response to exercise. Four dogs completed two 60-minute trials of treadmill exercise (5 km/hr, 21% elevation). One trial was performed in a hydrated state while the other was performed in a hypohydrated state (48 hour water deprivation). Resting levels of norepinephrine were similar prior to each trial, while resting epinephrine was significantly (p< 0.05) higher in hypohydrated dogs. During exercise, no significant changes in norepinephrine and epinephrine occurred in the control dogs. However, significant increases for both catecholamines were observed in the hypohydrated dogs. The release of epinephrine during exercise has been shown to be enhanced by dehydration (43,44), most likely in an attempt to maintain cardiovascular integrity (45).

An increased release of epinephrine during exercise has been associated with a greater utilization of carbohydrates (46). Additionally, it is generally believed that reduced muscle blood flow with dehydration during exercise may compromise oxygen availability to mitochondria of working skeletal muscle, causing a shift to nonoxidative sources of energy production. However, González-Alonso et al. (44) demonstrated that muscle blood flow reduction from dehydration during exercise does not impair oxygen delivery to exercising muscle.

Roy et al. (45) examined the effects of diuretic-induced hypohydration on substrate turnover and oxidation. Subjects for the study performed two 90-minute bouts of cycling at approximately 61 percent of VO_2Peak separated by at least one week. One bout was performed after four days of placebo administration while the other bout followed four days of diuretic administration (Novetramazide: 100mg triamterene and 50 mg hydrochlorohiazide), which resulted in a 14.6 percent decrease in resting plasma volume. The trials were completed in a randomized, single-blind order. Not all subjects completed the 90 minutes of exercise, thus results from only 60 minutes were reported. Hypohydration had no effects on whole body carbohydrate or fat oxidation during exercise. Additionally, no differences in calculated muscle glycogen were observed between the trials. However, compared to the placebo trial, glucose oxidation during hypohydration was significantly lower ($p<0.05$) during the first 30 minutes of exercise, but higher at 60 minutes. The glucose rate of appearance mirrored glucose oxidation results, showing significantly lower ($p<0.05$) values at rest and at 15 and 30 minutes, but a higher reading at 60 minutes of exercise for the diuretic trial compared to the placebo trial. The authors concluded that the reduction in plasma volume from diuretic administration modified glucose kinetics during moderately intense prolonged exercise with the specific effect dependent on the time of exercise.

Conclusion

Hypohydration, a state of low body fluid, adversely affects the body's responses to exercise. Hypohydration of as little as one to two percent body weight can adversely affect thermoregulation and cardiovascular function. Furthermore, impairments of thermoregulation and cardiovascular function may affect exercise performance and fuel usage.

Hypohydration hinders both dry and evaporative heat loss, which can have devastating effects on the thermoregulartory processes of the body during exercise. Studies have shown that in a hypohydrated state, whole-body sweat rates decrease due to an increased temperature threshold for sweating and a decreased sweating sensitivity. Dry heat exchange is also impaired and is most likely due to decreased cutaneous blood flow. The impaired heat loss results in an accelerated elevation of core temperature.

Hypohydration also has negative effects on cardiovascular function. Hypohydration results in a loss of plasma volume, which in turn, decreases blood volume and lowers central venous pressure. A decreased central venous pressure attenuates venous return to the heart lowering cardiac filling, end diastolic volume, and thus stroke volume.

Together, the impairments in thermoregulation and cardiovascular function due to hypohydration result in decreased maximal oxygen consumption, exercise performance, and exercise capacity. Additionally, research indicates that hypohydration during exercise may modify fuel usage, with a possible increase in carbohydrate use during prolonged exercise. This however, has not been substantiated.

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