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The effect of fluid composition on rehydration following heat and exercise-induced dehydration

Melinda Lee Ray
Iowa State University

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The effect of fluid composition on rehydration following heat and exercise-induced dehydration

by

Melinda Lee Ray

A dissertation submitted to the graduate faculty
in partial fulfillment of the requirements for the degree of
DOCTOR OF PHILOSOPHY

Co-majors: Nutrition and Physiology
Major Professors: Richard L. Engen, Douglas S. King, and Rick L. Sharp

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Graduate College
Iowa State University

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Committee Member

Signature was redacted for privacy.

Committee Member

Signature was redacted for privacy.

Co-major Professor

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Co-major Professor

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Co-major Professor

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For the Co-major Program

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For the Graduate College

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ABSTRACT

The influence of fluid composition on rehydration effectiveness was assessed following exercise and heat (65°C) exposure that produced a 2.6% body weight loss. In a randomized cross-over design, 18 subjects rehydrated for 3 h with water (H_2O), and broths containing various sodium concentrations (LO: 31.5 mmol/l; MED: 109.5 mmol/l; HI: 159.5 mmol/l). Beverages were given in equal volumes every 20 min for a total volume equal to the body weight loss during dehydration. Significant differences ($p<0.05$) among the treatments were determined using ANOVA. Body weight recovery was higher in MED compared with LO (73 ± 3% vs 61 ± 4%). Plasma volume recovery was higher in MED (105 ± 1%) and HI (104 ± 2%) compared with H_2O (97 ± 2%). Urine volume was higher in H_2O (351 ± 57 ml) and LO (379 ± 29 ml) compared with MED (229 ± 18 ml) and HI (195 ± 21 ml). Plasma osmolality was higher in HI and MED compared with H_2O, while the plasma sodium concentration was higher in LO, MED, and HI compared with H_2O. The plasma potassium concentration was higher in LO compared with all other beverages.

In the second study, 30 subjects were studied during 2 h of rehydration after a 2.5% body weight loss. In a randomized cross-over design, subjects rehydrated with water (H_2O), chicken broth (CB: Na=109.5; K=25.3 mmol/l), a carbohydrate-electrolyte drink (CE: Na=16.0; K=3.3 mmol/l), and chicken noodle soup (SOUP: Na=333.8; K=13.7 mmol/l). Subjects ingested 175 ml at the start of rehydration and 20 min later; water was given every 20 min thereafter for a total volume equal to body weight loss during dehydration. Plasma volume recovery was greater in SOUP (99 ± 1%) and CB (98 ± 1%) compared with H_2O (94

± 1%). Urine volume was greater in CE (310 ± 30 ml) compared with CB (188 ± 20 ml). Urine osmolality was higher in CB and SOUP compared with CE. Urinary sodium concentration was higher in SOUP and CB compared with CE and H_2O. These results suggest that including sodium in rehydration beverages improves whole body and plasma volume restoration.

INTRODUCTION

When individuals undergo prolonged exercise, particularly in the heat, body water losses caused by sweating can compromise the ability to perform exercise. Although body water is lost both from the intracellular and extracellular fluid compartments, a relatively greater loss of fluid occurs from the extracellular space, resulting in a drop in plasma volume (17). The reduced plasma volume decreases venous return and stroke volume, while heart rate increases to maintain cardiac output (65). This loss of body water from the intravascular space, in combination with the displacement of a portion of the blood volume toward the periphery for cooling, reduces the effectiveness of the circulatory system in delivering blood both to the skin and working muscle. A reduction in blood flow to the skin and muscle impairs thermoregulation (65) and decreases the ability to perform both aerobic and anaerobic exercise, although prolonged endurance exercise is more likely to be affected by dehydration (4). Thus recent attention has focused on the need for rapid restoration of body water as a means for maintaining exercise performance.

It has been observed that humans do not voluntarily consume enough fluid to replace body water losses occurring during heat and exercise-induced dehydration (1). This phenomenon is referred to as involuntary dehydration, and occurs both at rest in the heat and during exercise, although it occurs to a greater extent under stressful conditions such as exercise in the heat (1). The composition of the fluid ingested is a significant factor affecting the degree of involuntary dehydration observed in athletes, and thus the extent to which rehydration is attained. There are a variety of different factors that can influence an individual to consume a particular beverage, including temperature (90), palatability (6, 45), and beverage carbohydrate and electrolyte content (22, 55, 58, 86). Food consumption has also been shown to influence fluid intake (2) and subsequent rehydration (56).

The composition of a rehydration beverage influences not only the extent to which an athlete will consume a beverage, but also the extent to which body fluid balance is restored. The addition of sodium may serve to retain the osmotic and volume dependent drives for drinking, reducing involuntary dehydration (70). Absorption of water through the small intestine is facilitated by active transport of both sodium and glucose (29). Furthermore, the addition of sodium to a rehydration beverage promotes fluid retention in the extracellular space, leading to greater plasma volume recovery and lower urine volumes (55, 70).

The role that potassium may play in fluid balance restoration is not completely clear. There is evidence which suggests that ingestion of high concentrations of potassium may delay body weight and plasma volume recovery (68) due to a restoration of the intracellular fluid compartment at the expense of the extracellular fluid. However, other investigators have shown that including potassium in a rehydration beverage is as effective as sodium in promoting rehydration (58).

Adding significant quantities of sodium, potassium, and carbohydrate to a rehydration beverage increases the osmolality of the beverage. Previous investigators have shown that fluids with high osmotic concentrations impair gastric emptying (12, 23) and intestinal absorption of water (47, 48, 85, 95), effects that would be expected to impair whole body rehydration. However, other investigators have found that ingesting hypertonic carbohydrate-electrolyte solutions does not impair rehydration (22, 54). Thus, the optimal osmolality of a rehydration beverage, as well as its sodium, potassium, and carbohydrate content, remains unknown.

Many investigations have shown that consuming fluid *during exercise* is essential in offsetting fluid and electrolyte losses commonly observed during exercise in the heat (13, 73). Rehydration following exercise has not been examined in as much detail, but is equally important, particularly for athletes who train or compete soon after dehydration. Relatively low sodium concentrations are used in most studies as well as in many commercially available sports drinks in order to match sweat electrolyte concentrations and preserve palatability. It is not known whether ingesting beverages containing higher sodium concentrations than those currently used would enhance the effectiveness of post-exercise rehydration. Therefore, the first investigation examined rehydration following heat and exercise-induced dehydration with water and three different beverages containing low, medium, and high concentrations of sodium.

Previous studies show that voluntary fluid intake is stimulated when ingesting food (2, 27, 91). Thus, consuming food following exercise may have a significant impact on rehydration. However, there is very little data examining the effect of consuming a meal consisting of both fluids and solids on post-exercise rehydration (56, 88). As many athletes are often hungry following exercise, it seems reasonable that ingesting a meal along with a beverage, or ingesting a meal and beverage simultaneously in the form of a soup, would serve the dual purposes of minimizing hunger and replacing valuable fluid and electrolyte losses.

It is not often practical for athletes to frequently consume large volumes of fluid following exercise due to the inadequacy of the thirst mechanism. In addition, consuming high fluid volumes may lead to large gastric and urine volumes. It is possible that consuming a small volume of fluid at the onset of rehydration followed by water would promote effective body water restoration following exercise. Therefore, the second investigation compared the effectiveness of rehydration with small volumes of water, two beverages containing high and low electrolyte concentrations, and soup following heat and exercise-induced dehydration.

Dissertation Organization

The remainder of the dissertation includes a review of the literature pertaining to the effects of heat and exercise-induced dehydration and subsequent rehydration on body fluid balance and restoration. Following this review, two papers describing studies that have examined the effectiveness of rehydration with beverages containing different amounts of sodium, potassium, and carbohydrate, as well as different osmolalities, will be presented. The dissertation will close with a general discussion on the conclusions drawn from these studies, as well as some recommendations for future research regarding post-exercise rehydration. The references cited in the general introduction, review of literature, and general conclusions will be listed at the end of the dissertation.

REVIEW OF LITERATURE

General Physiology

Water is the most ubiquitous and essential component of the human body, representing approximately 60% of body weight (40). Approximately 60% of total body water is contained in the intracellular fluid compartment (ICF), while 30% is contained in the extracellular fluid compartment (ECF). The extracellular space can be further divided into fluid located between the tissues (interstitial fluid compartment), in which 75% of the extracellular water is contained, and the noncellular portion of the blood (plasma) containing the remainder of the extracellular water. The maintenance of fluid balance across the different compartments is profoundly influenced by the electrolyte distribution among the intracellular and extracellular spaces. As a result of transient alterations in electrolyte concentration, water is redistributed across the cell membrane until the two fluid spaces are of equal osmolality. Table 2.1 shows the electrolyte distribution in the various body fluid compartments (40). The osmolality and

Table 2.1. The electrolyte distribution in the extracellular and intracellular fluid space.

	ECF (mEq/L)	ICF (mEq/L)
Na^+	142	10
K^+	4	140
Ca^{2+}	5	< 1
Cl^-	103	4
Mg^{2+}	3	58
SO_4^{2-}	1	2
proteins	5	40

volume of the ECF is determined almost entirely by the sodium concentration simply because sodium is the most abundant ion in the ECF. Consequently, disturbances in sodium balance are closely associated with changes in the extracellular fluid volume. On the other hand, potassium and magnesium are more important in the maintenance of intracellular volume and osmolarity.

Three control mechanisms operate in close association with one another to regulate the extracellular volume and sodium concentration, and consequent osmolality, and thus have an important impact on the control of fluid intake and output from the body. These include the osmosodium receptor-arginine vasopressin system, the volume-sensing mechanism, and the thirst mechanism (40).

In the osmosodium receptor-arginine vasopressin system, sodium is the crucial factor in the control of water balance. An increase in the ECF sodium concentration, and thus osmolality, stimulates osmoreceptors located in the supraoptic nuclei of the hypothalamus. This stimulation results in the release of arginine vasopressin (AVP) from the posterior pituitary gland, increasing renal reabsorption of water, but not electrolytes. The reabsorption of water, but not solutes, dilutes the ECF sodium concentration, correcting the initial elevation in ECF osmolality. The stimulation of the osmoreceptors by increasing plasma osmolality and consequent cellular dehydration also triggers the thirst mechanism, prompting the individual to drink (38).

A change in the ECF volume is the trigger for control of body fluid balance in the volume-sensing system. A decrease in the ECF volume, which can occur as a result of dehydration, decreases central venous filling pressure, cardiac output, and blood pressure. Stretch receptors located in the right atrium sense the drop in pressure and activate the renin-angiotensin system, causing vasoconstriction, stimulation of aldosterone secretion, increased tubular reabsorption of sodium, release of AVP, decreased urinary output, and increased thirst. It is thought that this mechanism is less sensitive than the osmosodium receptor-arginine vasopressin system (38).

Although both the osmotic-arginine vasopressin and volume-sensing mechanisms appear to be involved in the maintenance of body fluid balance, the degree to which an individual relies on each mechanism for the restoration of fluid balance and their subsequent impact on thirst and drinking remains unknown. The thirst center, located adjacent to the supraoptic nuclei in the hypothalamus, can be stimulated by many factors, including intracellular dehydration, an increase in circulating angiotensin levels, and dryness of the mouth (40). Under resting conditions, the thirst mechanism is adequate in maintaining body fluid balance. However, under certain physiological conditions such as exercise in the heat, thirst is not a sufficient stimulus for maintaining body water balance, contributing to a progressive decline in body water if exercise is continued. This loss in body water has important implications for physiological processes essential to exercise performance.

Consequences of Heat and Exercise-induced Dehydration

Effects of dehydration on the cardiovascular and thermoregulatory systems

Humans have a remarkable ability to thermoregulate effectively in a variety of environmental conditions. However, the combined stresses of heat exposure and exercise can place conflicting demands on the body. Physical exercise increases the metabolic rate, requiring an increase in heat dissipation from the body to maintain heat balance. This need is magnified during exercise in the heat. The primary way heat is lost from the body during exercise is by evaporative cooling; this process is even more important during exercise in the heat as the body is gaining heat by the processes of radiation, convection, and conduction. Sweating enables evaporative cooling to take place but can lead to significant losses in body water, particularly from the intravascular space (1, 19, 41, 44, 64).

This continous loss of body water, in addition to the displacement of a portion of the blood volume toward the periphery for cooling, can lead to adverse cardiovascular and thermoregulatory consequences. A reduction in central blood volume can compromise venous return and stroke volume (63, 65). As a result, heart rate increases to maintain cardiac output (12, 30, 44), increasing with progressive levels of dehydration (63, 81). However, if exercise continues, especially at higher intensities, the elevation in heart rate is not sufficient to maintain cardiac output (65). Consequently, the effectiveness of the circulatory system in delivering blood both to the skin and working muscles is compromised. In the attempt to maintain central blood volume and blood flow to the active muscles, blood flow is redistributed away from the periphery (30, 44, 63, 65). A decrease in blood flow to the periphery of the body coupled with decreases in total body sweat rates (44, 87) with increasing levels of dehydration results in an increase in core body temperature (12, 44, 81). This increase in core body temperature is directly related to the magnitude of dehydration accrued during exercise (1). Adolph (1947) observed that subjects had an elevation in core temperature of 0.20°C for each percent decrease in body weight occuring during work in the heat.

Effects of dehydration on physical performance

Humans can commonly lose 2-8% of their body weight during exercise (78), especially during exercise in hot temperatures (1, 17). This loss of body water is associated with a marked reduction in the ability to perform both aerobic and anaerobic exercise, although prolonged aerobic exercise is more likely to be affected by dehydration. Adolph (1947) reported that soldiers walking in the desert were less likely to suffer heat exhaustion when consuming water ad libitum compared to those who consumed no water at all. Sawka et al. (1985b) observed that eight subjects could walk 140 minutes in the heat (49°C) when euhydrated or dehydrated by 3% of their body weight; however, one subject completed only 134 minutes after losing 5% of his initial body weight. When dehydrated by 7% of initial body weight, six subjects were able to walk only 64 minutes. Finally, running performance in 1,500 m, 5,000 m, and 10,000 m distances was reduced when runners had lost 2% of their body weight after diuretic administration (4). Running times were reduced to a greater extent in the longer distance races.

Decreases in anaerobic power have been observed in athletes after a 5% dehydration (15, 96), although others have reported no change in anaerobic power after dehydration (50). Torranin et al. (1989) observed decreases in both isotonic and isometric muscular endurance (29% and 31%, respectively) at 75% of maximal voluntary contraction after 4% dehydration. Maximal aerobic power does not seem to be affected in a neutral environment until a 3% body weight loss is achieved; however, 2-4% losses in the heat progressively decrease maximal aerobic power (24).

Body Fluid Shifts during Dehydration

The factors that govern body fluid shifts occurring as a result of losses in body water are complex and often difficult to discern because of the wide variety of experimental protocols used to examine these factors. Filtration and absorption of water and solute across capillary membranes can vary from one tissue to another and may change in response to such influences as body posture (37) and the type (33) and intensity of exercise (83). The hydration status of subjects (33), as well as acclimation to the heat (80) and gender are additional factors that affect the degree of fluid loss observed during heat and exercise exposure. In addition, the various measurements used to determine changes in body water, primarily plasma volume (hematocrit, hemoglobin, and plasma protein) can all give different impressions of the plasma volume response to heat and exercise.

Effect of dehydration on plasma volume and resulting hemoconcentration

As mentioned previously, thermal stress and exercise are usually accompanied by losses in body fluid volume. While water is lost from all body fluid compartments as a consequence of free fluid exchange, more water is lost from the extracellular space (1, 17, 44); as body water loss increases, a proportionately greater percentage of the fluid lost in sweat comes from the intracellular compartment (17). However, the method used to induce dehydration may affect the relative loss of fluid from the body fluid compartments. Plasma volume may be reduced to a greater extent during thermal dehydration compared to exercise-induced dehydration (53), although this is not always observed (19). Administering diuretics to induce dehydration appears to result in greater water losses from the intravascular space (4). Decreases in plasma volume observed during thermal or exercise stress range from 4-20% (10, 17, 19, 25, 30, 42, 44, 64). In general, the more severe the stress, the greater the reduction in plasma volume.

The loss of fluid from the intravascular space leads to an increase in the concentration of intravascular constituents, referred to as hemoconcentration. Sodium and chloride are the major electrolytes lost in sweat, but sweat is hypotonic relative to plasma. Therefore, plasma sodium and chloride concentrations are frequently, but not always, higher after dehydration (19, 63, 64). Changes in plasma osmolality are closely associated with changes in plasma sodium concentration, as sodium is the primary determinant of plasma tonicity. Heat (82) or exercise-induced dehydration results in an increase in plasma osmolality (10, 12, 17, 19, 30, 64) that is directly related to the degree of dehydration accrued (63, 81). Further, plasma osmolality stays elevated during (10) and after (63) exercise unless the fluid deficit is replaced (22).

Indices used to determine plasma volume changes

Contributing to the large range of values observed for plasma volume reductions resulting from heat and exercise-induced dehydration may be the variety of methods used to determine plasma volume changes. The hematocrit, hemoglobin concentration, and plasma protein concentration are the most commonly used indices to measure relative changes in plasma volume, usually expressed as a percent change from control or initial values. However, changes in each of these indices may occur independently of changes in plasma volume, leading to incorrect plasma volume determinations. For instance, some investigators have observed differences in plasma volume using the hematocrit and when determined independently of hematocrit changes (20, 94). Using the hematocrit to estimate changes in plasma volume also assumes that the ratio between venous hematocrit and whole-body hematocrit does not change with dehydration (20). Blood samples are usually taken from a peripheral vein, resulting in higher hematocrit values than those averaged over the total cell volume. For this reason, a correction factor of 0.91 is often used (14). In addition, the use of the hematocrit to determine plasma volume changes assumes that factors altering plasma volume do not alter either the total volume occupied by the circulating red blood cells, or the volume of the individual red blood cells, referred to as mean corpuscular volume (MCV). Previous research indicates that red cell volume is not affected by heat stress or exercise (20). However, research regarding the effect of heat and/or exercise on MCV is not as conclusive. Greenleaf et al. (1979) observed that heat and exercise exposure does not alter MCV, whereas dehydration and long term (> 2 hours) stress does. Similarly, Costill et al. (1974) observed that 2% and 4% body weight losses achieved by intermittent heat exposure altered MCV, and that changes in MCV were closely associated with changes in mean corpuscular hemoglobin concentration. Thus, the evidence regarding changes in MCV during heat and exercise exposure warrants the use of both the hematocrit and hemoglobin concentration to determine changes in plasma volume associated with dehydration.

Plasma protein concentration has also been used to estimate changes in plasma volume during heat and exercise exposure. However, the use of plasma proteins for this purpose assumes that they do not enter or leave the vascular system, or that the rate at which protein leaves the intravascular space and the rate at which it returns is constant. Evidence suggests that these assumptions are not valid (82, 94).

The hormonal response to dehydration

The volume and composition of vascular fluids are also controlled by neuroendocrine systems, whose essential components are the renin-angiotensin-aldosterone system and AVP. Heat exposure and exercise in the heat increases circulating levels of angiotensin II (52), plasma renin (10, 32, 51, 52, 62), plasma aldosterone (10, 32, 52, 62, 71, 78), and AVP (10, 78); these elevated levels are maintained even during recovery from exercise (78). However, changes in the circulating levels of these hormones during and following exercise are influenced by hydration (9, 10, 31, 32, 71, 86). Rehydrating with water or an isotonic solution during intermittent exercise in the heat greatly reduced plasma renin and AVP levels compared to the same exercise in which subjects received no fluid (10). Similar results are observed in studies examining post-exercise rehydration, although the extent of the reduction in these fluid-regulating hormones depends somewhat on the composition of the rehydration beverage consumed. The reduction is particularly marked when the beverage being consumed is water or a very dilute electrolyte solution. Plasma renin activity and aldosterone concentration returned to control levels in subjects who had lost 2.5% of their body weight after one hour of rehydration with a dilute electrolyte solution (14.98 mmol/l sodium, 7.95 mmol/l potassium) (62). The reduced plasma renin activity and plasma aldosterone concentration resulted in an inhibition of sodium retention by the kidneys, and an increase in urine volume leading to an incomplete recovery of plasma volume and total body water.

Factors Affecting Body Water Restoration following Dehydration

Involuntary dehydration

Individuals have been concerned with fluid balance during and after physical activity such as military training, industrial labor, and even marathon running since the turn of the century. However, earlier advice regarding fluid replacement tended toward discouraging drinking, as this was thought to improve the mental toughness of the athlete as well as test their fitness level. Since then, research examining the adverse cardiovascular and thermoregulatory effects of dehydration has documented the advantages of adequate fluid replacement. However, even when fluids are consumed a large body of evidence indicates that humans have a poor ability to fully rehydrate themselves following dehydration. This phenomenon is termed involuntary dehydration and was first defined by Edward Adolph in 1947 as a delay in the full restoration of a body water deficit by drinking (1). Although it occurs in athletes (3, 13, 70), and the elderly (61, 72), relatively little is known about the physiological mechanisms underlying this phenomenon.

In a series of classical experiments, Adolph and his associates studied their responses to rest and exercise in desert conditions (2). They observed elevations in sweat rate, evaporation and urine concentration, as well as decreases in sweat concentration and urine output in the desert. Water loss was fairly closely matched to water intake during resting conditions; however, subjects had little desire for water during exercise, and failed to adequately replace water losses during recovery. In fact, the desire for water seemed to be attenuated before much of the water that was ingested was absorbed into the bloodstream. In support of this, Takamata et al. (1994) recently observed an increase in the subjective rating of thirst in subjects after dehydration; this rating returned to control levels immediately after the onset of drinking, even though body water balance was not completely restored.

Later experiments by Adolph et al. (1947) both in the desert and a hot room again demonstrated that men working in desert conditions did not replace all the water lost by sweating even though water was readily available. Adolph et al. (1947) also observed that men drank less when exercising as opposed to resting, and that thirst was not perceived until a 2% loss in body weight was attained. A study by Pitts et al. (1944) showed that ad libitum fluid intake is better than consuming no fluid in desert conditions since heart rate and rectal temperature remain lower while marching (73). However, when soldiers were forced to drink a volume equal to the volume lost in sweat every hour they were able to march up to 16 hours with no adverse cardiovascular or thermoregulatory effects. These findings suggest that involuntary dehydration arises because the thirst sensation is temporarily relieved once drinking takes place, even before all of the ingested water has been absorbed from the gastrointestinal tract. Consequently, subsequent research has focused on factors that may influence an athlete to consume greater fluid volumes, as well as promote a greater body water restoration through improved gastric emptying and/or intestinal absorption.

Composition of a rehydration beverage

The composition of the fluid available for ingestion may affect the degree of voluntary dehydration experienced by an individual, and thus the degree of rehydration achieved. Factors such as temperature, pH, caffeine, carbonation, volume consumed, and palatability of the beverage, as well as exercise and heat stress, addition of carbohydrates and electrolytes, and concommittent food consumption all influence not only the extent to which an individual ingests fluids, but also the availability of fluids once digestion and absorption has taken place.

The rate at which a fluid enters the vascular system is a combination of how quickly that fluid is emptied from the stomach and how quickly it is absorbed by the intestine. Gastric emptying can be influenced by a number of factors, including environmental conditions, exercise intensity, and hydration status (21, 67, 77), as well as beverage temperature, volume, and concentration (21). Intestinal absorption is also affected by several factors, including carbohydrate and electrolyte concentration (29).

Temperature

Colder beverages (5°C) empty from the stomach faster than warmer ones (21), although this is not always observed (59, 89). In addition, colder rehydration beverages are ingested ad libitum to a much greater extent during rehydration compared to warmer beverages (1, 90, 91). During intermittent work in the heat, subjects ingested larger volumes of 15°C water compared with 40°C water (91), thereby increasing plasma volume and minimizing body weight loss. Boulze et al. (1983) studied water intake at a range of temperatures and found an increase in voluntary consumption of water between 0°C and 15°C; ingestion declined when water temperatures were greater than 15°C. Interestingly, when subjects were allowed to choose water temperature according to their own preference, the mean temperature was 14.9°C.

pH

Although intestinal pH may influence intestinal transport of water and electrolytes (34, 74), there are no data regarding the influence of beverage pH on rehydration following exercise or thermal dehydration, and only one investigation on fluid replacement during exercise (7). In this study, the ingestion of a carbohydrate-electrolyte solution with a neutral pH (6.1) resulted in a significantly higher plasma volume after three hours of exercise compared to water or an acid carbohydrate-electrolyte solution (pH 3.4).

Caffeine

Because of caffeine's well known effect of promoting fluid excretion by the kidneys, it is not surprising that the inclusion of caffeine in a rehydration beverage impairs restoration of fluid balance (36). In this study, inclusion of caffeine resulted in a larger urine volume and significantly lower recovery of body water (54%) compared with either water (64%) or a carbohydrate-electrolyte beverage (69%).

Carbonation

The presence of carbonation in a rehydration beverage may affect both the palatability of the beverage as well as how quickly the beverage leaves the stomach, although this is not commonly observed (43, 54). No differences were observed during exercise and recovery from dehydration between glucose beverages with or without carbonation when subjects consumed ad libitum (43) or drank a volume equal to the volume of fluid lost during dehydration (54).

Exercise and heat stress

Gastric emptying rates are reduced by 35% in hot compared to neutral temperatures, making it difficult to consume fluid at the same rate that it is lost in sweat (67). Gastric emptying rates are also reduced when subjects are hypohydrated and exercising in the heat (67). Exercise intensities up to 65-70% VO_2max have no effect on gastric emptying while intensities beyond this tend to inhibit gastric emptying (21). Gastric emptying does not appear to be affected by the duration of exercise (21) or heat acclimation (67).

Palatability

The addition of sodium to a rehydration beverage may affect the palatability of that beverage, although this is not always observed. Baker et al. (1963) observed that voluntary water intake increased with beverages containing 393 mOsm/l and 530 mOsm/l NaCl, but not when beverages contained 803 mOsm/l and 1,104 mOsm/l NaCl. However, palatability of sodium-containing solutions may change throughout the process of dehydration and subsequent rehydration (92). Prior to dehydration, subjects rated the palatability of hypotonic NaCl solutions as neutral; palatability ratings of hypertonic solutions were increasingly negative with increasing NaCl concentrations. One hour following exercise, palatability ratings increased for hypotonic solutions, and decreased one hour after the onset of rehydration. Interestingly, as rehydration progressed, palatability ratings to hypertonic NaCl solutions became less negative (especially 17 and 23 hours later).

However, the sodium concentration of a rehydration beverage does not always affect palatability and thus the degree to which athletes will consume a particular beverage. Meyer et al. (1995) showed no differences in total volume intake during 30 minutes of recovery from exercise in 9-12 year olds between water and three different carbohydrate drinks containing different sodium levels (0, 8.8, and 18.5 mmol/l). Similarly, Maughan et al. (1995) observed no differences in palatability ratings of beverages containing 2, 26, 52, and 100 mmol/l sodium. Similar results were oberved in subjects consuming beverages containing either 23 mmol/l sodium or 61 mmol/l sodium in volumes equal to 50, 100, 150, and 200% of the fluid volume lost during dehydration (86).

Flavoring the beverage can also have a significant influence on fluid intake. Hubbard et al. (1984) observed that subjects walking in simulated desert conditions consumed more of a cooled (15°C) cherry-flavored beverage at a faster rate compared to warm (40°C) unflavored water, leading to 80.5% vs 37% restoration of body weight, respectively. However, the addition of flavoring to a rehydration beverage may be more important for individuals classified as reluctant drinkers (those that do not drink enough to maintain at least a 2% body weight loss) (90). Drinkers restored their body weight by 82% when drinking cool water compared to 77% for cool flavored water, whereas reluctant drinkers had a greater rehydration level when cool water was flavored (63%) compared with non-flavored (54%) water.

Carbohydrates

There is some evidence that beverages with more than 2.5% carbohydrate inhibit gastric emptying and may therefore slow fluid delivery to the vasculature (21). On the other hand, at least two studies have shown that ingestion of 10% carbohydrate solutions are as effective in replacing water deficits as water (22, 54). However, fluid replacement depends on both gastric emptying and intestinal absorption. Absorption of water through the small intestine membrane is accelerated by the active transport of both glucose and sodium (35), apparently through a common cotransporter (29). Besides providing energy, the addition of carbohydrate to a rehydration beverage may therefore facilitate net water absorption in the small intestine. Inclusion of carbohydrate in rehydration beverages would be particularly desirable during the period immediately following exercise, since muscle glycogen resynthesis is tripled when carbohydrate is fed immediately after exercise, compared with a feeding two hours later (49).

It has been reported that gastric emptying is reduced with increases in glucose concentration (84). However, glucose solutions empty at similar rates when gastric emptying rates are expressed as the rate at which calories empty from the stomach (11). Gastric emptying may also be affected by the type of monosaccaride ingested (84). Xylose and arabanose markedly prolong gastric emptying compared to glucose, possibly due to the slow absorption of these pentoses which increases luminal osmolality. Although these authors found that sucrose, fructose and polyhexose, a synthetic polysaccaride, had similar rates of gastric emptying to glucose, others have observed that isocaloric fructose solutions empty faster than glucose solutions (26). However, since ingestion of high concentrations (10%) of fructose may result in gastrointestinal distress and diarrhoea, the addition of fructose to rehydration beverages for active individuals may not be optimal (75). Finally, a mixture of different carbohydrate types may be desirable, since activation of multiple solute transport mechanisms may promote intestinal water reabsorption (85).

Osmolality

The importance of osmolality in rehydration solutions is a complex and unsettled issue. Hypertonic drinks may slow gastric emptying (12, 23, 46) and impair rehydration (12, 57). In addition, hypertonic solutions can result in gastrointestinal discomfort (12). Therefore, isotonic fluids have been recommended to the active individual for fluid replacement. In contrast, some human studies suggest that hypertonic carbohydrate-electrolyte solutions do not impair rehydration compared with water (22, 54).

Intestinal water absorption has been shown to be negatively correlated to the osmolality of the test solution. When a hypertonic solution is infused directly into the small intestine, net water secretion occurs, resulting in a drop in plasma volume (11). Thus, moderately hypotonic solutions (180-240 mOsm/L) may promote a greater water absorption than solutions of a higher (310-333 mOsm/L) tonicity (28, 47, 48, 95). Shi et al. (1994) determined the intestinal absorption of test solutions with osmolalities of 186, 283, and 403 mOsm/L. Although each solution contained 6% carbohydrate, different combinations of glucose, sucrose, fructose, and maltodextrin were used to alter osmolality. These authors found that differences in solution osmolality were eliminated in the proximal duodenum. Net fluid absorption from both mixing and test segments was 17% higher with the hypotonic solution compared with the hypertonic solution. Surprisingly, however, the improved absorption of water did not improve plasma volume restoration.

Electrolytes

As mentioned previously, sodium and glucose significantly enhance net fluid absorption in the small intestine (29). Saunders and Sillery (1985) have determined that intestinal sodium concentrations ranging from 90-120 mmol/l result in maximum water absorption. However, most sports drinks contain much lower concentrations of sodium than is optimal for water absorption. Nonetheless, many studies show that consuming sodium in a rehydration beverage is more effective in promoting body water restoration compared with ingesting water. Nose et al. (1988a) studied subjects rehydrating ad libitum with tap water and capsules containing either placebo or 0.45g NaCl/100ml water after a 2.3% dehydration. Plasma volume returned to control levels by 20 minutes when NaCl was consumed compared to 60 minutes with the placebo. Subjects restored 68% of the water lost with the placebo and 82% when NaCl was given. This improved recovery of body fluid status was associated with a significantly reduced urine volume. These findings of a reduced urine production and improved restoration of plasma volume with the inclusion of sodium have been observed by others (55, 58, 86). Maughan et al. (1994) reported lower urine volumes and a more rapid recovery in plasma volume when subjects consumed beverages containing sodium, potassium, glucose, or a combination of all three compared to an electrolyte-free beverage. Thus, the addition of sodium to a rehydration beverage not only facilitates glucose and water absorption, but may also serve to retain both the osmotic and volume dependent drives for drinking, thus reducing voluntary dehydration. Ingesting sodium increases plasma osmolality and ECF sodium concentration, stimulating both the osmoreceptor-mediated increase in AVP secretion as well as thirst. The thirst mechanism is also stimulated by the renin-angiotensin system in response to a drop in ECF volume. Sodium ingestion prevents the rapid increase in plasma volume without simultaneous solute replacement that occurs with water ingestion. The voluntary dehydration observed when only water is given may serve as a defense mechanism against hypo-osmolality of the extracellular and intracellular compartments. Without this defense mechanism in place, plasma sodium levels may fall dangerously low in rare cases, leading to hypotonic hyponatremia, or water intoxication (69).

Interestingly, inclusion of additional sodium in the diet may facilitate the adaptations that occur in response to heat acclimation. Consumption of a high sodium diet (399 mmol/day) may accelerate the increase in plasma volume and lowering of heart rate and body temperature associated with heat acclimation compared with a low sodium (89 mmol/day) diet (5). On the other hand, others have not shown an enhanced rate of acclimation when subjects drink a commercial carbohydrate-electrolyte drink compared with water (18).

It has been hypothesized that since potassium is the major cation of the intracellular space, inclusion of potassium in a rehydration beverage may enhance the replacement of intracellular water after exercise, promoting rehydration (66). Maughan et al. (1994) have recently shown that potassium is as effective as sodium in promoting whole-body water retention, while the restoration of plasma volume is delayed compared with the ingestion of a sodium-containing beverage. In this study, there did not appear to be any additive effect of including both electrolytes. Nielsen et al. (1986) also observed a slower rate of plasma volume restoration with a potassium-sodium drink compared with a drink containing only sodium. Although it is difficult due to methodological considerations to distinquish between changes in the volume of different fluid compartments, these data suggest that sodium and potassium may preferentially promote restoration of extra-and intracellular volumes, respectively.

To date there have been no studies which have examined whether adding calcium to a rehydration beverage would enhance the effectiveness of rehydration. It has been shown, however, that calcium may reduce gastric emptying and therefore limit fluid delivery (84).

Volume

It appears that there is a relationship between the electrolyte concentration of a rehydration beverage and the volume consumed since simply adding electrolytes to a rehydration beverage is generally not adequate in restoring body fluid balance when subjects are allowed to consume ad libitum (3, 70). Wrestlers with a 4.6% body weight loss induced by fluid deprivation, semi-starvation, and moderate exercise did not fully restore body fluid losses after one hour despite consuming a 5% glucose-electrolyte solution ad libitum (3). Body weight and plasma volume were still 2.6% and 1.6% below pre-dehydration values, respectively. Similarly, subjects only replaced 35-47% of the fluid lost during exercise when consuming ad libitum an 8% carbohydrate drink for one hour after exercise (43). Body fluid deficits ranged from ~2.5-3.0% of pre-dehydration body weight after the rehydration period.

Requiring subjects to consume a volume of fluid equal to or greater than the volume of fluid lost greatly improves body water and plasma volume restoration, but 100% rehydration is not always achieved if the beverage is a dilute solution low in electrolyte concentration. Subjects rehydrating with a commercial glucose-electrolyte solution (21 mmol/l sodium, 2.5 mmol/l potassium) after 4% dehydration returned to initial body weight after 4 hours of rehydration (93). However, plasma volume was still lower than initial levels, despite the fact that athletes consumed fluid volumes that were equal to the fluid deficit attained during dehydration. In addition, fluid replacement was not effective in restoring isometric and isotonic muscular endurance to levels achieved prior to dehydration. Costill and Sparks (1973) determined that a glucose-electrolyte beverage (22 mmol/l sodium) ingested after a 4% loss in body weight achieved via heat-induced dehydration was more effective in restoring plasma volume to initial levels than either receiving no fluid or water. Plasma volume remained 11-12% below normal with no fluid, but returned toward initial levels with water and the glucose-electrolyte beverage. Interestingly, neither beverage completely restored PV by the end of the three hour rehydration period. In fact, PV remained 2.4 and 5.5% below predehydration values with ingestion of the glucose-electrolyte beverage and water, respectively, 24 hours after the rehydration period. Ingesting water caused a decline in serum osmolality, resulting in a higher urine volume which contributed toward the lack of plasma volume restoration.

On the other hand, Gonzales-Alonso et al. (1992) observed a restoration in blood volume in subjects consuming a carbohydrate-electrolyte beverage with the same sodium concentration used in the previous study (22 mmol/l sodium). Consuming water and a caffeinated diet cola did not restore blood volume after two hours of rehydration. Serum osmolality was significantly higher with ingestion of the carbohydrate-electrolyte beverage compared with water and diet cola, resulting in a lower urine volume and greater percent rehydration (69%, 64%, and 54%, respectively). One explanation for the difference noted between these two studies may be the shorter rehydration period used in the latter study, which resulted in the consumption of higher fluid volumes. Ingesting large volumes increases gastric emptying (21, 62), although volumes greater than 600 mls do not further increase gastric emptying. A greater gastric emptying rate would increase the rate of fluid entry into the vascular system, possibly accounting for the greater blood volume restoration seen in Gonzales-Alonso et al. (1992).

The observation that consuming fluid volumes equal to the volumes lost during dehydration is not always effective in restoring body weight and plasma volume to initial levels (due to ongoing urine formation) has led some investigators to suggest that consuming volumes exceeding those lost during dehydration are necessary to achieve adequate rehydration. Mitchell et al. (1994) examined subjects consuming a carbohydrate-electrolyte beverage (14.98 mmol/l sodium, 7.95 mmol/l potassium) after dehydration in volumes equal to 100% and 150% of the volume lost during exercise. A greater percent rehydration was achieved in the 150% condition (67.9%) compared with the 100% condition (48.1%); however, this was accompanied by large gastric and urine volumes. In addition, plasma volume was not completely returned to pre-dehydration levels in either condition. There were no significant differences in plasma renin or aldosterone between conditions, although these hormones were elevated following exercise and returned to pre-dehydration levels after one hour of rehydration. Again, it appears that rehydrating with large volumes of a dilute electrolyte beverage causes a drop in plasma osmolality and sodium concentrations, leading to an increase in urine output. This is further exacerbated by the reduction in the fluid regulating hormones. Nielsen et al. (1986) observed a complete plasma volume restoration 30-45 minutes after consuming three beverages containing various amounts of sodium and glucose in nine 300 ml portions every 15 minutes. After two hours of rehydration, plasma volume was significantly higher than pre-exercise levels while urine volumes were lower with the drinks containing the highest sodium concentrations. The mean weight loss during dehydration was 2,530 g (range 2,050-3,650 g) whereas the drink volume was 2,700 ml; therefore some subjects may have ingested more fluid than they lost during dehydration. The difference in these results and those obtained by Mitchell et al. (1994) are likely due to the higher sodium concentrations used in Nielsen et al. (1986).

Interaction between fluid volume consumed and sodium content

Maughan et al. (1995) examined the effect of increasing sodium concentrations (2, 26, 52, and 100 mmol/l) on rehydration when subjects consumed a fluid volume equal to 150% of that lost during dehydration. As expected, the fraction of ingested fluid retained was directly related to the sodium concentration. Urine volumes were smaller with increasing sodium concentrations, leading to a greater plasma volume recovery in subjects consuming 52 and 100 mmol/l sodium beverages. This resulted in subjects achieving net fluid balance six hours following a 30 minute rehydration period. However, simply increasing the sodium concentration of a rehydration beverage without consuming an adequate volume will not ensure hydration is achieved; likewise, increasing the volume consumed without providing enough sodium will lead to the same end. In subjects consuming a low sodium beverage (23 mmol/l), increasing the volume consumed from a volume equal to 150% to one approximating 200% of the fluid volume lost during exercise merely increases urine volume; net fluid balance was the same six hours after a 60 minute rehydration period (86). In addition, ingesting fluid volumes equal to 200% of the volume lost during exercise resulted in significantly lower plasma aldosterone and angiotensin II concentrations compared to ingesting volumes equal to 50% of the volume lost. When the same volumes of a beverage containing 61 mmol/l sodium are consumed, subjects were significantly better hydrated in the 200% condition. Thus, ingesting a rehydration beverage with an adequate sodium concentration in an appropriate volume maintains the elevation in fluid-regulating hormones, which in turn promotes sodium and water reabsorption by the kidneys.

Food consumption

It has previously been shown that food consumption has a significant impact on fluid intake (1, 90, 91) and consequently rehydration (56, 88). Adolph and Dill (1938) observed that while individuals adjusting to desert conditions did not replace their fluid losses adequately, they consumed more fluid at mealtime and after exercise than other times of day. This has since been observed in individuals both at rest and during exercise. Beverage intake during meals was significantly greater than the volume of beverage consumed between meals in resting men; 68% of the total daily fluid intake was consumed at mealtimes (27). Individuals allowed to drink ad libitum while walking six hours in simulated desert conditions increased their fluid intake by 50-100% during a 30 minute period when food was available (91).

There are relatively few studies that have examined the effect of simultaneous food and fluid intake on rehydration and subsequent exercise performance. Sproles et al. (1976) observed that athletes were able to restore 4% and 7% body weight losses after a five hour rehydration period when subjects consumed a carbohydrate-electrolyte beverage (21 mmol/l sodium, 2.5 mmol/l potassium) along with a meal. In addition, stroke volume, cardiac output, and arteriovenous oxygen differences were returned to pre-dehydration levels after rehydration. Similar results were observed by Maughan et al. (1996) in subjects consuming a meal along with water in a volume equal to 150% of the mass lost during dehydration. Subjects were in a more positive fluid balance one hour after the end of the rehydration period, and were euhydrated six hours later, whereas subjects consuming the beverage only were in net negative fluid balance throughout the six hour period. The concentration of angiotensin II was higher in the meal condition compared to the liquid only trial; this contributed toward smaller cumulative urine volumes, greater electrolyte retention, and a greater fraction of the ingested fluid retained. These data provide evidence that food ingestion following heat and exercise-induced dehydration may be significant in promoting optimal body fluid restoration. However, the effect of food ingestion and the hormonal changes caused by food intake needs further evaluation due to the limited data available.

Summary

Rehydration with water dilutes the blood, decreases plasma osmolality and plasma sodium concentrations, and alters fluid regulating hormone concentrations, and results in an increase in urine formation and delay in rehydration. It is clear that to effectively counteract the body fluid losses occurring during heat and exercise-induced dehydration, rehydration beverages containing sodium must be consumed in a volume that matches or exceeds the volume lost during dehydration. However, consuming large volumes of fluid at frequent intervals following exercise is not always practical for the athlete, and may lead to large gastric volumes. In addition, the optimal concentration of sodium required in a rehydration beverage remains unclear. The sodium concentrations of commonly used sports drinks are quite low in the attempt to match sweat electrolyte concentrations. Perhaps the ingestion of higher sodium concentrations will enhance rehydration, as well as reduce the volume of beverage an athlete is required to drink. Furthermore, ingesting fluid as well as food following dehydration, a common practice among athletes, may significantly impact body water restoration.

REHYDRATION AFTER EXERCISE AND THERMAL DEHYDRATION: EFFECT OF SODIUM CONCENTRATION

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Melinda L. Ray, Rick L. Sharp, Susan D. O'Sullivan, Kris A. Moss, Timothy M. Ruden, Douglas S. King

Abstract

To investigate the influence of sodium concentration on rehydration, 18 subjects (10 male, 8 female) were studied during a three hour rehydration period following a 2.6% loss in body weight, attained with exercise and heat (65 °C) exposure. On four different days, subjects rehydrated with water (H_2O), and broth containing various concentrations of sodium (LO: 31.5 mmol/l; MED: 109.5 mmol/l; HI 159.5 mmol/l). Broth was given in equal volumes every 20 minutes for a total volume equal to body weight loss during dehydration. After three hours of rehydration, recovery of body weight was higher ($p<0.05$) in MED vs LO (73 ± 3% vs 61 ± 4%). Percent recovery in plasma volume (PV) was higher ($p < 0.05$) in MED (105 ± 1%) and HI (104 ± 2%) compared with H_2O (97 ± 2%). Urine volume was greater ($p<0.05$) in H_2O (351 ± 57 ml) and LO (379 ± 29 ml) vs MED (229 ± 18 ml) and HI (195 ± 21 ml). Urine specific gravity and osmolality were higher ($p < 0.05$) in MED and HI vs H_2O and LO. Plasma osmolality was higher in HI and MED compared with H_2O, while plasma sodium was higher in LO, MED, and HI compared with H_2O ($p < 0.05$). Plasma potassium concentration was higher in LO compared to all other beverages, and higher in MED compared with HI ($p < 0.05$). Plasma calcium concentrations were higher ($p < 0.05$) in LO, MED, and HI compared with H_2O. There were no significant differences in blood pressure or rectal temperature dur-

ing the rehydration period among groups consuming the different beverages. These results provide evidence that the inclusion of sodium in rehydration beverages increases fluid retention and improves whole body and plasma volume restoration.

Introduction

Exercise in the heat induces substantial body water and electrolyte losses which may adversely affect both cardiovascular and thermoregulatory processes. Offsetting this loss by ingesting fluid during or following exercise is important for the athlete, particularly those facing subsequent exercise bouts. However, humans often do not voluntarily consume adequate amounts of fluid to replace body water losses (2, 4, 17), a phenomenon referred to as involuntary dehydration (1). Even when athletes consume volumes equal to or greater than 100% of the fluid volume lost during exercise, complete restoration of body weight loss may not be achieved when the rehydration beverage is water or a solution low in electrolyte concentration (16, 21, 22). These dilute electrolyte beverages may not restore body weight and plasma volume to initial levels due to the large urine volumes generated, secondary to decreases in plasma osmolality and sodium concentration (22).

Evidence from the few studies that have examined post-exercise rehydration support the addition of electrolytes to a rehydration beverage for promotion of body water restoration, although the composition of the rehydration beverage, as well as the methodology used in these studies differs widely (15, 20, 24, 26). As sodium is the major extracellular ion, it follows that including sodium in a rehydration beverage may influence the restoration of the extracellular (and consequently plasma volume) fluid space. Greater recoveries in body water restoration are observed when subjects consume beverages containing higher sodium concentrations (15, 21, 24). For example, Maughan et al. (1995) observed a positive net fluid balance (calculated from the volumes of fluid ingested, sweat loss, and urine output) when subjects consumed beverages containing 52 and 100 mmol/l sodium, while solutions containing less sodium (≤ 26 mmol/l) resulted in a negative net fluid balance 5.5 hours after a 30 minute rehydration period.

Interestingly, previous investigations suggest that drinks containing high potassium concentrations do not restore plasma volume or body weight as effectively as those containing high sodium concentrations, possibly due to a preferential restoration of the intracellular fluid space (23, 24). On the other hand, Maughan et al. (1994) found no significant differences in net fluid balance after subjects rehydrated with drinks containing sodium or potassium.

It is clear that both the sodium concentration of the rehydration beverage, as well as the volume ingested, are important in adequately restoring body water losses. Subjects ingesting beverages containing 60 mmol/l sodium in volumes equal to 150% and 200% of the fluid volume lost during dehydration were in net fluid balance in the 150% condition and hyperhydrated in the 200% condition at the end of the six hour study period (30). However, a greater fraction of the ingested fluid was retained in subjects consuming a volume equal to 100% of the volume lost during dehydration compared to those ingesting volumes equal to 50%, 150%, and 200% of the fluid volume lost, leading to smaller urine volumes. Similarly, a greater percent rehydration was seen in subjects consuming volumes equal to 150% of the fluid volume lost during dehydration compared to 100%, although this resulted in large gastric and urine volumes (22). Thus, it is unclear as to whether there is an advantage to ingesting volumes of fluid that exceed the volume lost during exercise due to the gastric fullness and large urine volumes that result, possibly delaying rehydration.

Relatively low electrolyte concentrations were used in previous studies as well as in most current sports drinks in an attempt to preserve palatability and to match sweat electrolyte concentrations. We hypothesized that an adequate level of rehydration may be achieved without ingesting extreme volumes of fluid if the sodium concentration in the rehydration beverage is increased. Therefore, the purpose of this study was to examine the effectiveness of three beverages containing low, medium, and high sodium concentrations in restoring body weight and plasma volume losses when beverage volume is matched to fluid loss.

Methods

Subjects. Eighteen subjects (10 male, 8 female) were recruited to participate as subjects in this study. These subjects were physically active college age subjects who typically exercised three to four days per week. Informed consent was obtained from the subjects in accordance with the guidelines established by the Human Subjects Review Board of Iowa State University. Laboratory measurements were made on four different days, separated by at least one week. Physical characteristics of the subjects are presented in Table 1.

Dehydration. Subjects underwent a combination of thermal and exercise-induced dehydration, followed by a three-hour rehydration period with one of four different beverages, assigned in a randomized cross-over design. Subjects reported to the laboratory at 7:00 am after an overnight fast and at least 16 hours after exercise. Subjects voided and a body weight was obtained. A resting blood sample (5 ml) was obtained by venipuncture without stasis for the determination of hemoglobin, hematocrit, osmolality, and plasma sodium, potassium, and calcium concentrations. A probe was inserted to a depth of 8 cm beyond the anal sphincter for the measurement of rectal temperature. Subjects then underwent 20 minutes of light exercise on a cycle ergometer (50-100 watts) at 20°C, followed by 10 minutes of sauna exposure at 65 °C. Subjects repeated the alternating periods of exercise and sauna exposure until between 2-3% of the initial body weight was lost. During the dehydration period, which took 90-120 minutes, rectal temperature and heart rate were monitored every 30 minutes. All urine was collected and pooled for the determination of total urine volume, specific gravity, osmolality, and sodium and potassium concentrations.

Rehydration. After the dehydration period subjects underwent a 30 minute transition period to allow the body fluid compartments to stabilize (25). During this time, subjects changed into dry clothes and a teflon catheter was inserted into a forearm vein. The catheter was kept patent with infusion of 1-3 ml of 0.9% sodium chloride every 20 minutes during the rehydration period. Following the 30 minute transition period, subjects began a three-hour rehydration period in a thermoneutral environment (20°C). Subjects were in a seated position throughout the rehydration period. Subjects rehydrated with an equal volume of one of four different beverages including water (H_2O) and three chicken-based broths of low (LO), medium (MED), and high (HI) sodium concentration (Table 2). Although all beverages were essentially isotonic, osmolality increased with increasing sodium concentration. The potassium concentration was markedly higher in the LO compared with the MED and HI beverages. The beverages were kept at a temperature of 30°C. Subjects ingested equal volumes of the beverage every 20 minutes during the rehydration period. The total volume ingested by each subject throughout the three-hour rehydration period was equal to the volume of water lost during dehydration. The total sodium intake averaged 64.0 ± 4.8 mmol, 220.8 ± 15.0 mmol, and 320.4 ± 22.1 mmol for LO, MED, and HI, respectively. Blood samples, blood pressure, rectal temperature, and body weight were obtained at the beginning of the rehydration period and every 20 minutes thereafter. Blood samples were taken after the fluid in the dead space of the catheter was discarded, and were immediately transferred into tubes containing lithium heparin for later analysis. Upon completion of the rehydration period, subjects voided and a final body weight was obtained. Urine was collected and measured for total volume, specific gravity, osmolality, and sodium and potassium concentrations.

Percent rehydration. The percent of body weight lost during dehydration that was regained during rehydration was used as an index of whole body rehydration (15). The percent rehydration represented the amount of ingested fluid that was retained after the rehydration period. Percent rehydration was determined using body weight and was calculated as:

$$\text{Percent rehydration} = \frac{[BW_{DH} - (BW_{PRE} - BW_{RH})(\text{kg})]}{\text{Fluid intake (kg)}} \times 100$$

where: BW_{PRE} = initial body weight
BW_{DH} = body weight lost during exercise
BW_{RH} = body weight after rehydration

Biochemical analysis. Hemoglobin concentration was determined in triplicate using the cyanmethemoglobin technique and hematocrit was determined in triplicate after microcentrifugation. Hematocrit measurements were corrected for plasma trapped within the packed red cells (0.96) and also for venous to total body hematocrit ratio (0.91) (5). Percent changes in plasma volume from pre-exercise values were calculated using hematocrit and hemoglobin concentrations according to Dill and Costill (1974):

$BV_A = BV_B(Hb_B/Hb_A)$ $\Delta BV, \% = 100(BV_A - BV_B)/BV_B$
$CV_A = BV_A(Hct_A)$ $\Delta CV, \% = 100(CV_A - CV_B)CV_B$
$PV_A = Bv_A - CV_A$ $\Delta PV, \% = 100(PV_A - PV_B)/PV_B$

where:
BV = blood volume
CV = red cell volume
PV = plasma volume
$BV_B = 100$
Hb = hemoglobin concentration
Hct = hematocrit
$_{B, A}$ = before and after dehydration

All plasma volume changes were calculated with reference to the pre-dehydration values obtained for the water trial. Blood samples were then centrifuged, and the plasma separated and stored at -20°C for later analysis of plasma electrolytes and osmolality. Plasma and urine osmolality were determined in duplicate using a Vapor Pressure Osmometer (model 5520, Wescor Inc., Logan, Utah). Plasma and urine electrolytes were measured in duplicate using a digital flame analyzer (model 2655-00, Cole-Parmer, Chicago, Illinois).

Dietary and exercise control. Subjects maintained a dietary record for three days prior to the initial trial. Subjects were required to duplicate this diet for three days prior to each of the last three trials. In addition, subjects were instructed to drink one extra liter of water the day before all four trials to ensure euhydration. Diet composition for the day prior to each trial was analyzed using a computer program (FoodComp, ISU). There were no significant differences in diet composition due to trial (Table 3). Subjects also recorded all physical activity performed for three days prior to the initial trial, and reproduced this activity pattern for the three days prior to the following trials.

Statistics. Results in the text, tables, and figures are expressed as means ± SE. The blood measurements, blood pressure, and rectal temperature during rehydration were subjected to an initial two-way repeated measures analyses of variance; this was followed by Newman-Keuls post hoc tests where appropriate. All other data were analyzed using one-way analyses of variance. Differences among treatments were accepted as being significant when a p value of less than 0.05 was obtained.

Results

The mean weight loss due to combined exercise and temperature exposure was 1.86 ± 0.09 kg, a percent body weight loss of 2.6 ± 0.1%. There were no significant differences in body weight or percent change in body weight before and after dehydration and after rehydration with respect to trial. During the rehydration period, subjects drank 207 ± 8 ml every 20 minutes. Body weight was significantly greater in the males, leading to a greater ($p < 0.05$) percent weight loss (2.8 ± 0.1% vs 2.4 ± 1.0%) and total volume of fluid consumed (2,426 ± 97 ml vs 1,624 ± 64 ml) in the males compared with the females. There were no significant differences between males and females in percent recovery of body weight and plasma volume, or in any of the urinary measurements. Therefore, the data for both the males and females were combined.

Percent rehydration. At the end of the three hour rehydration period, subjects remained somewhat hypohydrated under all conditions studied (Table 4). Fluid lost during the rehydration period in urine, sweat, and respiration, as well as the body weight lost due to metabolism, contributed to the incomplete rehydration. The percent of body weight loss that was regained at the end of the three-hour period during MED was significantly greater than LO (72.8 ± 2.6% vs 60.9 ± 4.2%, respectively; $p<0.05$). There were no significant differences in percent rehydration after ingesting the other beverages.

There were no significant differences in rectal temperature due to trial during the rehydration period. In addition, there were no significant differences in systolic or diastolic blood pressure during the rehydration period between trials (Table 5).

Plasma volume. Following combined intermittent exercise and sauna exposure, plasma volume decreased by 7.8% for all trials combined. The percent recovery in plasma volume was significantly ($p<0.05$) higher in MED (104.6 ± 1.2%) and HI (103.6 ± 2.0%) compared with H_2O (96.6 ± 1.6%), and was not different in LO (99.6 ± 2.3%) compared with the other trials (Figure 1).

Urine volume, specific gravity, osmolality and electrolytes. Urine volumes measured during and at the end of the rehydration period were significantly lower in MED and HI compared with LO and H_2O ($p<0.05$; Table 6). Urine specific gravity and osmolality were significantly higher in MED and HI compared with H_2O and LO ($p<0.05$). In addition, urine osmolality was significantly higher in LO than H_2O ($p<0.05$). Urinary sodium concentration was significantly higher in LO, MED, and HI compared with H_2O; there were no other significant differences in urinary sodium concentration with respect to trial ($p<0.05$). Despite the greater urinary sodium concentrations observed after ingesting LO, MED, and HI, subjects retained more sodium and were in a greater sodium balance ($p<0.05$) after ingestion of these beverages compared with water, and ingestion of MED and HI compared with H_2O and LO (Table 7). Similarly, subjects retained more potassium ($p<0.05$) with ingestion of LO and MED compared with H_2O and HI despite the significantly higher urinary potassium concentrations in LO and MED compared with H_2O and HI. Urinary potassium concentration was also significantly higher after ingesting HI compared to H_2O ($p<0.05$).

Plasma osmolality. At baseline, plasma osmolality averaged 277.7 ± 0.8 mmol/l (Figure 2). Exposure to heat and prolonged exercise resulted in a mean increase in plasma osmolality to 282.0 ± 0.8 mmol/l. After ingesting HI, plasma osmolality was significantly higher than H_2O at 160 minutes of rehydration. Plasma osmolality in MED was significantly higher than H_2O at 160 and 180 minutes of rehydration ($p<0.05$).

Plasma electrolytes. The mean plasma sodium concentration (Figure 3) increased from 137. 5 ± 0.3 mmol/l to 140.2 ± 0.3 mmol/l after dehydration. Plasma sodium concentration was significantly higher in LO, MED, and HI compared with H_2O for the last hour of the rehydration period, and higher in MED compared to H_2O at minutes 80 and 100 of the rehydration period ($p<0.05$). In addition, the plasma sodium concentration in LO was significantly lower than HI at minutes 100, 160, and 180 of the rehydration period ($p<0.05$). The baseline plasma potassium concentration of 3.81 ± 0.03 mmol/l increased to 3.96 ± 0.03 mmol/l after dehydration. The plasma potassium concentration was significantly higher after ingesting LO compared to all other beverages from 60 to 180 minutes of the rehydration period (Figure 4; $p < 0.05$). In addition, MED was significantly higher than HI at minutes 100-140 of the rehydration period. The plasma calcium concentration increased from 2.34 ± 0.01 mmol/l to 2.38 ± 0.01 mmol/l with dehydration. Plasma calcium concentrations were significantly higher after ingesting LO, MED, and HI compared with H_2O (main effect; $p<0.007$).

Discussion

The results of this study demonstrate that rehydration after heat and exercise-induced dehydration is more effective when ingesting rehydration beverages containing sodium concentrations of 109.5 mmol/l and 154.5 mmol/l. To date, these are the highest sodium concentrations used in a rehydration beverage and are higher than the upper range for sweat electrolyte concentrations (3). Most sports drinks commonly contain 10-25 mmol/l sodium; oral rehydration solutions used for the treatment of diarrhea-induced dehydration have sodium concentrations of approximately 90 mmol/l (19).

It has previously been suggested that beverages containing sodium concentrations higher than 40-60 mmol/l would not be palatable (23). However, Maughan et al. (1995) observed no differences in drink acceptance and palatability between four drinks containing 2, 26, 52, and 100 mmol/l sodium. Similarly, no differences in palatability were seen when subjects consumed various volumes of a drink containing 60 mmol/l sodium (30). In the present study, beverage palatability was not assessed, although the LO drink appeared to be the least appealing to the subjects. However, the seemingly low appeal of LO had no impact on rehydration as subjects were required to consume a specific volume of fluid during the rehydration period.

After drinking a volume equal to the fluid volume lost during dehydration, percent recovery of body weight tended to be higher with MED and HI compared with LO and H_2O, although the only statistically significant difference was between MED and LO. All beverages failed to restore body weight to pre-dehydration levels due to ongoing urine formation and weight loss due to respiration, metabolism, and insensible water loss. Similar values for percent rehydration have been observed by others. For example, Gonzalez-Alonso et al. (1992) reported a 69% rehydration with a drink containing 20 mmol/l sodium compared with 64% with ingestion of water alone. Costill and Sparks (1973) showed greater rehydration with a drink containing 20 mmol/l sodium compared to water, although plasma volume recovery was still incomplete after four hours of rehydration. In the present study, a significantly higher percent recovery in plasma volume was observed in MED and HI (104.6% and 103.6%, respectively) compared to H_2O (96.6%). As there were no significant differences in body weight before exercise, and after dehydration and rehydration between trials, the higher plasma volume recovery implies that a large portion of the ingested fluid in MED and HI moved to the extracellular space during rehydration (26).

Interestingly, plasma volume tended to be lower in LO compared to the other three beverages throughout the entire rehydration period. However, the percent recovery in plasma volume was higher in LO compared with H_2O, and not significantly different from MED and HI. Previous investigators have suggested that ingestion of beverages high in potassium concentration may delay rates of plasma volume recovery due to restoration of the intracellular fluid compartment at the expense of extracellular fluid (20, 24). Maughan et al. (1994) reported a slower rate of plasma volume recovery in subjects consuming a beverage containing 25 mmol/l KCl compared to beverages containing glucose and sodium. However, no significant differences in plasma volume due to beverage were observed by the end of the 6 hour study period, leading the authors to suggest that potassium may be just as effective as sodium in restoring plasma volume. In the present study, it appears that ingesting LO is more effective than H_2O in restoring plasma volume, although not as effective as ingesting beverages containing higher sodium concentrations.

Contributing to the lower overall percent rehydration and plasma volume recovery in H_2O and LO were the large urine volumes generated due to the low plasma osmolality and sodium concentrations observed throughout the 3 hour rehydration period. The osmolality of the extracellular fluid is determined primarily by the extracellular sodium concentration as sodium is the predominant ion. Since sweat is hypotonic compared to body fluids, an increase in osmolality and electrolyte concentration is typically seen after exercise and heat-induced dehydration. Fluid-regulating hormones, including renin, angiotensin II, aldosterone, and anti-diuretic hormone are released in response to heat exposure (18), exercise (8, 29), and increases in osmolality (32), promoting the reabsorption of water and active uptake of solutes in the kidney. Previous studies have shown that consuming water or dilute electrolyte solutions after dehydration results in a drop in plasma osmolality and sodium concentrations, as well as renin, angiotensin II, and aldosterone concentrations (7, 15, 27, 30, 32). Further drops in plasma osmolality, sodium, and hormone concentrations are seen when subjects ingest very large volumes, i.e. 1.5 and 2 times the fluid volume lost during exercise (30). In the present study, rehydrating with H_2O and LO appeared to dilute the extracellular fluid and may have prevented the maintenance of the dehydration-induced increase in fluid retention hormones. Consequently, excess fluid was filtered by the kidneys while solutes were reabsorbed, leading to the production of large urine volumes. The excess filtration of fluid and greater solute reabsorption by the kidney after ingestion of H_2O and LO explain the significantly lower urinary electrolyte concentrations in H_2O vs the other beverages, as well as the lower specific gravity and urine osmolality in H_2O and LO vs MED and HI. These findings suggest that beverages with a high cation content maintain plasma osmolality and sodium concentration, and promote conservation of water, but not solutes, by the kidneys.

The higher urinary potassium concentration observed in LO compared to the other three beverages is most likely due to the increase in extracellular potassium concentration brought about by dehydration and then maintained by ingesting LO. The higher plasma potassium concentration observed in LO throughout the rehydration period may have promoted potassium excretion by the kidneys in an attempt to restore extracellular potassium concentrations. It has previously been shown that an increase in plasma potassium concentration causes a reduction in the tubular reabsorption of sodium, due to an inhibition of renin (33) and aldosterone release (13). This may help explain the significantly higher sodium excretion as well as the drop in plasma sodium levels throughout the three hour rehydration period when ingesting LO.

One reason for the lower body weight restoration and plasma volume recovery observed in H_2O and LO may be that a large portion of the ingested fluid remained in the gastrointestinal tract. The availability of ingested fluid depends on the gastric emptying rate, primarily determined by fluid volume and composition (6). In the present study volume, osmolality, and temperature were similar for all beverages. Furthermore, it has been shown that the addition of electrolytes to rehydration beverages does not alter the rate of gastric emptying (28). Therefore, it is unlikely that gastric emptying was a significant factor in this investigation. The second barrier to the availability of ingested fluids is their rate of intestinal absorption. Water absorption through the small intestine is significantly enhanced by the active transport of glucose and sodium, which occurs through a common protein carrier (11). Gisolfi et al. (1990) observed greater glucose, sodium, and potassium absorption from a carbohydrate electrolyte solution compared to distilled water, resulting in greater fluid absorption. Previous research performed on animals suggests that optimum water absorption occurs when intestinal sodium concentration is in the range of 90-120 mmol/l (31), which is similar to the sodium concentrations of the MED and HI beverages used in the present study. Thus, unless the sodium concentration of the beverage is markedly altered between ingestion and arrival at the intestine, the MED and HI beverages contained a sodium concentration consistent with optimum water absorption (30). It is, therefore, possible that the higher sodium concentrations in MED and HI promoted greater fluid absorption in the small intestine than H_2O or LO, leading to improved overall rehydration.

Previous studies have shown that fluid replacement beverages containing high electrolyte concentrations may cause an increase in plasma osmolality, resulting in a reduction in skin blood flow and sweating, thus impairing thermoregulation (12). However, the high electrolyte concentrations used in the present study did not appear to affect the subjects' ability to thermoregulate effectively as there were no significant increases or differences in rectal temperature throughout the rehydration period. However, further studies should examine the question of whether thermoregulation during a subsequent exercise/heat challenge is affected by the prior rehydration protocol. Most recently, greater attention has been paid to sodium as it relates to blood pressure; excessive sodium intake has been shown to be a risk factor for hypertension (9). The higher sodium concentrations in MED and HI did not appear to affect blood pressure as there were no significant differences in systolic or diastolic blood pressure throughout the rehydration period. It should be noted, however, that the subjects used in this study were young with no apparent compromised blood pressure regulation.

There were no significant differences observed in percent rehydration or plasma volume recovery after ingesting MED and HI, suggesting that adding sodium to a rehydration beverage in concentrations greater than 109.5 mmol/l may provide no additional benefit in terms of body fluid restoration. In addition, it has previously been shown that a high sodium intake may result in an increased calcium excretion (34), a finding which may be particularly significant for older populations. Thus it appears that the addition of sodium in moderate concentrations is adequate and prudent for restoring body weight and plasma volume losses following dehydration.

In conclusion, greater fluid retention, resulting in greater body weight restoration and plasma volume recovery, was observed when subjects ingested beverages containing higher concentrations of sodium. The ingestion of a beverage high in potassium concentration was more effective than water in restoring plasma volume, although not as effective as beverages containing higher sodium concentrations. The sodium concentration of the beverages used in this study are higher than those used in previous investigations. These high sodium concentrations maintained plasma osmolality and sodium concentrations which reduced urine output, while having no deleterious effects on blood pressure and thermoregulation. Thus it appears that increasing the sodium concentration of rehydration beverages commonly used by athletes may be warranted.

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References

1. Adolph, E.F. Physiology of man in the desert. New York: *Interscience*, 1947.

2. Allen, T.E., D.P. Smith, and D.K. Miller. Hemodynamic response to submaximal exercise after dehydration and rehydration in high school wrestlers. *Med. Sci. Sport Exerc.* 9(3): 159-163, 1977.

3. Brouns, F., W. Saris, and H. Schneider. Rationale for upper limits of electrolyte replacement during exercise. *Int. J. Sport Nutr.* 2: 229-238, 1992.

4. Carter, J.E. and C.V. Gisolfi. Fluid replacement during and after exercise in the heat. *Med. Sci. Sports Exerc.* 21(5): 532-539, 1989.

5. Chaplin, H., P.L. Mollison, and H. Vetter. The body/venous hematocrit ratio: its constancy over a wide hematocrit range. *J. Clin. Invest.* 32:1309-1316, 1953.

6. Costill, D.L. and B. Saltin. Factors limiting gastric emptying during rest and exercise. *J. Appl. Physiol.* 37(5): 679-683, 1974.

7. Costill, D.L. and K.E. Sparks. Rapid fluid replacement following thermal dehydration. *J. Appl. Physiol.* 34(3): 299-303, 1973.

8. Costill, D.L., G. Branam, W. Fink, and R. Nelson. Exercise induced sodium conservation: changes in plasma renin and aldosterone. *Med. Sci. Sports Exerc.* 8(4): 209-213, 1976.

9. Dahl, L.K. Salt and Hypertension. *Am. J. Clin. Nutr.* 25: 231-244, 1972.

10. Dill, D.B. and D.L. Costill. Calculation of percentage changes in volumes of blood, plasma, and red cells in dehydration. *J. Appl. Physiol.* 37(2): 247-248, 1974.

11. Fordtran, J.S. Stimulation of active and passive sodium absorption of sugars in the human jejunum. *J. Clin. Invest.* 55: 728-737, 1975.

12. Fortney, S.M., C.B. Wenger, J.R. Bove, and E.R. Nadel. Effect of hyperosmolality on control of blood flow and sweating. *J. Appl. Physiol.: Respirat. Environ. Exercise Physiol.* 57(6): 1688-1695, 1984.

13. Francis, K.T. and R. MacGregor. Effect of exercise in the heat on plasma renin and aldosterone with either water or a potassium-rich electrolyte solution. *Aviat. Space Environ. Med.* 49: 461-465, 1978.

14. Gisolfi, C.V., R.W. Summers, H.P. Schedl, T.L. Bleiler, and R.A. Oppliger. Human intestinal water absorption: direct vs. indirect measurements. *Am. J. Physiol. 258 (Gastrointest. Liver Physiol.)* 21: G216-G222, 1990.

15. Gonzalez-Alonso, J., C.L. Heaps, and E.F. Coyle. Rehydration after exercise with common beverages and water. *Int. J. Sports Med.* 13(5): 399-406, 1992.

16. Grandjean, P.W., A.P. Cassidy, K.J. Cole, and J.B. Mitchell. Fluid volume effects on rehydration and body fluid balance following exercise induced dehydration. *Med. Sci. Sports Exerc.* Abstract. 24(5): S155, 1992.

17. Greenleaf, J.E. and F. Sargent. Voluntary dehydration in man. *J. Appl. Physiol.* 20(4): 719-724, 1965.

18. Kosunen, K.J., A.J. Pakarinen, K. Kuoppasalmi, and H. Adlercreutz. Plasma renin activity, angiotensin II, and aldosterone during intense heat stress. *J. Appl. Physiol.* 41(3): 323-327, 1976.

19. Maughan, R.J. Fluid and electrolyte loss and replacement in exercise. *J. Sports Sci.* 9: 117-142, 1991.

20. Maughan, R.J., J.H. Owen, S.M. Shirreffs, and J.B. Leiper. Post-exercise rehydration in man: effects of electrolyte addition to ingested fluids. *Eur. J. Appl. Physiol.* 69: 209-215, 1994.

21. Maughan, R.J. and J.B. Leiper. Sodium intake and post-exercise rehydration in man. *Eur. J. Appl. Physiol.* 71: 311-319, 1995.

22. Mitchell, J.B., P.W. Grandjean, F.X. Pizza, R.D. Starling, and R.W. Holtz. The effect of volume ingested on rehydration and gastric emptying following exercise-induced dehydration. *Med. Sci. Sports Exerc.* 26(9): 1135-1143, 1994.

23. Nadel, E.R., G.W. Mack, and H. Nose. Influence of fluid replacement beverages on body fluid homeostasis during exercise and recovery. In: *Perspectives in Exercise Science and Sports Medicine, Vol. 3, Fluid Homeostasis during exercise,* C.V. Gisolfi and D.R. Lamb (Eds.). Carmel, IN: Benchmark Press, 1990, pp. 181-205.

24. Nielsen, B., G. Sjogaard, J. Ugelvig, B. Knudsen, and B. Dohlmann. Fluid balance in exercise dehydration and rehydration with different glucose-electrolyte drinks. *Eur. J. Appl. Physiol.* 55: 318-323, 1986.

25. Nose, H., G.W. Mack, X. Shi, and E.R. Nadel. Shift in body fluid compartments after dehydration in humans. *J. Appl. Physiol.* 65(1): 318-324, 1988.

26. Nose, H., G.W. Mack, X. Shi, and E.R. Nadel. Role of osmolality and plasma volume during rehydration in humans. *J. Appl. Physiol.* 65(1): 325-331, 1988.

27. Nose, H., G.W. Mack, X. Shi, and E.R. Nadel. Involvement of sodium retention hormones during rehydration in humans. *J. Appl. Physiol.* 65(1): 332-336, 1988.

28. Rehrer, N.J. Limits to fluid availability during exercise. De Vrieseborsch, Haarlem. 1990.

29. Rocker, L., K.A. Kirsch, B. Heyduck, and H.U. Altenkirch. Influence of prolonged physical exercise on plasma volume, plasma proteins, electrolytes, and fluid-regulating hormones. *Int. J. Sports Med.*, 10(4); 270-274, 1989.

30. Shirreffs, S.M., A.J. Taylor, J.B. Leiper, and R.J. Maughan. Post-exercise rehydration in man: effects of volume consumed and drink sodium content. *Med. Sci. Sports Exerc.* 28(10): 1260-1271, 1996.

31. Saunders, D.R., and J.K. Sillery. Absorption of carbohydrate-electrolyte solutions in rat duodenojejunum. Implications for the composition of oral electrolyte solutions in man. *Dig. Dis. Sci.* 30(2): 154-160, 1985.

32. Takamata, A., G.W. Mack, C.M. Gillen, and E.R. Nadel. Sodium appetite, thirst, and body fluid regulation in humans during rehydration without sodium replacement. *Am. J. Physiol.* 266: R1493-R1502, 1994.

33. Vander, A.J. Direct effects of potassium on renin secretion and renal function. *Am. J. Physiol.* 219(2): 455-459, 1970.

34. Zarkadas, M., R. Gougeon-Reyburn, E.B. Marliss, E. Block, M. Alton-Mackey. Sodium chloride supplementation and urinary calcium excretion in postmenopausal women. *Am. J. Clin. Nutr.* 50: 1088-1094, 1989.

Table 1. Subject characteristics

	Age (yr)	Height (cm)	Weight (kg)	BMI (kg/m^2)
Males	26 ± 1	176.0 ± 3.1*	78.0 ± 4.1*	25.1 ± 0.7
Females	26 ± 1	166.5 ± 1.7	61.9 ± 2.6	22.3 ± 0.9
All	26 ± 1	171.8 ± 2.2	70.8 ± 3.2	23.8 ± 0.7

Data are means ± SE for 10 male and 8 female subjects.
* males significantly greater than females; $p<0.05$.

Table 2. Beverage characteristics

	H_2O	LO	MED	HI
Osmolality (mmol/l)	24.5	267.5	306.5	345.5
$[Na^+]$ (mmol/l)	0.0	31.5	109.5	159.5
$[K^+]$ (mmol/l)	0.0	75.8	25.3	7.5
$[Ca^{2+}]$ (mmol/l)	0.0	0.9	2.0	2.5

Table 3. Diet composition the day prior to each trial

Nutrient	H_2O	LO	MED	HI
Energy intake (kJ/d)±	1,1369 ± 1,406	1,1454 ± 2,013	1,1251 ± 2,100	1,0762 ± 2,029
Sodium (mg/d)	4,315 ± 828	4,132 ± 627	3,633 ± 881	3,932 ± 833
Potassium (mg/d)	3,544 ± 647	3,609 ± 803	3,550 ± 739	3,262 ± 712
Calcium (mg/d)	956 ± 130	1,140 ± 136	1,027 ± 189	1,008 ± 135
% energy as protein	17 ± 3	16 ± 1	17 ± 2	17 ± 2
% energy as fat	22 ± 4	22 ± 3	23 ± 4	22 ± 4
% energy as carbohydrate	60 ± 6	62 ± 4	58 ± 5	59 ± 5

Data are means ± SE for 10 male and 8 female subjects. There were no significant differences in diet composition due to trial ($p>0.05$).

Table 4. Mean body weight before and after dehydration, and after the rehydration period

Body weight (kg)	H_2O	LO	MED	HI
Baseline	71.0 ± 3.21	70.9 ± 3.17	70.6 ± 3.24	70.6 ± 3.15
Dehydrated	69.0 ± 3.07	69.0 ± 3.08	68.8 ± 3.17	68.7 ± 3.06
Rehydrated	70.4 ± 3.17	70.2 ± 3.16	70.1 ± 3.24	70.1 ± 3.16

Data are means ± SE for 10 male and 8 female subjects. There were no significant differences in body weight due to trial ($p>0.05$).

Table 5. Mean systolic and diastolic blood pressure during rehydration

	Systolic blood pressure				Diastolic blood pressure			
Time (min)	H_2O	LO	MED	HI	H_2O	LO	MED	HI
0	112 ± 3	110 ± 2	108 ± 2	112 ± 2	76 ± 3	76 ± 2	72 ± 2	74 ± 2
60	110 ± 2	110 ± 2	108 ± 2	110 ± 2	74 ± 2	74 ± 2	76 ± 2	74 ± 2
120	108 ± 2	110 ± 2	110 ± 3	114 ± 2	74 ±2	74 ± 2	74 ± 2	74 ± 2
180	114 ± 3	110 ± 2	114 ± 3	114 ± 2	75 ± 3	72 ± 2	70 ± 2	72 ± 2

Data are means ± SE for 10 male and 8 female subjects. There were no significant differences in systolic or diastolic blood pressure due to trial ($p>0.05$).

Table 6. Urinary measurements taken during rehydration

	H_2O	LO	MED	HI
Volume (ml)	351 ± 57^{cd}	379 ± 29^{cd}	229 ± 18	195 ± 21
Specific gravity	1.018 ± 0.002	1.021 ± 0.001	1.025 ± 0.001^{ab}	1.025 ± $.001^{ab}$
Osmolality (mmol/l)	486.8 ± 61.7	639.7 ± 27.6^{a}	794.7 ± 33.5^{ab}	807.3 ± 25.6^{ab}
$[Na^+]$ (mmol/l)	53.7 ± 9.5^{bcd}	121.8 ± 6.9	122.3 ± 7.5	132.2 ± 7.6
$[K^+]$ (mmol/l)	64.0 ± 8.6	128.2 ± 5.4^{ad}	127.6 ± 6.5^{ad}	103.9 ± 5.6^{a}

Values are means ± SE, N = 18; [a] significantly different than H_2O; [b] significantly different than LO; [c] significantly different than MED; [d] significantly different than HI ($p<0.05$).

Table 7. Intake and total urinary output of sodium and potassium

	H_2O	LO	MED	HI
Sodium intake (mmol)	0.0*	64.0 ± 4.8*	220.8 ± 15.0*	320.4 ± 22.1*
Potassium intake (mmol)	0.0	154.1 ± 11.6^a	51.0 ± 3.5^c	15.1 ± 1.0
Sodium output (mmol)	13.1 ± 2.3^b	42.9 ± 4.4^a	29.1 ± 3.2	25.1 ± 3.2
Potassium output (mmol)	17.2 ± 2.4	45.4 ± 4.5^a	29.0 ± 2.5^c	18.3 ± 1.7

Values are means ± SE for 18 subjects. * significantly different from each other; [a] significantly higher in LO compared with H_2O, MED, and HI; [b] significantly lower in H_2O compared with MED, HI; [c] significantly higher in MED compared with H_2O and HI ($p<0.05$).

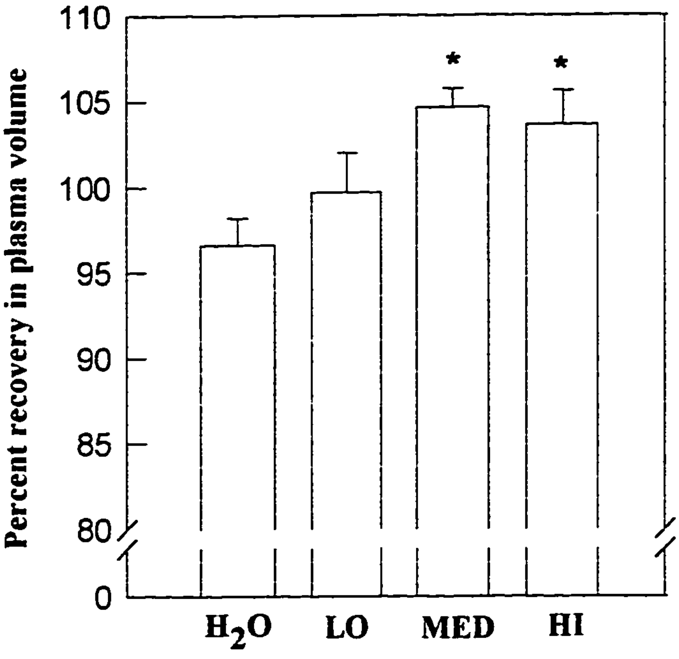

Figure 1. Percent recovery in plasma volume during three hours of rehydration. Data are means ± SE; * MED, HI significantly higher than H_2O (N=18).

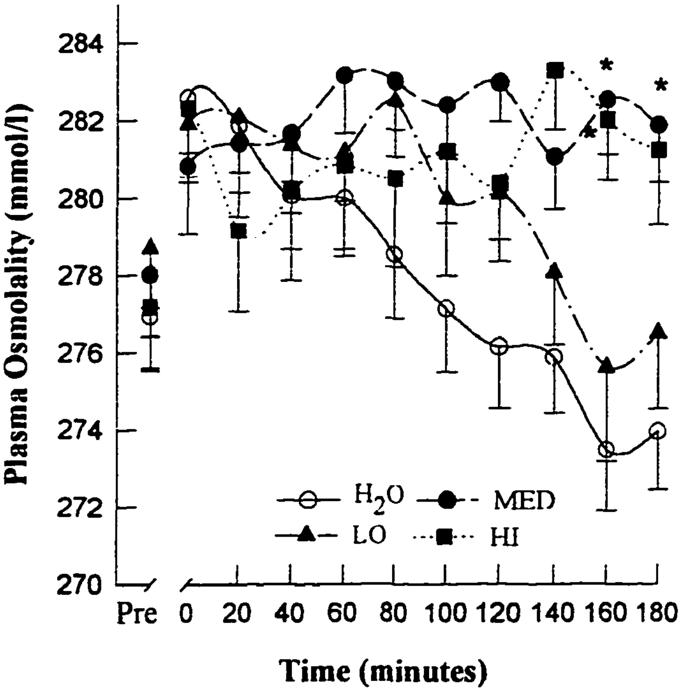

Figure 2. Plasma osmolality during three hours of rehydration. Data are means ± SE for N=18. Plasma osmolality is significantly higher in MED at 160 and 180 minutes and HI at 160 minutes compared with H_2O ($p < 0.05$).

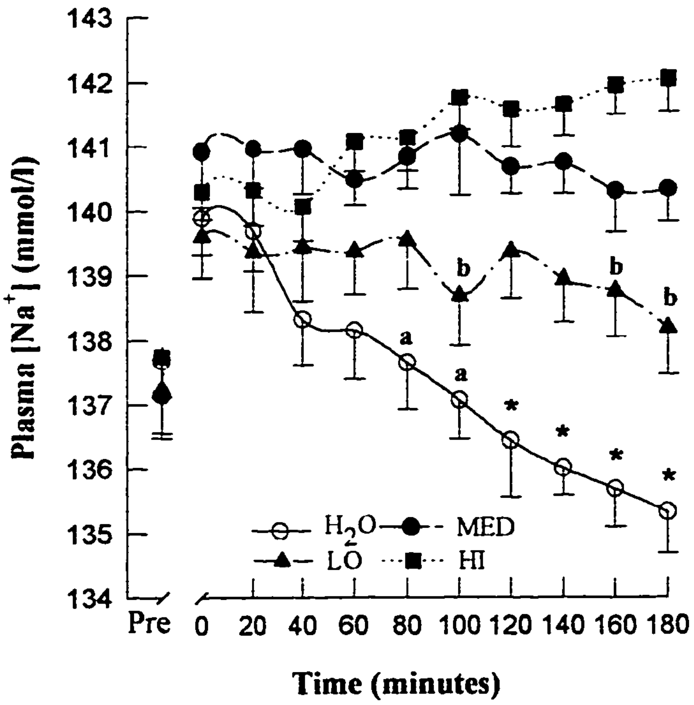

Figure 3. Plasma [Na$^+$] during three hours of rehydration. Data are means ± SE for N=18. Plasma [Na$^+$] in H_2O is significantly lower than MED at 80, 100 minutes (a), and LO, MED, HI at 120-180 minutes (*). Plasma [Na$^+$] in LO is significantly lower than HI at 100, 160, and 180 minutes (b) ($p<0.05$).

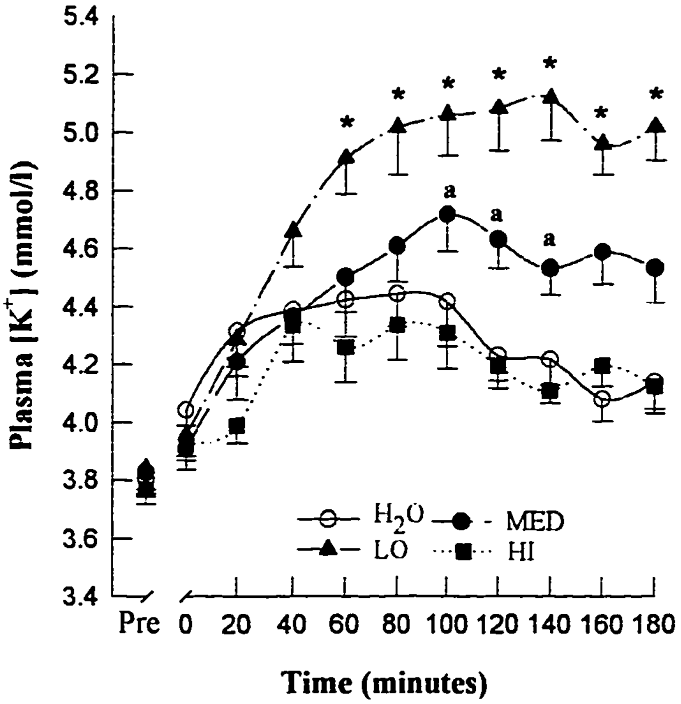

Figure 4. Plasma [K^+] during three hours of rehydration. Data are means ± SE for N=18. Plasma [K^+] concentration is significantly higher in LO than H_2O, MED, HI at 60-180 minutes (*) and higher in MED than HI at 100-140 minutes (a) ($p < 0.05$).

THE EFFECT OF SODIUM IN A REHYDRATION BEVERAGE WHEN CONSUMED AS A FLUID OR MEAL

A paper to be submitted to the Journal of Applied Physiology

Melinda L. Ray, Mark W. Bryan, Timothy M. Ruden, Shawn M. Baier, Rick L. Sharp, and Douglas S. King

Abstract

To investigate the impact of fluid composition on rehydration effectiveness, 30 subjects (15 male, 15 female) were studied during a 2 h rehydration period following a 2.5% body weight loss attained via exercise and heat (65°C) exposure. In a randomized cross-over design, subjects rehydrated with water (H_2O), chicken broth (CB: Na=109.5; K=25.3 mmol/l), a carbohydrate-electrolyte drink (CE: Na=16.0; K=3.3 mmol/l), and chicken noodle soup (SOUP: Na=333.8; K=13.7 mmol/l). Subjects were given 175 ml (6 oz) of the respective beverage at the start of the rehydration period and 20 min later; water was given every 20 min for the remaining 100 min for a total volume equal to body weight loss during dehydration. There were no significant differences in percent recovery of body weight during rehydration (H_2O: 75.9 ± 3.2%; CB: 76.0 ± 1.8%; CE: 74.9 ± 2.9%; SOUP: 78.2 ± 2.9%). While none of the beverages resulted in complete plasma volume restoration, the percent recovery in plasma volume was significantly greater in SOUP (98.6 ± 0.8%) and CE (98.4 ± 1.1%) compared with H_2O (94.4 ± 1.1%) ($p<0.05$). Plasma osmolality was significantly higher in CB and CE compared with H_2O (significant main effect; $p<0.05$). Urine volume was significantly greater in CE (310 ± 30 ml) compared with CB (188 ± 20 ml) ($p<0.05$). Urine osmolality was significantly higher in CB and SOUP compared with CE ($p<0.05$). Urinary sodium concentra-

tions were significantly greater in CB and SOUP compared with CE and H_2O ($p<0.05$). Urinary potassium concentration was significantly higher in CB compared with the other beverages ($p<0.05$). There were no significant differences in blood pressure or rectal temperature measured during the rehydration period among the different rehydration beverages. These results provide evidence that the inclusion of sodium in rehydration beverages as well as consuming a sodium-containing liquid meal increases fluid retention and improves plasma volume restoration.

Introduction

Adolph and Dill (1938) observed individuals adapting to desert conditions ingested water to a greater extent immediately after exercise and during mealtime than at any other time of day. However, fluid ingestion still lagged behind fluid loss during exercise and heat-induced dehydration; in fact, subjects typically ingested fluids until roughly half of their fluid loss had been restored. Failure to adequately replace body fluid losses by ad libitum ingestion, referred to as involuntary dehydration, has since been observed by others (1, 24). Subsequent research has attempted to determine the factors that enhance both fluid intake by the athlete and its absorption and subsequent restoration of body weight and plasma volume.

Evidence from the few studies that have examined post-exercise rehydration support the addition of electrolytes, particularly sodium, to a rehydration beverage for promotion of body water restoration (7, 16, 17, 29). Sodium is the major extracellular ion; thus including sodium in a rehydration beverage influences the restoration of the extracellular (and consequently plasma volume) fluid space. Costill and Sparks (1973) observed a greater plasma volume recovery in subjects consuming a carbohydrate-electrolyte beverage (22 mmol/l sodium) compared to water after 4% dehydration. However, neither beverage completely restored plasma volume to pre-dehydration levels after 4 hours of rehydration. Body water restoration may be accelerated when subjects consume beverages containing higher sodium concentrations. For example, Maughan et al. (1995) observed a positive net fluid balance when subjects consumed beverages containing 52 and 100 mmol/l sodium 5.5 hours after a 30 minute rehydration period. In contrast, solutions containing less sodium (< 26 mmol/l) resulted in a negative fluid balance. Recently, we observed a greater percent recovery of plasma volume when subjects consumed beverages containing 109.5 mmol/l and 154.5 mmol/l sodium compared to either water or a beverage containing 31.5 mmol/l sodium (26).

Previous research indicates that food consumption stimulates fluid intake both at rest and during exercise (2, 10, 32). The beverage volume consumed during meals was significantly greater than the beverage volume consumed between meals in resting men: 68% of the total daily fluid intake was consumed at mealtimes (10). Subjects provided with water ad libitum while walking 14.4 km for 6 hours in desert conditions increased their water intake by 50-200% during a 30 minute period in which food was available (32).

Few studies have examined the effectiveness of consuming food and fluid simultaneously on body water restoration following exercise. In one study, subjects were able to restore body weight losses of 4-7% after a five hour rehydration period in which subjects ingested a 5% carbohydrate-electrolyte beverage along with a meal in a volume equal to the volume of fluid lost during exercise (30). Maughan et al. (1996) reported a more positive net fluid balance six hours after subjects consumed a meal and water after exercise and thermal-induced dehydration compared to subjects receiving a carbohydrate-electrolyte beverage alone. Lower cumulative urine volumes were observed with ingestion of the meal, leading to a greater retention of the ingested fluid.

Based on these studies, it is clear that inclusion of sodium in high concentrations in a rehydration beverage is essential in promoting body fluid restoration following heat and exercise-induced dehydration. In addition, the limited data available on post-exercise rehydration with a meal indicate that food consumption may significantly enhance body weight and fluid balance restoration. Solid food is not always available or appealing to the athlete following exercise; consuming a high sodium beverage and meal simultaneously in the form of soup would provide the athlete with both fluid and electrolytes while minimizing gastric fullness and hunger. As it is not often practical for athletes to frequently consume large volumes of fluid following exercise, we sought to determine if consuming a small volume of fluid at the onset of rehydration followed by water promoted effective body water restoration. Therefore, the purpose of this investigation was to examine the effectiveness of rehydration with four different beverages: water, a commonly used carbohydrate-electrolyte beverage, and chicken broth and chicken noodle soup containing high concentrations of sodium.

Methods

Subjects. Thirty subjects (15 male, 15 female) were recruited to participate as subjects in this study. These subjects were physically active college age subjects who typically exercised three to four days per week. Informed consent was obtained from the subjects in accordance with the guidelines established by the Human Subjects Review Board of Iowa State University. Laboratory measurements were made on four randomly assigned days, separated by at least one week. Physical characteristics of the subjects are presented in Table 1.

Dehydration. On each of four visits to the laboratory, subjects underwent a combination of thermal and exercise-induced dehydration, followed by a two-hour rehydration period with one of four different beverages in a randomized cross-over design. Subjects reported to the laboratory at 7:00 am following an overnight fast and at least 16 hours after exercise. Subjects voided and a body weight was obtained. A resting blood sample (5 ml) was obtained by venipuncture without stasis for the determination of hemoglobin, hematocrit, osmolality, and plasma sodium and potassium concentrations. A probe was inserted to a depth of 8 cm beyond the anal sphincter for the measurement of rectal body temperature. Subjects then underwent 20 minutes of light exercise on a cycle ergometer (50-100 watts) at 20°C, followed by 10 minutes of sauna exposure at 65°C. Subjects repeated the alternating periods of exercise and sauna exposure until 2-3% of the initial body weight was lost. During the dehydration period, which lasted 90-120 minutes, rectal temperature and heart rate were monitored every 30 minutes. All urine was collected and pooled for the determination of total urine volume, specific gravity, osmolality, and sodium and potassium concentrations.

Rehydration. After the dehydration period subjects underwent a 30 minute transition period to allow the body fluid compartments to stabilize (23). During this time, subjects changed into dry clothes and a teflon catheter was inserted into a forearm vein. The catheter was kept patent with infusion of 1-3 ml of 0.9% sodium chloride every 20 minutes during the rehydration period. Following the 30 minute transition period, subjects began a two-hour rehydration period in a thermoneutral environment (20°C). Subjects were in a seated position throughout the rehydration period. On each day, subjects rehydrated with either water (H_2O), chicken broth (CB), a carbohydrate-electrolyte beverage (CE), or chicken noodle soup (SOUP) (Table 2). The water was kept at a temperature of 22°C and CE was kept at a temperature of 4°C. Both CB and SOUP were heated to a temperature of 120°F prior to ingestion. Subjects ingested 175 ml (6 oz) of the respective beverage at the beginning of the rehydration period, and 175 ml 20 minutes later. For the remainder of the rehydration period, subjects ingested an equal volume of water every twenty minutes. The total volume ingested by each subject throughout the two-hour rehydration period was equal to the volume of water lost during dehydration. The total amount of sodium ingested was 40.7 mmol (CB), 6.4 mmol (CE), and 118.4 mmol (SOUP). The total amount of potassium ingested was 9.47 mmol (CB), 1.27 mmol (CE), and 4.86 mmol (SOUP). Total carbohydrate ingested was 0.28 g (CB), 22.96 g (CE), and 33.0 g (SOUP). The chicken noodle soup contained the highest sodium and total carbohydrate concentration compared with the other beverages. The chicken broth also contained a significant sodium concentration, and had the highest potassium concentration compared with the other beverages. Both CB and SOUP were isotonic, whereas CE was hypertonic containing a high total carbohydrate content and the lowest electrolyte concentrations compared with the other beverages. Blood samples, blood pressure, rectal temperature, and body weight were obtained at the beginning of the rehydration period and every 20 minutes thereafter. Blood samples were taken after the fluid in the dead space of the catheter was discarded, and were then immediately transferred into tubes containing lithium heparin for later analysis. Upon completion of the rehydration period, subjects voided and a final body weight was obtained. Urine was collected and measured for total volume, specific gravity, osmolality, and sodium and potassium concentrations.

Percent rehydration. The percent of body weight lost during dehydration that was regained during rehydration was used as an index of whole body rehydration (12). The percent rehydration represented the amount of ingested fluid that was retained after the rehydration period. Percent rehydration was determined using body weight and was calculated as:

$$\text{Percent rehydration} = \frac{[BW_{DH} - (BW_{PRE} - BW_{RH})(kg)]}{\text{Fluid intake (kg)}} \times 100$$

where:

BW_{PRE} = initial body weight

BW_{DH} = body weight lost during exercise

BW_{RH} = body weight after rehydration

Biochemical analysis. Hemoglobin concentration was determined in triplicate using the cyanmethemoglobin technique and hematocrit was determined in triplicate after microcentrifugation. Hematocrit measurements were corrected for plasma trapped within the packed red cells (0.96) and also for venous to total body hematocrit ratio (0.91) (4). Percent changes in plasma volume from pre-exercise values were calculated using hematocrit and hemoglobin concentrations according to Dill and Costill (1974):

$$BV_A = BV_B(Hb_B/Hb_A) \qquad \Delta BV, \% = 100(BV_A - BV_B)/BV_B$$
$$CV_A = BV_A(Hct_A) \qquad \Delta CV, \% = 100(CV_A - CV_B)CV_B$$
$$PV_A = Bv_A - CV_A \qquad \Delta PV, \% = 100(PV_A - PV_B)/PV_B$$

where:

BV = blood volume

CV = red cell volume

PV = plasma volume

BV_B = 100

Hb = hemoglobin concentration

Hct = hematocrit

$_{B,\ A}$ = before and after dehydration

All plasma volume changes were calculated with reference to the pre-dehydration values obtained for the water trial. Blood samples were then centrifuged, and the plasma separated and stored at -20°C for later analysis of plasma electrolytes and osmolality. Plasma and urine osmolality were determined in duplicate using a Vapor Pressure Osmometer (model 5520, Wescor Inc., Logan, Utah). Plasma and urine electrolytes were measured in duplicate using a digital flame analyzer (model 2655-00, Cole-Parmer, Chicago, Illinois).

Dietary and exercise control. Subjects maintained a dietary record for three days prior to the initial trial. Subjects were required to duplicate this diet for three days prior to each of the last three trials. In addition, subjects were instructed to drink one extra liter of water the day before all four trials to ensure euhydration. Diet composition was analyzed for the day prior to each trial using a computer program (FoodComp, ISU). There were no significant differences in diet composition due to trial (Table 3). Subjects also recorded all physical activity performed for three days prior to the initial trial, and reproduced this activity pattern for the three days prior to the following trials.

Statistics. Results in the text, tables, and figures are expressed as means ± SE. The blood measurements, blood pressure, and rectal temperature during rehydration were subjected to an initial two-way repeated measures analyses of variance; this was followed by Newman-Keuls post hoc tests where appropriate. All other data were analyzed using one-way analysis of variance. Differences among treatments were accepted as being significant when a p value of less than 0.05 was obtained.

Results

The mean weight loss due to combined exercise and sauna exposure was 1.82 ± 0.06 kg, corresponding to a percent body weight loss of 2.5 ± 0.1%. There were no significant differences in body weight prior to and after exercise and after rehydration, or percent change in body weight after dehydration with respect to trial. During the rehydration period, the subjects drank an average of 370 ± 13 ml of water every 20 minutes from 40-120 minutes of the rehydration period for a total volume of 1,836 ± 53 ml; there were no significant differences in drink volume with respect to trial. Due to the significantly greater body weight in males compared with females, there was a greater ($p<0.05$) percent weight loss (2.6 ± 0.1% vs 2.4 ± 0.1%) and total drink volume (2,185 ± 68 ml vs 1,487 ± 50 ml) in the males compared with the females. There were no significant differences in percent recovery in body weight and plasma volume, or in any of the urinary measurements between males and females. Therefore, the data for males and females were combined.

Percent rehydration. At the end of the two hour rehydration period, the subjects were still somewhat hypohydrated under all conditions studied (Table 4). Fluid lost during the rehydration period in urine, sweat, and respiration, as well as the body weight lost due to metabolism contributed to the incomplete rehydration. There were no significant differences in the percent of body weight loss that was regained at the end of the two hour period (percent rehydration) (H_2O: 75.9 ± 3.2%; CB: 76.0 ± 1.8%; CE: 74.9 ± 2.9%; SOUP: 78.2 ± 2.9%).

There were no significant differences in rectal temperature due to trial during the rehydration period. In addition, there were no significant differences in systolic or diastolic blood pressure during the rehydration period between trials (Table 5).

Plasma volume. Following combined intermittent exercise and sauna exposure, plasma volume decreased by 7.0 ± 0.7% for all trials combined. There were no significant differences in plasma volume due to trial. Although the mean percent recovery in plasma volume was significantly higher in CB and SOUP compared to H_2O ($p = 0.007$) none of the beverages resulted in complete plasma volume restoration (Figure 1; H_2O: 94.4 ± 1.1%; CB: 98.4 ± 1.1%; CE: 95.8 ± 1.0%; SOUP: 98.6 ± 0.8%).

Urine volume, specific gravity, osmolality, and electrolytes. Urine volume measured during and at the end of the rehydration period was significantly greater in CE compared with CB (Table 6; $p = 0.02$). There were no significant differences in urine specific gravity with respect to trial. Urine osmolality was significantly higher in CB and SOUP compared with CE ($p = .01$). Urinary sodium concentration was significantly higher in CB and SOUP compared with CE and H_2O ($p = .0004$). Despite the greater urinary sodium concentrations with CB and SOUP, more sodium was retained with ingestion of these beverages compared with CE and H_2O (Table 7; $p<0.05$). In fact, urinary sodium output exceeded sodium intake in both CE and H_2O. Urinary potassium concentration was significantly higher in CB compared with the other three beverages ($p = 0.007$).

Plasma Osmolality. Prior to dehydration, plasma osmolality averaged 274.9 ± 0.6 mmol/l (Figure 2). Exposure to heat and prolonged exercise resulted in a mean increase in plasma osmolality to 281.6 ± 0.6 mmol/l. Plasma osmolality in CB and CE was significantly greater than H_2O (significant main effect; $p = 0.04$).

Plasma electrolytes. The mean plasma sodium concentration (Figure 3) increased from 137.0 ± 0.2 mmol/l to 140.3 ± 0.2 mmol/l after dehydration. There were no significant differences in plasma sodium concentration due to trial. The plasma potassium concentration increased from 3.92 ± 0.04 mmol/l to 4.01 ± 0.03 mmol/l after dehydration. The plasma potassium concentration in SOUP was significantly lower than CB at 20-120 minutes, H_2O at 40-80 and 120 minutes, and CE at 40 minutes ($p<0.05$). In addition, the plasma potassium concentration was higher in CB compared with CE at 60 and 80 minutes of rehydration.

Discussion

Consuming chicken broth or chicken noodle soup following heat and exercise-induced dehydration resulted in a significant recovery in plasma volume and reduced urine volumes compared to water. In contrast, ingestion of a commonly used carbohydrate-electrolyte beverage did not restore plasma volume more effectively than ingestion of water, and resulted in a greater urine production compared to the other beverages. These results are interesting since subjects ingested only 350 ml (12 ounces) of each beverage during the first 20 minutes of the rehydration period.

Previous studies have shown that the extent to which body fluid balance is restored varies with the composition of a rehydration beverage. Both CB and SOUP contain greater electrolyte concentrations (109.5 mmol/l sodium, 25.3 mmol/l potassium and 333.8 mmol/l sodium, 13.7 mmol/l potassium, respectively), than many sports drinks used for rehydration following exercise, including the CE beverage used in this study (16 mmol/l sodium, 3.3 mmol/l potassium). The chicken noodle soup contained the highest carbohydrate concentration, followed by CE and CB, whereas CE was the most concentrated beverage; CB and SOUP were relatively isotonic. Consequently, analysis of the effect that consuming these beverages has on rehydration is somewhat complex due to the variation in electrolyte and carbohydrate concentration, as well as osmolality, among these beverages.

The addition of sodium to a rehydration beverage significantly increases fluid retention in the extracellular space, leading to a greater plasma volume restoration than is observed after ingestion of water and dilute electrolyte solutions (7, 12, 24, 26). The higher sodium concentration in CB and SOUP was associated with a significantly higher plasma volume recovery and lower urine volumes compared with ingestion of H_2O; this finding has been observed by others. Nose et al. (1988b) reported faster plasma volume restoration and lower urine volumes in subjects consuming water and capsules containing sodium (77 mmol/l) compared with water alone. Recently, we observed significantly higher recovery of plasma volume and lower urine volumes when ingesting beverages containing 109.5 mmol/l sodium and 159.5 mmol/l sodium compared with water and a beverage containing 31.5 mmol/l sodium (26). In the present study, consuming CE resulted in a similar plasma volume recovery and larger urine volume compared with ingestion of H_2O. These findings do not agree with previous studies demonstrating greater plasma volume recovery and reduced urine volumes with ingestion of beverages similar in composition to CE compared with water (7, 12). The reason for the differences between these studies and the present study is unclear, particularly given the similarity in methodology used in these studies. However, the relatively large number of subjects used in the present study reduces the possibility that the high urine volumes observed in CE can be attributed to experimental error.

The production of larger volumes of dilute urine produced in CE compared with H_2O is puzzling in light of the higher plasma osmolality in CE. One possibility is that the temperature at which CE was administered (4°C) influenced the rate at which fluid emptied from the stomach, as some have reported that colder beverages empty faster than warmer beverages (6). In contrast, others have observed no effect of beverage temperature on gastric emptying (19) or a slowing of gastric emptying with cold drinks (31). Therefore, it is unlikely that the temperature of CE affected gastric emptying. An additional possibility may be a direct effect of beverage temperature on arginine vasopressin secretion. Plasma arginine vasopressin concentrations have been reported to be reduced in dehydrated men eating ice chips, despite no change in plasma osmolality and sodium concentrations (28). Thus there may be cold-sensitive oropharyngeal receptors that inhibit arginine vasopressin secretion. An inhibition of vasopressin may account in part for the greater urine volume observed in CE compared to water, although further investigation is needed to clarify the effects of beverage temperature on gastric emptying and urine production.

The high sodium intake in CB and SOUP may have stimulated fluid control mechanisms which reduced urine output and thereby increased plasma volume. Fluid-regulating hormones, including renin, angiotensin II, aldosterone, and arginine vasopressin are all released in response to heat exposure (14), exercise (5, 27), and increases in plasma osmolality (33), promoting the absorption of water and active uptake of solutes by the kidney. Previous studies have shown that rehydrating with water or a dilute electrolyte solution results in a drop in plasma osmolality and plasma sodium concentrations, as well as renin, angiotensin II, and aldosterone concentrations (7, 12, 25, 29, 33). In the present study, plasma osmolality was lower in H_2O compared with CB and CE. The lower plasma osmolality in H_2O may have prevented the maintenance of the fluid-regulating hormones, leading to excess fluid filtration and renal solute reabsorption. A reduction in the concentration of fluid regulating hormones would explain the higher urine volumes in H_2O compared with CB, and lower urine osmolality and electrolyte concentrations in H_2O compared with CB and SOUP.

The significantly higher plasma potassium concentration in CB is likely due to the increase in extracellular potassium concentration brought about by dehydration and maintained by ingesting CB, the beverage containing the highest potassium concentration. The urinary potassium concentration was significantly higher in CB compared with the other beverages. Nielsen et al. (1986) observed similar elevations in plasma potassium concentration and urinary potassium excretion after consuming a beverage containing high concentrations of potassium compared with beverages containing glucose and sodium. Thus, the higher plasma potassium concentration may have promoted potassium excretion by the kidneys in the attempt to restore extracellular potassium concentrations.

The explanation for the elevated plasma potassium concentrations throughout the rehydration period in all beverages is unclear, particularly since subjects only ingested 350 ml of each beverage at the beginning of the rehydration period. Others have shown no significant differences in plasma potassium concentrations after ingesting a meal or beverages containing varying concentrations of potassium (17, 18). The significantly lower plasma potassium concentrations observed in SOUP compared to the other beverages is also somewhat surprising given the greater amount of potassium present in SOUP compared to CE and H_2O. However, a significant portion of the potassium in SOUP is likely contained within the chicken pieces; thus, the time required for digestion and absorption may have resulted in the lower plasma potassium concentrations.

Previous investigators have suggested that ingestion of beverages high in potassium concentration may delay rates of plasma volume recovery due to restoration of the intracellular fluid compartment at the expense of extracellular fluid (21, 22). However, Maughan et al. (1994) observed no differences in plasma volume recovery six hours after rehydration with four beverages containing glucose, sodium, potassium, and a combination of glucose, sodium, and potassium. Recently, we observed a lower plasma volume recovery after ingesting a low sodium beverage containing high concentrations of potassium (75.8 mmol/l) compared with beverages containing lower potassium and higher sodium concentrations (26). In the present study, consuming CB resulted in a significantly greater plasma volume recovery compared with water, despite containing the highest potassium concentration (25.3 mmol/l). However, the potassium concentration in CB is not as high as the high potassium beverage used in the previous study. Taken together, these studies suggest that consuming high concentrations of potassium may not impair rehydration provided the sodium concentration of the beverage is adequate.

The few studies that have examined the effects of food ingestion on post-exercise rehydration report a greater restoration of body weight and plasma volume when consuming a meal and beverage compared with a beverage alone (18, 30), presumably due to the greater intake of electrolytes as well as protein and carbohydrate with the meal. One might expect that consuming SOUP, which contained higher concentrations of sodium, protein, and carbohydrate compared with the other beverages, would result in a lower urine volume and greater body weight restoration than was observed due to the impact that each of these nutrients has on fluid absorption. It is clearly established that sodium enhances intestinal water absorption and promotes greater fluid retention in the extracellular space (11, 24). In addition, specific amino acids such as glycine and alanine also promote net fluid absorption by the small intestine (13). Finally, the addition of glucose to a rehydration beverage has been shown to stimulate both sodium and water absorption in the small intestine (11).

Whether the enhanced fluid absorption in the small intestine observed with protein and carbohydrate results in an improved whole body water restoration remains unclear. The consumption of CE, which contained a high carbohydrate concentration, did not result in a significant plasma volume recovery, whereas similar plasma volume recovery was observed with SOUP, which contained significant carbohydrate, and CB, which contained minimal carbohydrate. It is possible that the lack of body water restoration is related to the high osmolality of CE relative to the other beverages. It has previously been shown that fluids with high osmotic concentrations slow gastric emptying (3, 8). On the other hand, others have found that relatively hypertonic carbohydrate-electrolyte solutions do not impair rehydration compared with water (7, 15). Based on these studies, it is difficult to conclude whether the high osmolality, or a combination of the high osmolality and low electrolyte concentration, of CE impaired rehydration. It does appear, however, that greater attention should be paid to sodium as opposed to carbohydrate when formulating a beverage to be used for rehydration purposes. In this study, consuming isotonic beverages containing high sodium concentrations and high or low carbohydrate concentrations was more effective in restoring body water losses than consuming water or a relatively hypertonic beverage high in carbohydrate and low in sodium concentration.

In conclusion, greater plasma volume recovery and lower urine volumes were observed in subjects ingesting chicken broth and chicken noodle soup containing high concentrations of sodium compared to water and a carbohydrate-electrolyte solution. These differences were seen despite the ingestion of only 350 ml of each beverage at the onset of rehydration. Thus, the composition of a fluid consumed immediately following heat and exercise-induced dehydration has an important impact on body fluid restoration, and should be considered if rapid rehydration is a goal. While consuming a meal such as soup has the advantage of providing both fluid and electrolytes while minimizing hunger commonly experienced after exercise, additional research is needed in order to formulate a rehydration beverage containing the optimal combination of electrolytes, carbohydrates, and possibly protein to maximize body water restoration.

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References

1. Adolph, E.F. *Physiology of Man in the Desert.* New York: Interscience, 1947.
2. Adolph, E.F. and D.B. Dill. Observations on water metabolism in the desert. *Am. J. Physiol.* 123: 369-378, 1938.
3. Candas, V., J.P. Libert, G. Brandenberger, J.C. Sagot, C. Amoros, and J.M. Kahn. Hydration during exercise: effects on thermal and cardiovascular adjustments. *Eur. J. Appl. Physiol.* 55: 113-122, 1986.
4. Chaplin, H., P.L. Mollison, and H. Vetter. The body/venous hematocrit ratio: its constancy over a wide hematocrit range. *J. Clin. Invest.* 32:1309-1316, 1953.
5. Costill, D.L., G. Branam, W. Fink, and R. Nelson. Exercise induced sodium conservation: changes in plasma renin and aldosterone. *Med. Sci. Sports Exerc.* 8(4): 209-213, 1976.

6. Costill, D.L. and B. Saltin. Factors limiting gastric emptying during rest and exercise. *J. Appl. Physiol.* 37(5): 679-683, 1974.

7. Costill, D.L. and K.E. Sparks. Rapid fluid replacement following thermal dehydration. *J. Appl. Physiol.* 34(3): 299-303, 1973.

8. Coyle, E.F., D.L. Costill, W.J. Fink, and D.G. Hoopes. Gastric emptying rates for selected athletic drinks. *Res. Q.* 49: 119-124, 1978.

9. Dill, D.B. and D.L. Costill. Calculation of percentage changes in volumes of blood, plasma, and red cells in dehydration. *J. Appl. Physiol.* 37(2): 247-248, 1974.

10. Engell, D. Interdependency of food and water intake in humans. *Appetite.* 10: 133-141, 1988.

11. Fordtran, J.S. Stimulation of active and passive sodium absorption of sugars in the human jejunum. *J. Clin. Invest.* 55: 728-737, 1975.

12. Gonzalez-Alonso, J., C.L. Heaps, and E.F. Coyle. Rehydration after exercise with common beverages and water. *Int. J. Sports Med.* 13(5): 399-406, 1992.

13. Hellier, M.D., C. Thirumalai, and D.D. Holdsworth. The effect of amino acids and dipeptides on sodium and water absorption in man. *Gut.* 14: 41-45, 1973.

14. Kosunen, K.J., A.J. Pakarinen, K. Kuoppasalmi, and H. Adlercreutz. Plasma renin activity, angiotensin II, and aldosterone during intense heat stress. *J. Appl. Physiol.* 41(3): 323-327, 1976.

15. Lambert, C.P., D.L. Costill, G.K. McConell, M.A. Benedict, G.P. Lambert, R.A. Robergs, and W.J. Fink. Fluid replacement after dehydration: influence of beverage carbonation and carbohydrate content. *Int. J. Sports Med.* 13(4): 285-292, 1992.

16. Maughan, R.J. and J.B. Leiper. Sodium intake and post-exercise rehydration in man. *Eur. J. Appl. Physiol.* 71: 311-319, 1995.

17. Maughan, R.J., J.H. Owen, S.M. Shirreffs, and J.B. Leiper. Post-exercise rehydration in man: effects of electrolyte addition to ingested fluids. *Eur. J. Appl. Physiol.* 69: 209-215, 1994.

18. Maughan, R.J., J.B. Leiper, and S.M. Shirreffs. Restoration of fluid balance after exercise-induced dehydration: effects of food and fluid intake. *Eur. J. Appl. Physiol.* 73: 317-325, 1996.

19. McArthur, K.E. and M. Feldman. Gastric acid secretion, gastrin release, and gastric temperature in humans as affected by liquid meal temperature. *Am. J. Clin. Nutr.* 49: 51-54, 1989.

20. Mitchell, J.B., P.W. Grandjean, F.X. Pizza, R.D. Starling, and R.W. Holtz. The effect of volume ingested on rehydration and gastric emptying following exercise-induced dehydration. *Med. Sci. Sports Exerc.* 26(9): 1135-1143, 1994.

21. Nadel, E.R., G.W. Mack, and H. Nose. Influence of fluid replacement beverages on body fluid homeostasis during exercise and recovery. In: *Perspectives in Exercise Science and Sports Medicine, Vol. 3, Fluid Homeostasis during exercise,* C.V. Gisolfi and D.R. Lamb (Eds.). Carmel, IN: Benchmark Press, 1990, pp. 181-205.

22. Nielsen, B., G. Sjogaard, J. Ugelvig, B. Knudsen, and B. Dohlmann. Fluid balance in exercise dehydration and rehydration with different glucose-electrolyte drinks. *Eur. J. Appl. Physiol.* 55: 318-323, 1986.

23. Nose, H., G.W. Mack, X. Shi, and E.R. Nadel. Shift in body fluid compartments after dehydration in humans. *J. Appl. Physiol.* 65(1): 318-324, 1988a.

24. Nose, H., G.W. Mack, X. Shi, and E.R. Nadel. Role of osmolality and plasma volume during rehydration in humans. *J. Appl. Physiol.* 65(1): 325-331, 1988b.

25. Nose, H., G.W. Mack, X. Shi, and E.R. Nadel. Involvement of sodium retention hormones during rehydration in humans. *J. Appl. Physiol.* 65(1): 332-336, 1988c.

26. Ray, M.L., R.L. Sharp, S.D. O'Sullivan, K.A. Moss, T.M. Ruden, and D.S. King. Rehydration after exercise and thermal dehydration: effect of sodium concentration. *unpublished observations.*

27. Rocker, L., K.A. Kirsch, B. Heyduck, and H.U. Altenkirch. Influence of prolonged physical exercise on plasma volume, plasma proteins, electrolytes, and fluid-regulating hormones. *Int. J. Sports Med.* 10(4); 270-274, 1989.

28. Salata, R.A., J.G. Verbalis, and A.G. Robinson. Cold water stimulation of oropharyngeal receptors in man inhibits release of vasopressin. *J. Clin. Endocrinol. Metab.* 65: 561-567, 1987.

29. Shirreffs, S.M., A.J. Taylor, J.B. Leiper, and R.J. Maughan. Post-exercise rehydration in man: effects of volume consumed and drink sodium content. *Med. Sci. Sports Exerc.* 28(10): 1260-1271, 1996.

30. Sproles, C.B., D.P. Smith, R.J. Byrd, and T.E. Allen. Circulatory responses to submaximal exercise after dehydration and rehydration. *J. Sports Med.* 16: 98-105, 1976.

31. Sun, W.M., L.A. Houghton, N.W. Read, D.G. Grundy, and A.G. Johnson. Effect of meal temperature on gastric emptying of liquids in man. *Gut.* 29: 302-305, 1988.

32. Szlyk, P.C., I.V. Sils, R.P. Francesconi, and R.W. Hubbard. Patterns of human drinking: effects of exercise, water temperature, and food consumption. *Aviat. Space Environ. Med.* 61: 43-48, 1990.

33. Takamata, A., G.W. Mack, C.M. Gillen, and E.R. Nadel. Sodium appetite, thirst, and body fluid regulation in humans during rehydration without sodium replacement. *Am. J. Physiol.* 266: R1493-R1502, 1994.

Table 1. Subject characteristics

	Age (yr)	Weight (kg)	Height (cm)	BMI (kg/m^2)
Males	25 ± 1	82.8 ± 3.2*	179.9 ± 2.3*	25.5 ± 0.6
Females	23 ± 1	61.1 ± 1.3	160.6 ± 2.0	23.8 ± 0.7
All	24 ± 1	72.0 ± 2.7	170.2 ± 2.3	24.7 ± 0.5

Data are means ± SE for 15 male and 15 female subjects.
*males significantly greater than females, $p<0.05$).

Table 2. Beverage characteristics

	H_2O	CB	CE	SOUP
Osmolality (mOsm/l)	24.5	306.5	359.3	270.5
$[Na^+]$ (mmol/l)	0.0	109.5	16.0	333.8
$[K^+]$ (mmol/l)	0.0	25.3	3.3	13.7
$[Ca^{2+}]$ (mmol/l)	0.0	1.8	3.7	5.7
Total CHO (g/l)	0.0	0.8	64.7	93.0

Table 3. Diet composition the day prior to each trial

	H_2O	CB	CE	SOUP
Energy intake (kJ/d)	1,2620 ± 1,365	1,1549 ± 1,798	1,4065 ± 2,992	1,4114 ± 1,689
Sodium (mg/d)	5,587 ± 971	4,952 ± 1215	6,588 ± 1878	5,760 ± 1240
Potassium (mg/d)	4,012 ± 416	3,241 ± 482	3,737 ± 552	3,571 ± 403
Calcium (mg/d)	1,400 ± 192	1,188 ± 287	1,437 ± 352	1,241 ± 266
% energy as protein	17 ± 1	16 ± 2	17 ± 2	16 ± 2
% energy as fat	22 ± 2	23 ± 3	23 ± 3	23 ± 2
% energy as carbohydrate	61 ± 3	61 ± 4	58 ± 5	60 ± 4

Values are means ± SE for thirty subjects; there were no significant differences in diet composition due to trial ($p > 0.05$).

Table 4. Body weight before and after dehydration, and after the rehydration period

Body Weight (kg)	H_2O	CB	CE	SOUP
Baseline	72.0 ± 2.7	72.3 ± 2.7	72.0 ± 2.7	72.2 ± 2.7
Dehydrated	70.2 ± 2.6	70.3 ± 2.6	70.2 ± 2.6	70.5 ± 2.6
Rehydrated	71.6 ± 2.7	71.8 ± 2.7	71.6 ± 2.7	71.8 ± 2.7

Data are means ± SE for 15 male and 15 female subjects. There were no significant differences in body weight due to trial ($p>0.05$).

Table 5. Systolic and diastolic blood pressure during rehydration

	Systolic blood pressure				Diastolic blood pressure			
Time (min)	H_2O	SOUP	CB	CE	H_2O	SOUP	CB	CE
0	104 ± 2	110 ± 1	106 ± 2	110 ± 2	72 ± 1	74 ± 2	74 ± 1	76 ± 2
60	104 ± 3	104 ± 1	104 ± 2	102 ± 2	70 ± 1	70 ± 1	72 ± 1	74 ± 1
120	104 ± 2	104 ± 2	104 ± 2	108 ± 2	74 ± 2	72 ± 1	74 ± 1	74 ± 2

Data are means ± SE for thirty subjects. There were no significant differences in systolic or diastolic blood pressure due to trial ($p > 0.05$).

Table 6. Urinary measurements taken during rehydration

	H_2O	CB	CE	SOUP
Volume (ml)	232.3 ± 31.2	188.2 ± 19.6	309.9 ± 30.2[a]	231.3 ± 28.6
Specific gravity	1.016 ± 0.001	1.026 ± 0.004	1.020 ± 0.005	1.019 ± 0.001
Osmolality (mOsm/l)	491.2 ± 48.9	609.7 ± 39.4[b]	401.8 ± 51.0	567.6 ± 51.2[b]
$[Na^+]$ (mmol/l)	60.9 ± 6.6	87.2 ± 6.7[c]	48.0 ± 7.0	90.2 ± 10.7[c]
$[K^+]$ (mmol/l)	65.4 ± 6.7	88.9 ± 6.3[d]	51.4 ± 6.0	68.0 ± 6.2

Values are means ± SE for thirty subjects. [a] significantly higher than CB ($p<0.05$); [b] significantly higher than CE ($p<0.05$) [c] significantly higher than CE, H_2O ($p<0.05$); [d] significantly higher than H_2O, SOUP, CE ($p<0.05$).

Table 7. Intake and total urinary output of sodium and potassium

	H_2O	CB	CE	SOUP
Sodium intake (mmol)	0.0*	40.7*	6.4*	118.4*
Potassium intake (mmol)	0.0*	8.9*	1.2*	4.9*
Sodium output (mmol)	16.2 ± 4.0	16.5 ± 2.2	14.8 ± 3.2	19.7 ± 3.2
Potassium output (mmol)	15.2 ± 2.9	16.5 ± 2.0	15.8 ± 3.2	16.4 ± 3.1

Data are means ± SE for thirty subjects. * significantly different from each other.

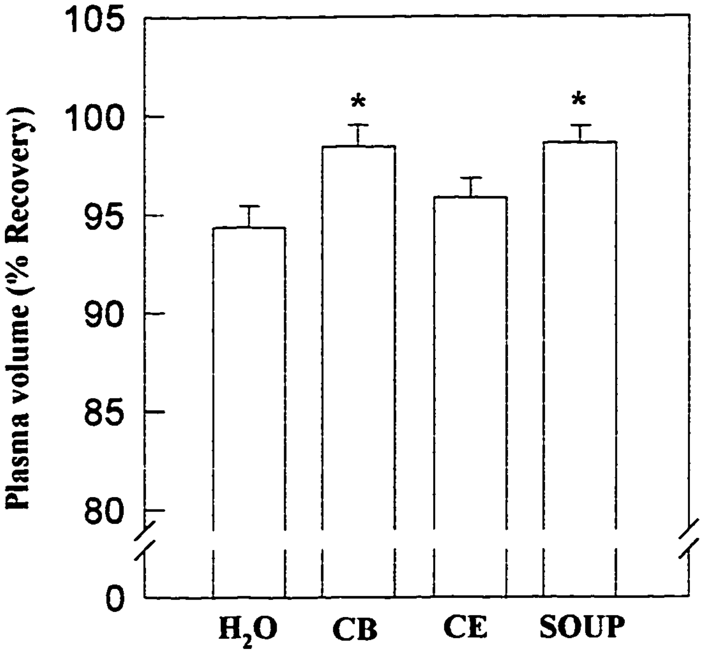

Figure 1. Percent recovery in plasma volume during two hours of rehydration. Data are means ± SE for N=30. * CB, SOUP significantly higher compared with H_2O ($p<0.05$).

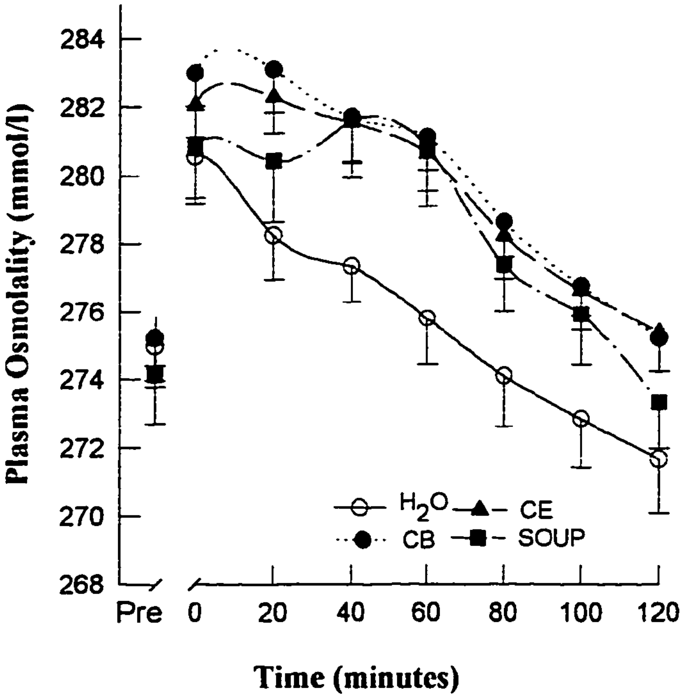

Figure 2. Plasma osmolality during two hours of rehydration. Data are means ± SE for N=30. Plasma osmolality is significantly higher in CB and CE compared with H_2O (significant main effect; p=0.04).

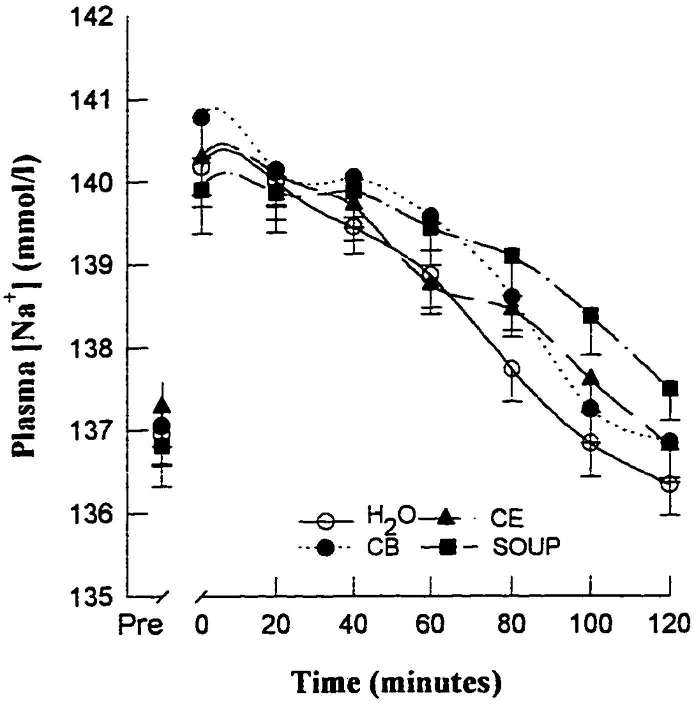

Figure 3. Plasma sodium concentrations during two hours of rehydration. Data are means ± SE for N=30.

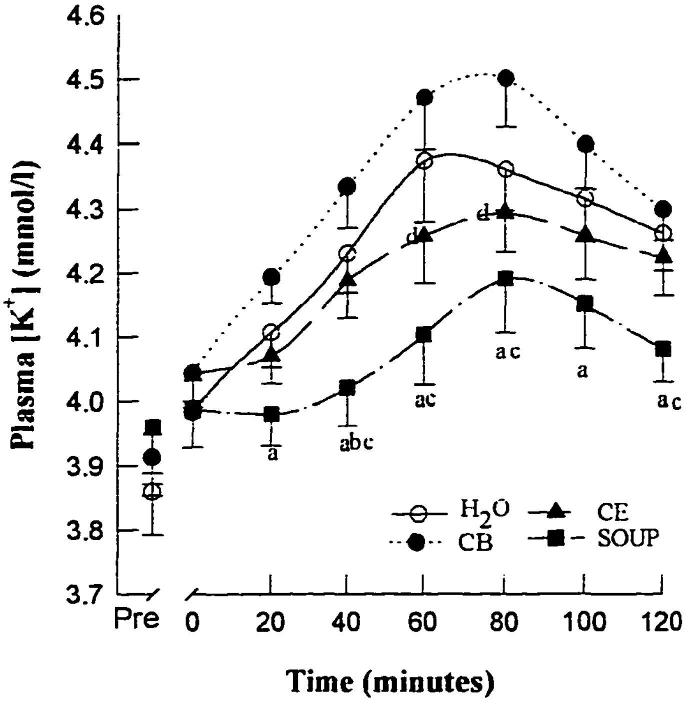

Figure 4. Plasma [K^+] concentration during two hours of rehydration. Data are means ± SE for N=30. Plasma [K^+] is significantly lower in SOUP than CB at 20-120 minutes (a); CE at 40 minutes (b); and H_2O at 40-80, and 120 minutes (c). In addition, CE is significantly lower than CB at 60, 80 minutes (d) ($p<0.05$).

CONCLUSIONS

The addition of sodium to a rehydration beverage is essential in achieving body fluid restoration following heat and exercise-induced dehydration. Ingesting beverages containing sodium concentrations of 109.5 mmol/l sodium and 159.5 mmol/l sodium resulted in a greater restoration of body weight and plasma volume compared with more dilute electrolyte solutions and water. Plasma osmolality and sodium concentrations were also higher, while urine volumes were lower, with ingestion of the high sodium beverages. Thus, increasing the cation content of a rehydration beverage maintains the dehydration-induced increase in plasma osmolality and plasma sodium concentrations. Other investigators have observed that maintenance of plasma osmolality and sodium concentrations prevents rapid declines in fluid-regulating hormone concentrations. Consequently, there is a greater reabsorption of water by the kidney, leading to lower urine volumes and a greater amount of the ingested fluid retained. Conversely, consuming water or dilute electrolyte solutions results in a decline in plasma osmolality, plasma electrolyte concentrations, and fluid-regulating hormones, leading to excess fluid filtration by the kidney. The resulting large urine volumes delay rehydration.

Although the addition of both sodium and potassium to a rehydration beverage is important in restoring fluid balance after dehydration, it appears that sodium impacts rehydration to a greater extent than potassium. A delay in plasma volume recovery as well as body weight restoration is often seen in subjects consuming rehydration beverages containing high concentrations of potassium. The delay may be due to a restoration of the intracellular fluid compartment at the expense of the extracellular fluid space. The results from these studies indicate that the ingestion of high concentrations of potassium may not impair rehydration provided the sodium concentration of the rehydration beverage is adequate.

Consuming a meal or soup containing high concentrations of sodium also resulted in a significantly greater recovery in plasma volume compared with water. Nutrients other than sodium that may have contributed to the greater plasma volume recovery include the carbohydrate and protein present in the soup. Glucose, as well as specific amino acids such as alanine and glycine enhance fluid absorption in the small intestine, although it remains to be seen whether an enhanced intestinal fluid absorption results in an improvement in overall rehydration. Including carbohydrate in a beverage that is high in osmolality, but low in sodium concentration delayed rehydration. On the other hand, consuming relatively isotonic beverages containing high sodium concentrations and high or low carbohydrate concentrations resulted in greater plasma volume recovery and lower urine volumes. These data suggest that the addition of sodium may be more important than carbohydrate in a rehydration beverage consumed following exercise-induced dehydration.

These results also suggest that the composition of a fluid or food consumed at the onset of a rehydration period has a significant impact on body fluid balance. Ingesting only 350 ml of one of four rehydration beverages shortly after exercise resulted in significant differences in plasma volume, plasma osmolality and potassium concentrations, as well as urine volume and electrolyte concentrations.

The results from these studies show that the composition of a rehydration beverage consumed following heat and exercise-induced dehydration significantly influences rehydration, even when consumed in fairly small volumes. The sodium concentrations used in these studies are higher than those used in previous investigations, as well as those found in many sports drinks used by athletes. However, ingestion of high concentrations of sodium did not appear to have any adverse thermoregulatory or cardiovascular consequences as rectal temperature and blood pressure measurements were similar for all the beverages studied. Therefore, when rapid rehydration is a goal, consideration should be given to increasing the sodium concentration of sports drinks currently used. In addition, attention should be given to an athlete's diet immediately following dehydration, as ingesting a meal containing high sodium concentrations may enhance the effectiveness of rehydration.

Recommendations for Future Research examining Post-Exercise Rehydration

Recommending consumption of volumes of fluid equal to or greater than the fluid volume lost during dehydration is necessary to ensure adequate fluid replacement. However, athletes typically do not consume such large volumes following exercise due to the inadequacy of the thirst mechanism. In order to assess the practicality of consuming these beverages outside the laboratory setting, voluntary intake of these high sodium beverages by athletes should be measured. Measuring voluntary intake would also be an indirect assessment of the palatability of each beverage.

There is some evidence to suggest that the addition of large amounts of potassium to a rehydration beverage may result in preferential restoration of the intracellular fluid compartment at the expense of the extracellular fluid compartment, leading to delays in plasma volume restoration. However, ingesting high potassium concentrations may not delay rehydration provided there is adequate sodium in a rehydration beverage. To sufficiently address this question, direct measurements of intracellular and extracellular fluid volumes should be made in order to determine whether ingestion of large concentrations of potassium does indeed promote a redistribution of water between the intracellular and extracellular fluid compartments.

Although rapid rehydration for many athletes is important, it is particularly essential for those athletes facing one or more exercise bouts in a day. While these two studies have established the importance of including sodium in fluids or foods that are consumed following exercise, they provide no information regarding the impact that rehydration with these beverages has on subsequent exercise performance. Future studies should determine whether anaerobic or aerobic exercise performance is similar to pre-dehydration levels after rehydrating with these high sodium beverages.

Consuming a liquid meal or soup in the attempt to restore body water losses has significant possibilities, and warrants further research since food consumption following exercise is a common ocurrance in both athletes and non-athletes. However, more research is needed to clarify the effects of including specific nutrients, such as carbohydrates, proteins, fats, vitamins, and minerals in a rehydration beverage, with attention given to their impact on gastric emptying, intestinal absorption, and whole body fluid restoration.

Rehydration during exercise has been shown to minimize body water losses and the subsequent impact of those losses on the cardiovascular and thermoregulatory systems. However, beverages commonly consumed during exercise have fairly low electrolyte concentrations. Future studies might examine whether ingestion of these beverages, which are higher in sodium concentration, is more effective at preventing or minimizing body fluid losses and thus maintaining exercise performance.

REFERENCES

1. Adolph, E.F. *Physiology of Man in the Desert.* New York: Interscience, 1947.

2. Adolph, E.F. and D.B. Dill. Observations on water metabolism in the desert. *Am. J. Physiol.* 123: 369-378, 1938.

3. Allen, T.E., Smith, D.P., Miller, D.K. Hemodynamic response to submaximal exercise after dehydration and rehydration in high school wrestlers. Med. Sci. Sport Exerc. 9(3): 159-163, 1977.

4. Armstrong, L.E., Costill, D.L., Fink, W.J. Influence of diuretic-induced dehydration on competitive running performance. Med. Sci. Sports Exerc. 17: 456-461, 1985.

5. Armstrong, L.E., Costill, D.L., Fink, W.J., Bassett, D., Hargreaves, M., Nishibata, I., King, D.S. Effects of dietary sodium on body and muscle potassium content during heat acclimation. Eur. J. Appl. Physiol. 54: 391-397, 1985.

6. Baker, E.M., Plough, I.C., Allen, T.H. Water requirements of men as related to salt intake. Am. J. Clin. Nutr. 12: 394-398, 1963.

7. Bothorel, B., Follenius, M., Gissinger, R., Candas, V. Physiological effects of dehydration and rehydration with water and acidic or neutral carbohydrate electrolyte solutions. Eur. J. Appl. Physiol. 60: 209-216, 1990.

8. Boulze, D., Montastruc, P., Cabanac, M. Water intake, pleasure and water temperature in humans. Physiol. Behav. 30: 97-102, 1983.

9. Brandenberger, G., Candas, V., Follenius, M., Kahn, J.M. The influence of the initial state of hydration on endocrine responses to exercise in the heat. Eur. J. Appl. Physiol. 58: 674-679, 1989.

10. Brandenberger, G. Candas, V., Follenius, M., Libert, J.P., Kahn, J.M. Vascular fluid shifts and endocrine responses to exercise in the heat. Eur. J. Appl. Physiol. 55: 123-129, 1986.

11. Brener, W., Hendrix, T.R., McHugh, P.R. Regulation of the gastric emptying of glucose. Gastroenterology. 85: 76-82, 1983.

12. Candas, V., Libert, J.P., Brandenberger, G., Sagot, J.C., Amoros, C., Kahn, J.M. Hydration during exercise: effects on thermal and cardiovascular adjustments. Eur. J. Appl. Physiol. 55: 113-122, 1986.

13. Carter, J.E. and C.V. Gisolfi. Fluid replacement during and after exercise in the heat. Med. Sci. Sports Exerc. 21(5): 532-539, 1989.

14. Chaplin, H., Mollison, P.L., Vetter, H. The body/venous hematocrit ratio: its constancy over a wide hematocrit range. J. Clin. Invest. 32:1309-1316, 1953.

15. Corrigan, D.L., Heinsman, K.M., Bauer, T.J. The effects of dehydration and rehydration on anaerobic exercise performance. Med. Sci. Sports Exerc. Abstract. 16: S112, 1984.

16. Costill, D.L., Branam, L., Eddy, D., Fink, W. Alterations in red cell volume following exercise and dehydration. J. Appl. Physiol. 37(6): 912-916, 1974.

17. Costill, D.L., Cote, R., Fink, W. Muscle water and electrolytes following varied levels of dehydration in man. J. Appl. Physiol. 40(1): 6-11, 1976.

18. Costill, D.L., Cote, R., Miller, E., Miller, T., Wynder, S. Water and electrolyte replacement during repeated days of work in the heat. Aviat. Space Environ. Med. 46(6): 795-800, 1975.

19. Costill, D.L. and W.J. Fink. Plasma volume changes following exercise and thermal dehydration. J. Appl. Physiol. 37)4): 521-525, 1974.

20. Costill, D.L. and B. Saltin. Changes in the ratio of venous to body hematocrit following dehydration. J. Appl. Physiol. 36(5): 608-610, 1974.

21. Costill, D.L. and B. Saltin. Factors limiting gastric emptying during rest and exercise. J. Appl. Physiol. 37(5): 679-683, 1974.

22. Costill, D.L. and K.E. Sparks. Rapid fluid replacement following thermal dehydration. J. Appl. Physiol. 34(3): 299-303, 1973.

23. Coyle, E.F., Costill, D.L., Fink, W.J., Hoopes, D.G. Gastric emptying rates for selected athletic drinks. Res. Q. 49: 119-124, 1978.

24. Craig, F.N. and E.G. Cummings. Dehydration and muscular work. J. Appl. Physiol. 21: 670-674, 1966.

25. Dill, D.B. and D.L. Costill. Calculation of percentage changes in volumes of blood, plasma, and red cells in dehydration. J. Appl. Physiol. 37(2): 247-248, 1974.

26. Elias, E., Gibson, G.J., Greenwood, L.F., Hunt, J.N., Tripp, H.J. The slowing of gastric emptying by monosaccarides and disaccarides in test meals. J. Physiol. 194: 317-326, 1968.

27. Engell, D. Interdependency of food and water intake in humans. *Appetite*. 10: 133-141, 1988.

28. Ferreira, R.M., Elliot, E.J., Watson, A.J.M., Brennan, E., Walker-Smither, J.A., Farthing, M.J.G. Dominant role of osmolality in the efficacy of glucose and glycine containing oral rehydration solutions: studies in a rat model of secretory diarrhoea. Acta Paediatr. 81: 46-50, 1992.

29. Fordtran, J.S. Stimulation of active and passive sodium absorption of sugars in the human jejunum. J. Clin. Invest. 55: 728-737, 1975.

30. Fortney, S.M., Wenger, C.B., Bove, J.R., Nadel, E.R. Effect of hyperosmolality on control of blood flow and sweating. J. Appl. Physiol.: Respirat. Environ. Exercise Physiol. 57(6): 1688-1695, 1984.

31. Francesconi, R.P., Sawka, M.N., Pandolf, K.B. Hypohydration and heat acclimation: plasma renin and aldosterone during exercise. J. Appl. Physiol.: Respirat. Environ. Exercise Physiol. 55(6): 1790-1794, 1983.

32. Francis, K.T. and R. MacGregor. Effect of exercise in the heat on plasma renin and aldosterone with either water or a potassium-rich electrolyte solution. Aviat. Space Environ. Med. 49: 461-465, 1978.

33. Gaebelein, C.,J. and L.C. Senay. Influence of exercise type, hydration, and heat on plasma volume shifts in men. J. Appl. Physiol.: Respirat. Environ. Exercise Physiol. 41(1): 119-123, 1980.

34. Ghishan, F.K. The transport of electrolytes in the gut and the use of oral rehydration solutions. Pediatr. Clin. North Am. 35: 35-51, 1988.

35. Gisolfi, C.V., Summers, R.W., Schedl, H.P., Bleiler, T.L., Oppliger, R.A. Human intestinal water absorption: direct vs. indirect measurements. Am. J. Physiol. 258 (Gastrointest. Liver Physiol. 21): G216-G222, 1990.

36. Gonzalez-Alonso, J., Heaps, C.L., Coyle, E.F. Rehydration after exercise with common beverages and water. Int. J. Sports Med. 13(5): 399-406, 1992.

37. Gore, C.J., Scroop, G.C., Marker, J.D., Catcheside, P.G. Plasma volume, osmolarity, total protein and electrolytes during treadmill running and cycle ergometer exercise. Eur. J. Appl. Physiol. 63: 302-310, 1992.

38. Greenleaf, J.E. Problem: thirst, drinking behavior, and involuntary dehydration. Med. Sci. Sports Exerc. 24 (6): 645-656, 1992.

39. Greenleaf, J.E., Convertino, V.A., Mangseth, G.R. Plasma volume during stress in man: osmolality and red cell volume. J. Appl. Physiol. 47: 1031-1038, 1979.

40. Guyton, A.C. *Textbook of medical physiology*. W.B. Saunders Co., Philadelphia, PA. 1986. pp. 382-435.

41. Harrison, M.H. Plasma volume changes during acute exposure to a high environmental temperature. J. Appl. Physiol. 37(1): 38-42, 1974.

42. Harrison, M.H., Edwards, R.J., Leitch, D.R. Effect of exercise and thermal stress on plasma volume. J. Appl. Physiol. 39(6): 925-931, 1975.

43. Hickey, M.S., Costill, D.L., Trappe, S.W. Drinking behavior and exercise-thermal stress: role of drink carbonation. Int. J. Sport Nutr. 4: 8-21, 1994.

44. Horstman, D.H., and S.M. Horvath. Cardiovascular and temperature regulatory changes during progressive dehydration and euhydration. J. Appl. Physiol. 33(4): 446-450, 1972.

45. Hubbard, R.W., Sandick, B.L., Matthew, W.T., Francesconi, R.P., Sampson, J.B., Durkot, M.J., Maller, O., Engell, D.B. Voluntary dehydration and alliesthesia for water. J. Appl. Physiol.: Respirat. Environ. Exercise Physiol. 57:868-875, 1984.

46. Hunt, J.N. The osmotic control of gastric emptying. Gastroenterology. 41: 49-51, 1961.

47. Hunt, J.B., Elliott, E.J., Fairclough, P.D., Clark, M.L., Farthing, M.J.G. Water and solute absorption from hypotonic glucose-electrolyte solutions in human jejunum. Gut. 33: 479-483, 1992.

48. Hunt, J.B., Thillainayagam, A.V., Salim, A.F.M., Carnaby, S., Elliott, E.J., Farthing, M.J.G. Water and solute absorption from a new hypotonic oral rehydration solution: evaluation in human and animal perfusion models. Gut. 33: 1652-1659, 1992.

49. Ivy, J.L., Katz, A.L., Cutler, C.L., Sherman, W.M., Coyle, E.F. Muscle glycogen synthesis after exercise: effect of time of carbohydrate ingestion. J. Appl. Physiol. 65: 2018-2023, 1988.

50. Jacobs, I. The effects of thermal dehydration on performance of the Wingate anaerobic test. Int. J. Sports Med. 1: 21-24, 1980.

51. Kirsch, K.A., vonAmeln, H., Wicke, H.J. Fluid control mechanisms after exercise dehydration. Eur. J. Appl. Physiol. 47: 191-196, 1981.

52. Kosunen, K.J., Pakarinen, A.J., Kuoppasalmi, K., Adlercreutz, H. Plasma renin activity, antiotensin II, and aldosterone during intense heat stress. J. Appl. Physiol. 41(3): 323-327, 1976.

53. Kozlowski, S. and B. Saltin. Effect of sweat loss on body fluids. J. Appl. Physiol. 19: 1119-1124, 1964.

54. Lambert, C.P., Costill, D.L., McConell, G.K., Benedict, M.A., Lambert, G.P., Robergs, R.A., Fink, W.J. Fluid replacement after dehydration: influence of beverage carbonation and carbohydrate content. Int. J. Sports Med. 13(4): 285-292, 1992.

55. Maughan, R.J. and J.B. Leiper. Sodium intake and post-exercise rehydration in man. Eur. J. Appl. Physiol. 71: 311-319, 1995.

56. Maughan, R.J., Leiper, J.B., Shirreffs, S.M. Restoration of fluid balance after exercise-induced dehydration: effects of food and fluid intake. Eur. J. Appl. Physiol. 73: 317-325, 1996.

57. Maughan, R.J., Fenn, C.E., Gleeson, M., Leiper, J.B. Metabolic and circulatory responses to the ingestion of glucose polymer and glucose-electrolyte solutions during exercise in man. Eur. J. Appl. Physiol. 56: 556-562, 1987.

58. Maughan, R.J., Owen, J.H., Shirreffs, S.M., Leiper, J.B. Post-exercise rehydration in man: effects of electrolyte addition to ingested fluids. Eur. J. Appl. Physiol. 69: 209-215, 1994.

59. McArthur, K.E., and M. Feldman. Gastric acid secretion, gastrin release, and gastric emptying in humans as affected by liquid meal temperature. Am J. Clin. Nutr. 49: 51-54, 1989.

60. Meyer, F., Bar-Or, O., Wilk, B. Children's perceptual responses to ingesting drinks of different compositions during and following exercise in the heat. Int. J. Sport Nutr. 5: 13-24, 1995.

61. Miescher, E., and S.M. Fortney. Responses to dehydration and rehydration during heat exposure in young and older men. Am. J. Physiol. 257 (Regulatory Integrative Comp. Physiol. 26): R1050-R1056, 1989.

62. Mitchell, J.B., Grandjean, P.W., Pizza, F.X., Starling, R.D., Holtz, R.W. The effect of volume ingested on rehydration and gastric emptying following exercise-induced dehydration. Med. Sci. Sports Exerc. 26(9): 1135-1143, 1994.

63. Montain, S.J. and E.F. Coyle. Influence of graded dehydration on hyperthermia and cardiovascular drift during exercise. J. Appl. Physiol. 73(4): 1340-1350, 1992.

64. Myhre, L.G. and S. Robinson. Fluid shifts during thermal stress with and without fluid replacement. J. Appl. Physiol.: Respirat. Environ. Exercise Physiol. 42(2): 252-256, 1977.

65. Nadel, E.R., Fortney, S.M., Wenger, C.B. Effect of hydration state on circulatory and thermal regulations. J. Appl. Physiol.: Respirat. Environ. Exercise Physiol. 49(4): 715-721, 1980.

66. Nadel, E.R., Mack, G.W., Nose, H. Influence of fluid replacement beverages on body fluid homeostasis during exercise and recovery. In: *Perspectives in Exercise Science and Sports Medicine, Vol. 3, Fluid Homeostasis during exercise,* C.V. Gisolfi and D.R. Lamb (Eds.). Carmel, IN: Benchmark Press, 1990, pp. 181-205.

67. Neufer, P.D., Young, A.J., Sawka, M.N. Gastric emptying during exercise: effects of heat stress and hypohydration. Eur. J. Appl. Physiol. 58: 433-439, 1989.

68. Nielsen, B., Sjogaard, G., Ugelvig, J., Knudsen, B., Dohlmann, B. Fluid balance in exercise dehydration and rehydration with different glucose-electrolyte drinks. Eur. J. Appl. Physiol. 55: 318-323, 1986.

69. Noakes, T.D. The hyponatremia of exercise. Int. J. Sport Nutr. 2: 205-228, 1992.

70. Nose, H., Mack, G.W., Shi, X., Nadel, E.R. Role of osmolality and plasma volume during rehydration in humans. J. Appl. Physiol. 65(1): 325-331, 1988a.

71. Nose, H., Mack, G.W., Shi, X., Nadel, E.R. Involvement of sodium retention hormones during rehydration in humans. J. Appl. Physiol. 65(1): 332-336, 1988b.

72. Phillips, P.A., Rolls, R.J., Ledingham, J.G.G., Forsling, M.L., Morton, J.J., Crowe, M.J., Wollner, L. Reduced thirst after water deprivation in healthy elderly men. N. Engl. J. Med. 311: 753-759, 1984.

73. Pitts, G.C., Johnson, R.E., Consolazio, F.C. Work in the heat as affected by intake of water, salt and glucose. Am. J. Phusiol. 142: 253-259, 1944.

74. Powell, D.W. Intestinal water and electrolytre transport. In: Johnson, L.R. (ed.) Physiology of the gastrointestinal tract. Raven Press, New York. 1987. pp.

75. Ravich, W.J., Bayless, T.M., Thomas, M. Fructose: incomplete intestinal absorption in humans. Gastroenterology. 84: 26-29, 1983.

76. Rehrer, N.J. Limits to fluid availability during exercise. De Vrieseborsch, Haarlem, 1990.

77. Rehrer, N.J., Beckers, E., Brouns, F., Ten Hoor, F., Saris, W.H.M. Exercise and training effects on gastric emptying of carbohydrate beverages. Med. Sci. Sports Exerc. 21(5): 540-549, 1989.

78. Rocker, L., Kirsch, K.A., Heyduck, B., Altenkirch, H.U. Influence of prolonged physical exercise on plasma volume, plasma proteins, electrolytes, and fluid-regulating hormones. Int. J. Sports Med., 10(4); 270-274, 1989.

79. Saunders, D.R., and J.K. Sillery. Absorption of carbohydrate-electrolyte solutions in rat duodenojejunum. Implications for the composition of oral electrolyte solutions in man. Dig. Dis. Sci. 30(2): 154-160, 1985.

80. Sawka, M.N., Young, A.J., Cadarette, B.S., Levine, L., Pandolf, K.B. Influence of heat stress and acclimation on maximal aerobic power. Eur. J. Appl. Physiol. 53: 294-298, 1985a.

81. Sawka, M.N., Young, A.J., Francesconi, R.P., Muza, S.R., Pandolf, K.B. Thermoregulatory and blood responses during exercise at graded hypohydration levels. J. Appl. Physiol. 59(5): 1394-1401, 1985b.

82. Senay, L.C. and M.L. Christensen. Changes in blood plasma during progressive dehydration. J. Appl. Physiol. 20(6): 1136-1140, 1965.

83. Senay, L.C., Rogers, G., Jooste, P. Changes in blood plasma during progressive treadmill and cycle exercise. J. Appl. Physiol. 49: 59-65, 1980.

84. Shafer, R.B., Levine, A.S., Marlette, J.M., Morley, J.E. Do calories, osmolality, or calcium determine gastric emptying? Am. J. Physiol. 248: R479-R483, 1985.

85. Shi, X., Summers, W., Schedl, H.P., Chang, R.T., Lambert, G.P., Gisolfi, C.V. Effects of solution osmolality on absorption of select fluid replacement solutions in human duodenojejunum. J. Appl. Physiol. 77(3): 1178-1184, 1994.

86. Shirreffs, S.M., Taylor, A.J., Leiper, J.B., Maughan, R.J. Post-exercise rehydration in man: effects of volume consumed and drink sodium content. Med. Sci. Sports Exerc. 28(10): 1260-1271, 1996.

87. Singh, M.V., Rawal, S.B., Pichan, G., Tyagi, A.K., Gupta, A.K. Changes in plasma volume during hypohydration and rehydration in subjects from the tropics. Eur. J. Appl. Physiol. 61: 258-262, 1990.

88. Sproles, C.B., Smith, D.P., Byrd, R.J., Allen, T.E. Circulatory responses to submaximal exercise after dehydration and rehydration. *J. Sports Med.* 16: 98-105, 1976.

89. Sun, W.M., Houghton, L.A., Read, N.W., Grundy, D.G., Johnson, A.G. Effect of meal temperature on gastric emptying of liquids in man. *Gut.* 29: 302-305, 1988.

90. Szlyk, P.C., Sils, I.V., Francesconi, R.P., Hubbard, R.W., Armstrong, L.E. Effects of water temperature and flavoring on voluntary dehydration in men. Physiol. Behav. 45: 639-647, 1989.

91. Szlyk, P.C., Sils, I.V., Francesconi, R.P., Hubbard, R.W. Patterns of human drinking: effects of exercise, water temperature, and food consumption. Aviat. Space Environ. Med. 61: 43-48, 1990.

92. Takamata, A., Mack, G.W., Gillen, C.M., Nadel, E.R. Sodium appetite, thirst, and body fluid regulation in humans during rehydration without sodium replacement. Am. J. Physiol. 266: R1493-R1502, 1994.

93. Torranin, C., Smith, D.P., Byrd, R.J. The effect of acute thermal dehydration and rapid rehydration on isometric and isotonic endurance. J. Sports Med. 19: 1-9, 1979.

94. VanBeaumont, W., Greenleaf, J.E., Juhos, L. Disproportional changes in hematocrit, plasma volume, and proteins during exercise and bed rest. J. Appl. Physiol. 33(1): 55-61, 1972.

95. Wapnir, R.A. and F. Lifshitz. Osmolality and solute concentration - their relationship with oral hydration solution effectiveness: an experimental assessment. Pediatr. Res. 19: 894-898, 1985.

96. Webster, S.F., Rutt, R.A., Weltman, A. Effects of typical dehydration practices on performance. Med. Sci. Sport. Exerc. (Abst.) 20:S 20, 1988.