The effect of sodium and carbohydrate in a rehydration beverage when consumed as a meal on subsequent exercise performance

Todd M. Weber
Iowa State University

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The effect of sodium and carbohydrate in a rehydration beverage when consumed as a meal on subsequent exercise performance

by

Todd M. Weber

A thesis submitted to the graduate faculty
in partial fulfillment of the requirements for the degree of
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Program of Study Committee:
Rick L. Sharp, Major Professor
Douglas S. King
Donald C. Beitz
Neil M. Johannsen

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ABSTRACT

The purpose of this investigation was to assess whether a food (chicken noodle soup) consumed during the initial stages of recovery from exercise in the heat improves subsequent temperature regulation and exercise performance by improving fluid retention and restoring plasma volume close to euhydrated levels. Ten subjects were studied during 2 h of rehydration after a 2.7% body mass loss. In a randomized crossover design, subjects rehydrated with chicken noodle soup (Soup: 161.0 mmol/l Na\(^+\), 5.3 mmol/l K\(^+\)) or sugar-free Kool Aid® (14.4 mmol/l Na\(^+\), 1.6 mmol/l K\(^+\)). Subjects ingested 175 ml at the start of rehydration and 20 min later; H\(_2\)O was given every 20 min thereafter for a total volume equal to body mass loss during dehydration. At the end of the rehydration period, plasma volume and fluid balance were similar between treatments, although urine volume was greater in the Placebo trial (P = 0.06). Plasma osmolality (P < 0.02) and plasma sodium (P < 0.02) were significantly higher during rehydration in the Soup trial. After rehydration, subjects performed 30 min of steady state exercise (SSE) at 70% VO\(_{2\text{peak}}\) followed by a time trial (TT) (30 min @ 70% VO\(_{2\text{peak}}\)) with no further fluid intake. Neither beverage conferred cardiovascular or temperature regulation benefits during SSE. There was a trend for improved performance (P = 0.127) with soup ingestion (Soup 30.6 ± 0.9 min; Placebo 32.2 ± 1.5 min). Future research is needed to determine whether ad libitum rehydration during the rehydration period, SSE, and TT provides benefits in temperature regulation and exercise performance.
CHAPTER 1. INTRODUCTION

In hot and humid environments, sweating is the predominate means of dissipating heat. Sweat rates of 0.5 to 2.0 l/hr (54) are common, whereas sweat rates of up to 3 l/hr (52) have been observed in extreme environments. Fluid balance is in constant flux and may be thought of as a continuum between dehydration and euhydration. There are various grades of dehydration, with greater dehydration resulting in more severe physiological consequences. Dehydration of as little as 1-2% of body mass results in many detrimental cardiovascular, thermoregulatory, and metabolic changes, along with concomitant decreases in physical work capacity and exercise performance.

Replacing fluid losses during exercise minimizes the consequences of dehydration by maintaining heart rate, sweat rate, core body temperature, and other physiological responses closer to euhydrated levels. However, humans do not fully rehydrate while drinking ad libitum during and after exercise despite several homeostatic mechanisms to maintain fluid balance and stimulate thirst. The failure to rehydrate despite access to fluids is a phenomenon known as “involuntary dehydration” (25). Several professional organizations have developed fluid replacement guidelines to prevent dehydration and reduce the risk of heat illness during and after exercise.

Water intake is adequate when used as a hydration beverage if the time before the next physical activity bout is sufficient (8-24 h) (29) and water is consumed with meals. However, if the recovery period is relatively short (< 3 h) sodium should be included in the drink. Research spanning the past 40 years has attempted to discover an optimal combination of nutrients to enable a rehydration beverage to quickly re-establish fluid balance post-exercise. Early research suggested that a carbohydrate electrolyte beverage was
superior to tap water in re-establishing fluid balance (13). More recent evidence suggests that sodium is the key constituent in a rehydration beverage. The inclusion of sodium in a rehydration beverage restores plasma volume and fluid balance more rapidly than water or beverages containing other combinations of electrolytes (36, 46). Potassium also effectively restores fluid balance, although this effect is delayed when matched with sodium as the primary electrolyte. Drinks containing sodium tend to reduce urinary water losses and stimulate thirst during ad libitum rehydration, thereby enhancing fluid restoration to the greatest extent.

During rehydration, the volume of beverage consumed is also an important consideration. The interaction between the volume of beverage consumed and sodium content in a rehydration beverage has been studied extensively. A regression analysis of sodium content and drink volume (59) showed that these factors account for 66% of the variance in body water recovery following dehydration. Sharp (59) speculated that other variables including temperature of ingested fluid, the presence of other electrolytes (potassium, calcium, and magnesium) and other nutrients (carbohydrate and protein) may contribute to the recovery of fluid balance and should be considered when formulating a recovery beverage.

Whole foods can be equally as effective as a carbohydrate electrolyte beverage in rapidly restoring fluid balance provided the electrolyte content of that food is high (35, 51). Previous work in our laboratory (51) demonstrated that consuming either chicken noodle soup or chicken broth at the beginning of rehydration returned plasma volume closer to euhydrated levels than a carbohydrate electrolyte beverage or water.
It is unknown whether this rapid fluid replacement confers cardiovascular, temperature regulation, metabolic, or performance benefits during a subsequent exercise bout. Many athletes and physical laborers perform several bouts of physical activity throughout the day. Replacing fluid and electrolyte losses prior to their next physical activity bout is of utmost importance to their health and occupational success. The purpose of this investigation was to determine whether the improved fluid balance and carbohydrate availability after consuming soup as a rehydration beverage confers temperature regulation or performance benefits. The effect of carbohydrate availability on subsequent exercise performance will be addressed in a separate paper.
CHAPTER 2. REVIEW OF LITERATURE

The human body is composed of nearly 60% water (26). Approximately 60% of this fluid is located within the intracellular fluid compartment (ICF) whereas roughly 30% is contained within the extracellular fluid compartment (ECF). The extracellular compartment can be further divided into the space between the cells (interstitial space) in which 75% of the fluid is contained while the cardiovascular system contains the remainder of the extracellular water. Each fluid compartment contains electrolytes, the composition and concentration of which is profoundly important in maintaining fluid balance and osmolality between body compartments. The ability of the body to redistribute fluid between these compartments is essential in maintaining homeostasis.

Physical exercise and heat stress lead to fluid and electrolyte imbalances that must be corrected. A fluid loss of 1-2% of body mass decreases physical work capacity (3, 8). In a study by Armstrong et al. (3), competitive runners completed distances of 1500, 5000, and 10000 meters while dehydrated by 1.9, 1.6, and 2.1% respectively.

Table 1. The electrolyte distribution among intracellular and extracellular compartments of the body (26).

<table>
<thead>
<tr>
<th></th>
<th>ECF (mEq/L)</th>
<th>ICF (mEq/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Na⁺</td>
<td>142</td>
<td>10</td>
</tr>
<tr>
<td>K⁺</td>
<td>4</td>
<td>140</td>
</tr>
<tr>
<td>Ca²⁺</td>
<td>5</td>
<td>&lt;1</td>
</tr>
<tr>
<td>Cl⁻</td>
<td>103</td>
<td>4</td>
</tr>
<tr>
<td>Mg²⁺</td>
<td>3</td>
<td>58</td>
</tr>
<tr>
<td>SO₄²⁻</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Proteins</td>
<td>5</td>
<td>40</td>
</tr>
</tbody>
</table>
Run times increased by 0.16, 1.31, and 2.62 min (3.4, 7.2, and 6.7%), respectively, and were strongly correlated with changes in body weight. As Armstrong demonstrated, prolonged aerobic exercise is more likely to be negatively impacted by dehydration than short-term anaerobic exercise.

The more pronounced the water deficit, the larger the reduction in physical work capacity with much larger decrements observed in hot as compared with temperate environments (24, 47). Performance decrements due to dehydration are manifested by increases in core temperature (11, 27, 40), heart rate (27, 40), ratings of perceived exertion (54), glycogen utilization (18, 28), and lactate production (18, 28) as well as reductions in stroke volume (27), cardiac output (27, 40), blood to the exercising muscle (18, 19), free fatty acid oxidation (18), and reduced cognitive/mental performance (29).

2.1 Heat Strain

During maximal exercise, heat production in active muscle may be 100 times that of inactive muscle (6). Roughly 60-65% of the heat produced by active muscle is dissipated directly to the surrounding environment (18) whereas the remainder is transferred to the vascular system and body core. In ambient temperatures, heat is dissipated through radiation, conduction, convection, and evaporation. As exercise intensity and environmental temperature increase, so does the dependence on evaporative heat loss (56). When the environmental temperature exceeds skin temperature, the body gains heat by radiation, conduction, and convection. Therefore, evaporation (sweating) is the only mechanism available for heat dissipation (6).
Sweat rate can vary considerably (0.5 to 2.0 l/h) (54) between individuals, leading to differences in thermoregulatory capacity and heat tolerance in hot environments. Body water losses through evaporative cooling augments dehydration and amplifies impairments in cardiovascular function.

During submaximal exercise with little heat strain, hypohydration elicits an increase in heart rate and decrease in stroke volume, but usually no change in cardiac output relative to euhydration levels. Heat stress and hypohydration, however, have additive effects on increasing cardiovascular strain (21).

The combination of exercise with heat strain results in a competition between the central and peripheral circulation for a limited blood volume (53). Dehydration aggravates this competition by reducing blood volume and increasing cardiovascular strain (22). As body temperature increases during exercise, skin capacitance increases and blood is rerouted to the periphery thereby decreasing central venous pressure and venous return. Heart rate cannot compensate for the decline in stroke volume necessary to maintain cardiac output during hypohydration (3-4% body mass) and heat strain.

Cardiovascular function is normalized with rehydration, although the degree of rehydration required remains unclear. Previous studies indicate a fluid restoration of 62-81% is necessary to restore cardiovascular function. Costill and Sparks (13) found that heart rate was normalized with a 62% replacement of body weight lost, despite an incomplete plasma volume restoration. During an exercise bout following dehydration, Nielsen et al. (46) demonstrated that heart rates were elevated after a fluid regimen that produced ~75% restoration of initial body mass lost and in some cases a positive plasma volume. Montain and Coyle (40) observed that a fluid balance restoration of ~81% of body mass lost was
essential to restore stroke volume and heart rate closer to euhydration levels. Regardless of the protocol used, rehydration can restore cardiovascular function similar to euhydrated levels.

2.2 Hyperthermia

Another hallmark of dehydration is an exaggerated elevation in body temperature at submaximal exercise intensities. Elevations in body temperature may be a contributing factor to limiting endurance performance in hot environments and critically high body temperatures have been shown to cause termination of exercise altogether (23). Core temperature tends to increase in proportion to the magnitude of body water loss during exercise-heat stress (1, 40, 57). The upper limit for core temperatures that can be tolerated during endurance exercise is reduced in the hypohydrated state and is due in part to a decrease in sweat rate as rectal temperature increases (57). In untrained subjects, core temperature at exhaustion from heat strain has been clearly shown to occur over a range of 38-40°C (33, 41, 44) and to be independent of exercise intensity (41). Previous studies testing the effects of hyperthermia on fatigue have demonstrated that fatigue was not associated with any reduction in cardiac output, exercising leg blood flow, leg substrate availability and utilization, or accumulation of lactate, potassium, or other proposed “fatigue” substances (23, 44, 45). Furthermore, muscle glycogen levels at the point of fatigue have been shown to be quite high in these conditions (>300 mmol/kg dry wt) (17, 19, 23, 45). Regardless of training status, attainment of a critically high body temperature will result in fatigue. Gonzalez-Alonso et al. (23) observed the effect initial body temperature has on exercise time to exhaustion in the heat (40°C, 19% RH). Initial body temperature was
manipulated by immersing cyclists in a water bath until reaching esophageal temperatures of 35.9 ± 0.2, 37.4 ± 0.1, and 38.2 ± 0.1 °C for pre-cooling, control, and pre-heating conditions respectively. On each occasion, the rate of heat storage, body mass loss, and level of dehydration were similar. However, during a performance ride time to exhaustion was significantly different (63 ± 3, 46 ± 3, and 28 ± 2 min) and inversely related to the starting body temperature.

Montain and Coyle (40) investigated the effect graded levels of dehydration have on hyperthermia, heart rate, and stroke volume. On different occasions, endurance trained cyclists ingested either no fluid or a small, moderate, or large amount of fluid while exercising in a warm environment (Table 2). Montain and Coyle were able to clearly demonstrate that hyperthermia is directly related to the amount of dehydration accumulated.

**Figure 1.** The Effect of Fluid Intake on Core Temperature during 120 min Exercise (40) *
* Significantly lower than no fluid. † Significantly lower than small volume of fluid. § Significantly lower than moderate volume of fluid. Fluid Volumes are listed in Table 2.
during moderate-intensity exercise in a warm environment with no fluid showing the greatest hyperthermic response and large fluid showing the lowest increase in core temperature (Figure 1).

**Table 2.** Percentage Change in Body Mass, Sweat Rate, Volume of Fluid Ingested, and Percentage of Sweat Loss Replaced during 120 min of exercise (40).

<table>
<thead>
<tr>
<th>Trial</th>
<th>% Change in Body Mass</th>
<th>Sweat Rate (l/h)</th>
<th>Volume of Fluid Ingested (ml)</th>
<th>% Sweat Loss Replaced</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Fluid</td>
<td>4.2 ± 0.1</td>
<td>1.32 ± 0.08</td>
<td>0 ± 0</td>
<td>0.0 ± 0</td>
</tr>
<tr>
<td>Small Fluid</td>
<td>3.4 ± 0.1</td>
<td>1.35 ± 0.06</td>
<td>583 ± 27</td>
<td>20.2 ± 0.9</td>
</tr>
<tr>
<td>Medium Fluid</td>
<td>2.3 ± 0.1</td>
<td>1.34 ± 0.05</td>
<td>1,423 ± 48</td>
<td>48.2 ± 1.3</td>
</tr>
<tr>
<td>Large Fluid</td>
<td>1.1 ± 0.1</td>
<td>1.39 ± 0.05</td>
<td>2,380 ± 93</td>
<td>80.5 ± 0.7</td>
</tr>
</tbody>
</table>

The large fluid trial in the Montain and Coyle study resulted in an average body mass loss of 1.1%. Core temperature continued to slowly rise at the end of the 120 minute observation period, and it is difficult to determine whether this rise in core temperature would be significantly different from a euhydrated condition, which was not used in this study. In a previous study by Hamilton et al. (27), subjects completely replaced a water deficit of 2.9% of initial body mass and rectal temperature leveled off during a subsequent exercise bout from 60 to 120 minutes compared with a no fluid condition (38.3 ± 0.12; 38.9 ± 0.15°C). However, it is difficult to compare these studies due to differences in environmental conditions; 33°C in the Montain and Coyle study and 22°C in the Hamilton et al study. No minimal standard of fluid replacement has been established to prevent hyperthermia; however, evidence suggests that maintaining a body mass loss of less than 1% should attenuate hyperthermia.
2.3 Involuntary Dehydration

Despite several homeostatic mechanisms designed to maintain fluid balance, humans fail to replace fluid lost in sweat and become “involuntary dehydrated” during prolonged endurance exercise (25). Thirst, also called “dipsogenic drive”, provides a poor index of body water requirements and ad libitum drinking results in incomplete fluid replacement. The failure to rehydrate despite access to fluids is a phenomenon known as “involuntary dehydration” (15, 19).

Dipsogenic drive is governed by a multitude of factors including mouth dryness, oropharyngeal metering, gastric distention, extracellular fluid volume, and plasma osmolality. In turn these factors are responsible for stimulating changes in many fluid regulatory hormones including angiotensin, aldosterone, and arginine-vasopressin. However, the physiological signals that govern fluid replacement to the greatest extent are plasma osmolality and extracellular fluid volume (47).

Elevated plasma osmolality and sodium concentration and decreased blood volume activate systems that defend fluid balance and stimulate thirst. In healthy, euhydrated adults, plasma osmolality range from 280 - 295 mosmol/kgH$_2$O and plasma sodium fluctuates between 136.0 – 142.0 mmol/l. When the plasma sodium concentration increases only 2 mmol/l above normal, the thirst mechanism is activated, causing a desire to drink (26). A consequence of dehydration is increased extracellular fluid osmolality. Increased extracellular osmolality acts to stimulate the release of arginine vasopressin from the posterior pituitary resulting in increased reabsorption of water but not electrolytes from the kidneys. The additional water reabsorbed by the kidneys assists in normalizing plasma
osmolality by diluting the extracellular fluid pool and bringing plasma osmolality back into typical range.

The renin-angiotensin system is activated when a decline in blood pressure (blood volume) is recognized by the kidneys. Through a series of steps (renin, angiotensinogen, angiotensin I, angiotensin II) angiotensin II is formed. Angiotensin II acts to promote sodium and water reabsorption in the kidney and also stimulates aldosterone secretion. In turn, aldosterone acts on the kidney to further increase sodium reabsorption and thus promotes fluid retention.

Nose and colleagues (48) demonstrated that ingestion of water after exercise results in a decrease in serum sodium concentration and plasma osmolality. Both of these factors diminish the drive to drink, resulting in a delayed or incomplete fluid restoration. After losing 2.3% of initial body mass, subjects in the Nose et al. study drank ad libitum while ingesting either placebo (sucrose) or 0.45 g sodium capsules per 100 ml water (77 mmol/l). In the placebo trial, sodium concentration ([Na\(^+\)]) and plasma osmolality (P\(_{osm}\)) returned to baseline at 10 and 30 min respectively. [Na\(^+\)] and P\(_{osm}\) remained significantly elevated in the sodium trial throughout the three hour observation period. Despite the differences in [Na\(^+\)] and P\(_{osm}\) between trials, fluid intake during the first 60 min of rehydration was identical. The impact of a higher [Na\(^+\)] and P\(_{osm}\) in the sodium trial was unapparent until 120 min into the rehydration period when net fluid gain became significantly greater and remained so throughout the remainder of the study. Cumulative fluid intake became significantly greater by 180 min as well.

Plasma volume restoration in the sodium trial became significantly greater at 30 min and remained greater throughout the rehydration period. By 120 min, plasma volume was
restored by ~80% in the placebo trial and over 100% in the sodium trial. Nose et al suggested that the plasma volume restoration of ~80% in the placebo trial at 120 min was sufficient to diminish the volume dependent dipsogenic drive and thus drinking tapered off. The volume stimulus was absent in the sodium trial after 60 min. However, both [Na+] and P\text{osm} remained elevated in the sodium trial thereby maintaining the osmotic stimulus to drink.

Subjects in the sodium trial retained 71% of the fluid ingested compared with only 51% in the placebo trial. Nose et al were able to demonstrate the importance of sodium in maintaining the osmotic drive to drink during ad libitum rehydration and its ability to improve fluid balance. In an adjacent study, Nose et al. (47) determined that the delayed rehydration seen in the placebo trial appeared to be the result of water and sodium lost through the urine due to reduced plasma renin activity and aldosterone concentration (47). The inclusion of sodium in a rehydration beverage prevents the drop in these fluid regulatory hormones and enhances the rehydration process.

Beverage palatability must also be considered when formulating a rehydration beverage. Wemple et al. (64) examined the effect a beverage containing sodium had on thirst during ad libitum rehydration after intense exercise in a warm environment. After losing 3% of initial body mass, subjects were followed for three hrs during which time they were allowed to rehydrate ad libitum with one of three beverages; (a) flavored and sweetened (aspartame) water, (b) 6% sucrose with 25 mmol/l sodium or (c) 6% sucrose with 50 mmol/l sodium. Net fluid gain during the three hours was 91%, 130%, and 105% respectively, which conflicts with previous results (34). Using a fixed fluid administration of 1.5 times body mass lost, Maughan and Leiper (34) observed subjects for 5.5 hours after consuming equal amounts of a 2, 26, 52, or 100 mmol/l sodium solution. Subjects consuming 52 and
100 mmol/l solutions were in a positive fluid balance from 3.5 hrs on whereas the trials in which they consumed 2 and 26 mmol/l solutions subjects were in a negative fluid balance at 1.5 and 3.5 hours respectively and continued to be so through the remainder of the study period.

The incongruent findings observed between the two studies were most likely the result of differences in the volume of fluid consumed (123%, 163%, and 133%) in the Wemple et al study. Evidence from Nose et al (48) would have suggested that the beverage containing 50 mmol/l sodium would have been consumed in the largest quantity due to its ability to elevate plasma sodium and stimulate thirst to the greatest extent. However, beverage palatability seemed to have played a role in the Wemple et al study during ad libitum drinking and thus overall fluid balance was different due to the volume of fluid consumed rather than sodium concentration of the respective drinks.

2.4 Recommendations for Exercise and Fluid Replacement

Despite several homeostatic mechanisms designed to maintain fluid balance, humans fail to replace enough of the fluid lost in sweat to stay properly hydrated. Several organizations, including the Institute of Medicine and the American College of Sports Medicine (ACSM) and have put forth guidelines for fluid replacement and maintenance of euhydration. The Institute of Medicine has established hydration guidelines for the general public during day to day activities. On the other hand, fluid replacement guidelines established by the American College of Sports Medicine are more geared towards exercising individuals as well as people engaged in strenuous physical activity as part of their
occupations. In general, ACSM fluid replacement guidelines are broken into pre-exercise, exercise, and post-exercise.

2.4.1 Hydration before Exercise

The goal of hydration before exercise is to start the physical activity bout euhydrated. Measuring body weight is the quickest, simplest, and most accurate technique for assessing body fluid balance. Individuals should attempt to maintain body weight within 1% of the normal baseline from day-to-day (2). A valid baseline value can be obtained by averaging the body weight taken on three consecutive mornings (10). However, in many field settings a scale is not available and other methods must be employed.

Monitoring urine color is another practical technique used in many field settings to assess hydration status. The American College of Sports Medicine recommends slowly consuming beverages (for example, ~5-7 ml/kg body weight) at least 4 hours before exercise (54). ACSM emphasizes consuming fluids slowly because when large quantities of fluid are rapidly consumed urine color loses its reliability as an indicator of hydration. If beverages are consumed slowly, a light colored urine signifies euhydration. Failure to produce urine or urine that is dark and highly concentrated, should be a signal to ingest additional fluids (for example, another ~3-5 ml/kg) about 2 hours before the event (54).

In addition to consuming adequate fluids, beverages with sodium (20-50 mmol/l) and/or small amounts of salted snacks or sodium containing foods at meals will help to stimulate thirst and retain the ingested fluid (35, 51, 61).
2.4.2 Hydration during Exercise

The goal of drinking during exercise is to prevent a body mass loss from rising above 2% while also preventing electrolyte imbalances (54). The amount and rate of fluid replacement depends on an array of items including large variations in individual sweating rate, exercise duration, and opportunities to drink (54). Moreover, general recommendations for fluid intake are made more complex by an interaction of factors including different exercise tasks (metabolic requirements, duration, clothing, and equipment), weather conditions, and other factors (genetic predisposition, heat acclimatization and training status) (54). To further demonstrate the difficulty in providing fluid replacement guidelines during exercise, Montain (39) has provided predicted sweating rates for individuals of different sizes running at various speeds. The sweating rates provided by Montain range from ~0.4 l/h to ~1.8 l/h for individuals weighing 50-90 kg running at speeds of 8.5 to 15 km/h in cool/temperate (18°C) and warm (28°C) weather.

The composition of the fluids consumed during exercise is also important. Sweat electrolyte losses depend on the total sweat losses and sweat electrolyte concentrations. Sweat sodium concentration averages ~35 mmol/l (range 10-70 mmol/l) and varies depending upon genetic predisposition, diet, sweating rate, and heat acclimatization state (7). Other electrolytes, K⁺, Ca²⁺, Mg⁺, and Cl⁻, are found in sweat in lesser amounts (54). Rehydration beverages should contain a similar electrolyte content to that lost in sweat. The Institute of Medicine recommends the composition of “sports beverages” to be ~20-30 mmol/l sodium, ~2-5 mmol/l potassium, and ~5-10% carbohydrate (29). The inclusion of sodium and potassium help replace sweat electrolyte losses, while sodium also helps to stimulate thirst, and carbohydrate provides energy (54).
The large differences in sweat rate within an individual due to changes in environmental conditions warrants the recommendation that individuals monitor their body weights before and after exercise bouts as well as monitoring during the season and in relation to the weather in order to prepare a customized fluid replacement program for each person’s unique fluid needs (54).

### 2.4.4 Hydration Post-Exercise

After exercise, the goal of hydration is to fully replace fluid and electrolyte deficits. The blueprint for rehydration is a function of the speed of rehydration needed and the magnitude of electrolyte losses (54). If recovery time is sufficient (8-24 h), fluid and electrolyte imbalances will be restored by resuming a normal meal pattern (which contains adequate amounts of electrolytes) and water (29). However, if recovery time is limited (<12 h) more aggressive rehydration methods are warranted (34, 33, 61).

### 2.5 Rapid Rehydration

Water is not the ideal rehydration beverage when a rapid restoration of plasma volume is desired. In one of the first studies to test the effectiveness of water as a rehydration beverage, Costill and Sparks (13) dehydrated subjects by 4% of initial body mass by way of passive heating. During the next three hours subjects rehydrated by ingesting either demineralized water or a glucose electrolyte solution equal to their body mass lost. Both beverages restored fluid balance to similar levels (74%) at the end of three hours although this was below euhydrated levels.
Ingestion of water caused a large fall in serum osmolality, resulting in an increased diuresis and incomplete plasma volume restoration. On the other hand, when a glucose-electrolyte solution was ingested, urine output was less and plasma volume was restored more closely to pre-dehydration levels by the end of the three hour observation period.

### 2.5.1 Beverage Content

Costill and Sparks (13) demonstrated that a glucose-electrolyte solution was more successful in restoring plasma volume closer to euhydration than water alone. This effect was largely due to a decrease in urine output. The mechanisms behind the improved restoration of plasma volume and reduction in urine production could not be identified because the glucose-electrolyte solution contained several different electrolytes and carbohydrate.

In a later study by Lambert et al. (32), it was determined that electrolytes rather than carbohydrate were the driving force behind the more effective plasma volume restoration observed by Costill and Sparks. Lambert et al (32) dehydrated subjects by 4% of initial body mass before following them during a 4 hour rehydration period. The four beverages used in the study contained approximately the same electrolyte content whereas two of the beverages contained 10 grams of carbohydrate per 100 ml consumed. The addition of carbohydrate did not provide an advantage in fluid balance compared to the beverages without carbohydrate. When the electrolyte content of drinks is similar it appears the addition of carbohydrate does not improve the restoration of plasma volume.

Gonzalez-Alonso et al. (20) demonstrated that the electrolyte content necessary to improve restoration of fluid balance is modest. A dilute carbohydrate-electrolyte solution
(60 g/l CHO, 20 mmol/l Na+, and 3 mmol/l K+) was more effective in promoting post exercise rehydration than either water or a low electrolyte diet cola. The disparity in fluid balance restoration between the drinks was again primarily the result of differences in urine output.

To determine which electrolytes are most effective in restoring fluid balance Nielsen et al. (46) dehydrated subjects by 3% of initial body mass before providing one of four solutions: a control (C-drink), a high potassium (K-drink), a high sodium (Na-drink), or a high sugar (S-drink). After 2 hours of rehydration, plasma volume was above the initial resting value with all 4 drinks; however, the plasma volumes in the Na-drink (+14%) and C-drink (+9%) trials were significantly higher.

Maughan et al. (36) sought to verify the results of Nielsen et al. by dehydrating subjects by 2% of initial body mass before having them ingest one of four beverages: drink A (90 mmol/l glucose solution); drink B (60 mmol/l Na+); Drink C (25 mmol/l K+); and drink D (90 mmol/l glucose, 60 mmol/l Na+, and 25 mmol/l K+).

Plasma volume increased to a similar extent after the rehydration period regardless of treatment. However, cumulative urine output was greater after the ingestion of the glucose only solution which resulted in a net negative fluid balance the morning after the trial. There were no differences in urine output or net fluid balance at anytime between the three electrolyte containing solutions.

An interesting finding in this study was that the drink containing only potassium resulted in a delayed restoration of plasma volume (2 hours) compared to all other beverages. However, after two hours, all beverages restored plasma volume to a similar extent. Potassium appeared to be as effective as sodium in restoring fluid balance following exercise
induced dehydration after two hours. However, there was no additive effect of having both potassium and sodium in a drink.

2.5.2 Role of Sodium

The ability of sodium to rapidly increase plasma volume and fluid balance during rehydration makes it a key constituent in rapid rehydration (36, 46). Potassium, the main intracellular cation, aids in the rehydration process, but it seems that sodium is more effective in rapid rehydration (36, 46).

The replacement of body water lost through exercise induced dehydration with water, if sufficiently large, may lead to hemodilution. If plasma osmolality falls far enough, the drive to drink is diminished (46). When sodium ingestion during rehydration is sufficient, a more rapid fluid absorption occurs, the drive to drink is maintained, and the loss of body water through urinary output are minimized (46, 47) by maintaining vasopressin levels. However, excessive sodium intake may result in natiuresis and an increased urine output (61).

Maughan and Lieper (34) examined the effects of systematic variations in the sodium content of rehydration beverages and their effectiveness in restoring fluid balance to determine the minimal amount of sodium needed to promote rapid rehydration and reduce urinary output.

On each of four occasions subjects dehydrated by ~1.9% of their initial body mass before drinking the equivalent of 1.5 times their body mass lost during a 30 min rehydration period. The sodium content of drinks in trials A, B, C, and D were 2, 26, 52, and 100 mmol/l, respectively. In this study urine volume was inversely related to the sodium content
of the drink and by the end of the observation period subjects were in a negative fluid
balance on trials A and B whereas subjects were approximately euhydrated in trials C and D.
It appears that at least 50 mmol/l sodium is needed in a rehydration beverage if ingested in a
bolus of 150% of body mass lost immediately post exercise to promote maximum retention
of ingested fluid.

In another study measuring the interaction between sodium content and fluid volume,
(37) subjects rehydrated with one of four fluid regimens: (1) low volume (100% fluid
replacement) low sodium (25 mmol/l), (2) low volume-high sodium (50 mmol/l), (3) high
volume (150% fluid replacement) low sodium, or (4) high volume-high sodium. Mitchell et
al. (37) found that consuming 150% of body mass lost was superior to each of the low
volume conditions provided at least 25 mmol/l of sodium was contained within the drink.
These results are in disagreement to those of Maughan and Lieper (34) however this is
probably due to differences in the method of fluid administration. Maughan and Lieper
provided a single bolus of fluid during a 30 minute period following exercise while Mitchell
et al. administered 30% of the rehydration beverage in the 30 minutes immediately following
exercise and divided the remaining doses into five equal volumes (14%) to be consumed at
30 minute intervals. By using the Cl⁻ method described by Costill et al. (11) and Nose et al.
(49), Mitchell et al. provided evidence to suggest that a greater sodium content seems to
favor extracellular fluid filling whereas higher volumes of fluid and lower sodium contents
seem to favor the intracellular compartment. However, it should be noted there were no
differences in cardiovascular function between trials.

Beverage palatability must be considered when formulating a rehydration beverage.
In an effort to maximize beverage palatability without sacrificing rehydrating efficiency,
Shirreffs et al. (62) provided two groups of subjects with drinks containing 23 or 61 mmol/l sodium in volumes equal to 50, 100, 150, and 200% of body mass lost. Subjects were followed for 6 hours after a 1 hour rehydration period. After two hours, subjects receiving 150 and 200% of body mass lost were in a positive fluid balance regardless of the sodium content consumed. The group consuming the beverage containing 61 mmol/l Na⁺ equal to 100% of body mass lost was essentially euhydrated after two hours. On the other hand, all other groups receiving 50 or 100% of body mass lost were in a negative fluid balance regardless of the sodium concentration consumed.

Fluid balance was essentially the same from hours 2-6 of the observation period in subjects consuming the beverage containing 61 mmol/l Na⁺ equal to 100% of body mass lost as it was in those subjects consuming the beverage containing 23 mmol/l Na⁺ equal to 150 and 200% of body mass lost. Shirreffs et al. demonstrated that a drink volume greater than that lost in sweat (>100%) must be ingested to restore fluid balance without considering sodium content. When the sodium content of the beverage is not sufficiently high (61 mmol/l Na⁺), the increased volume will simply result in an increased urinary output. Shirreffs et al. did not report any differences in beverage palatability between the groups which conflicts with previous observations (64). However, this effect may be due to the method of fluid administration (fixed vs. ad libitum).

In a follow up study by Sherriffs et al. (61), volunteers dehydrated by ~2% of initial body mass. During a 60 minute rehydration period subjects ingested one of four drinks containing sodium concentrations of 0, 25, 50, and 100 mmol/l Na⁺ in a volume equal to 150% of body mass lost. In agreement with previous observations (34), Sherriffs et al. found that the beverage containing 100 mmol/l sodium resulted in a positive fluid balance.
However subjects ingesting 50 mmol/l sodium did not completely restore fluid balance. An interesting finding in this study was that potassium excretion in the 100 mmol/l sodium trial was significantly greater than the other trials resulting in an undesirable short term electrolyte disturbance. Potassium may be needed in a rehydration beverage to offset the negative loss associated with the high amount of sodium required to promote rapid rehydration.

### 2.5.3 Role of Whole Foods in Rehydration

The restoration of fluid balance requires the ingestion of adequate amounts of both water and electrolytes. The interaction between the volume of drink consumed and sodium content in a rehydration beverage has been studied extensively. A regression analysis of sodium content and volume of drink consumed (59) indicates that sodium content and volume account for 66% of the variance in body water recovery following dehydration. Sharp (59) speculated that other variables including temperature of ingested fluid, the presence of other electrolytes (potassium, calcium, and magnesium) and other nutrients (carbohydrate and protein) may contribute to the recovery of fluid balance and should be considered when formulating a recovery beverage.

The ideal rehydration beverage should contain a combination of electrolytes (sodium in particular) and carbohydrate. Several authors have demonstrated that sodium and carbohydrate ingested as part of a whole food can be equally as effective as a high sodium beverage in rapidly restoring fluid balance when the electrolyte content of that food is high (35, 51). In many settings outside of the laboratory people consume food in addition to water to recover from exercise. The addition of electrolytes to water is not necessary if solid food
with appropriate quantities of sodium and potassium are consumed together with water (35, 51).

An interesting study performed in our laboratory (51) investigated the effects of a whole food on rapid rehydration. 30 subjects (15 men and 15 women) were studied over a 2 hour rehydration period after losing 2.5% of their initial body mass. Subjects rehydrated with water, a carbohydrate-electrolyte beverage (16.0 mmol/l sodium, 3.3 mmol/l potassium), chicken broth (109.5 mmol/l sodium, 25.3 mmol/l potassium), or chicken noodle soup (118.4 mmol/l sodium, 13.7 mmol/l potassium). During the 2 hour recovery period subjects ingested 175 ml of the experimental beverage at the start of rehydration and 175 ml 20 minutes later. The remainder of the fluid deficit was consumed as water every twenty minutes (4 equal feedings) until 100% of initial fluid loss was consumed. Greater plasma volume recovery and lower urine volumes were observed in the chicken broth and soup trials despite consuming only 350 ml of the respective beverage.

2.5.5 Summary of Rehydration after Exercise

After exercise, the goal of rehydration is to fully replace any fluid and electrolyte deficits. The blueprint for rehydration is a function of the speed of rehydration needed and the magnitude of electrolyte losses (54). If recovery time is sufficient (8-24 h), fluid and electrolyte imbalances will be restored by resuming a normal meal pattern (which contains adequate amounts of electrolytes) and consuming fluids with meals (29). However, if recovery time is limited (<12 h) more aggressive rehydration methods are warranted (34, 35, 61). Sodium seems to be the key constituent in promoting rehydration post exercise. Failure to consume adequate sodium results in excessive urine production and an inability to return
to a euhydrated state (34, 47, 60). The addition of sodium to a rehydration beverage optimizes the response of fluid regulatory hormones and stimulates thirst thereby causing more fluid to be consumed and retained. Individuals lose sodium at different rates; therefore recommendations for fluid and electrolyte replacement are vague. Sports beverages, food, and salty foods are thought to be helpful but there are no concrete recommendations (51, 54). However, most evidence suggests that beverages containing at least 50 mmol/l Na\(^+\) are needed to rapidly restore body fluid balance within 2 hours, (34, 51, 61) especially when the volume of fluid consumed is \(\leq 100\)% of body mass lost. Individuals looking to achieve rapid and complete recovery from dehydration should drink \(~1.5\) l/kg bw lost (61). The additional volume is needed to compensate for the increased urine production accompanying the rapid consumption of large volumes of fluid (60). Therefore, when possible, fluids should be consumed over time (and with sufficient electrolytes) rather than being ingested in large boluses to maximize fluid retention (31, 65).

### 2.6 Carbohydrate Availability and Subsequent Exercise Performance

There are numerous factors limiting performance in endurance events. Two factors that tend to receive the greatest attention are muscle glycogen (3) and body fluid balance (13). The hierarchy of nutritional needs during training and competition is for the provision of fluid, carbohydrate, and sodium (43).

Fallowfield et al. (16) demonstrated the importance of carbohydrate in a recovery drink on subsequent endurance capacity. After losing \(~2.6\)% of initial body mass subjects ingested either a placebo (P) or a 6.9% carbohydrate electrolyte solution (CE) providing 1.0 g
of CHO/kg body mass at hours 2 and 4 of the recovery period (totaling ~138 g CHO).
Subjects regained 65.9% of body mass lost in the P group and 62.6% in the CE group. In a
subsequent run to exhaustion, the CE group ran 22.2 min longer than the P group (39.8 min
vs. 62.0 min) or 35.8% longer. During partial rehydration, carbohydrate availability rather
than dehydration hastened the onset of fatigue during a subsequent exercise bout.

Expanding upon the work of Fallowfield et al. (16), Blizon et al. (4) sought to
determine the influence of drinking a 6.9% carbohydrate electrolyte (CE) beverage on short
term recovery and subsequent exercise capacity in a warm environment. During a 4 hour
recovery period subjects consumed equal amounts of a CE beverage or a sweetened placebo
at 0, 1, and 2 hours (equivalent to 100% body mass lost). After three hours subjects voided,
rewighted, and consumed the remaining fluid deficit (totaling ~140% of initial body mass
lost).

Each beverage restored plasma volume and fluid balance to similar levels. However, in
a subsequent run to exhaustion tympanic membrane temperature, heart rate, and ratings of
perceived exertion were significantly greater in the P trial compared to the CE trial after 30
min of exercise. In spite of a moderate to severe hypoglycemia in the CE trial (from 30
minutes on), subjects were able to run an average of 16 min or 35% longer compared to the P
trial. The longer run time may be due to the additional carbohydrate provided by the CE
beverage (138 g). However, it should be noted that subjects were allowed to drink during the
subsequent exercise bout which may have helped offset dehydration while masking any
possible thermoregulatory benefits the two experimental beverages may have had.

Additional evidence for the inclusion of carbohydrate in a rehydration beverage came
in a study from Wong et al. (66). Wong followed subjects during a four hour recovery in
which 200% of body mass lost (3%) was consumed in the form of a carbohydrate electrolyte beverage or placebo. Subjects in the carbohydrate electrolyte trial were able to run 54% longer during a subsequent run to exhaustion. There were also no significant differences in core temperature between trials but heart rate and ratings of perceived exertion were both significantly higher in the placebo trial.

Blizon (4) and others (16, 66) have shown that ingestion of carbohydrate during recovery may increase subsequent exercise capacity. To examine the dose response relationship between glucose ingested and subsequent exercise capacity, Blizon et al. (5) followed subjects during a four hour recovery period from exhausting exercise. During the recovery period, subjects ingested 55 grams of carbohydrate in the form of a 7.5% carbohydrate electrolyte drink immediately after exercise (C55). In the other trial subjects consumed either the same quantity of carbohydrate electrolyte beverage or an equivalent volume of the placebo at 60, 120, and 180 min during recovery resulting in a total of 220 grams of carbohydrate in the (C220) trial and 55 grams of carbohydrate in the (C55) trial.

Despite a marked increase in the amount of carbohydrate consumed and oxidized in the (C220) trial, exercise durations were similar in each trial. A key finding in this study was that both exercise periods were terminated by thermoregulatory incapacity (elevated core temperature) rather than substrate availability.

Not all studies have shown improved performance following rehydration with a carbohydrate electrolyte beverage compared with water. In a study by Singh et al. (63) subjects were followed during a two hour recovery period after losing 3% of body mass. Subjects ingested a high-sodium carbohydrate-electrolyte beverage (CE) or placebo to a
volume of 120% of their initial body mass. After the recovery period, subjects performed a 1 hour time trial, in accordance with the method developed by Jeukendrup et al. (30).

The ingestion of 120% of initial body mass lost was able to restore plasma volume to euhydrated levels in both trials at 1.5 hours, but plasma volume recovery at the end of the 2 hour period was significantly higher in the CE trial (70%) compared with the P trial (60%).

Despite the more effective plasma volume restoration in the high-sodium carbohydrate electrolyte trial compared to placebo, no performance differences were observed in the time trial. Singh et al. suggested the lack of difference between trials despite the hydration advantage in the CE trial was due to a rebound effect of carbohydrate metabolism lowering plasma glucose and decreasing free fatty acid availability.

2.7 Directions for Future Research

Physical laborers and multi-sport athletes frequently complete more than one bout of physical activity per day. In hot and humid environments, sweating is the predominate means of dissipating heat. Sweat rates of 0.5 to 2.0 l/hr (54) are common whereas sweat rates of up to 3 l/hr (52) have been observed in extreme environments. Fluid balance is in constant flux and may be thought of as a continuum between dehydration and euhydration. Dehydration of as little as 1-2% of body mass results in many detrimental cardiovascular, thermoregulatory, and metabolic changes along with concomitant decreases in physical work capacity and exercise performance.

Data from Montain and Coyle (40) clearly demonstrate that hyperthermia is directly related to the level of dehydration accumulated during moderate intensity exercise in a warm environment. Stroke volume, heart rate, and cardiovascular function can be normalized with
rehydration (13, 40, 46), although the minimal amount of fluid restoration necessary to normalize cardiovascular function and core temperature has yet to be established.

Few attempts have been made to determine whether rapid rehydration confers cardiovascular, temperature regulatory, metabolic, or performance benefits in a subsequent bout of exercise. Using four different carbohydrate-electrolyte beverages, Nielsen et al. (46) found that performance in a subsequent exercise bout was 20% less after dehydration regardless of the drink used to rehydrate. After two hours of rehydration, plasma volume was above baseline with all four drinks; however, the plasma volumes of the subjects consuming the two drinks containing Na\(^+\) as the major cation ((Na-drink (+14%) and C-drink (+9%)) were significantly higher. The lack of significant differences in performance may have been due to the similarity of the beverages or the type of performance trial utilized (Table 3). The time trial used in the Nielsen et al study was a supramaximal test to exhaustion (105% of VO\(_2\)peak) which may not be a valid indicator of endurance capacity.

**Table 3.** Composition of Rehydration Beverages used by Nielsen et al. (46).

<table>
<thead>
<tr>
<th></th>
<th>C-drink</th>
<th>K-drink</th>
<th>Na-drink</th>
<th>S-drink</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glucose (mmol)</td>
<td>375</td>
<td>375</td>
<td>375</td>
<td>750</td>
</tr>
<tr>
<td>Sucrose (mmol)</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Na(^+) (mmol)</td>
<td>116</td>
<td>116</td>
<td>346</td>
<td>35</td>
</tr>
<tr>
<td>K(^+) (mmol)</td>
<td>--</td>
<td>138</td>
<td>--</td>
<td>17</td>
</tr>
<tr>
<td>Osmolality (mOsm/kgH(_2)O)</td>
<td>229</td>
<td>323</td>
<td>387</td>
<td>465</td>
</tr>
</tbody>
</table>

Montain and Coyle (40) demonstrated that fluid ingestion during exercise attenuates dehydration and blunts core temperature rise. Gonzalez-Alonso et al. (22) sought to determine the effects of graded levels of dehydration on temperature regulation and exercise
performance by manipulating the degree of dehydration. Subjects remained euhydrated or dehydrated by 1.5%, 3.0%, and 4.2% of initial body mass before exercising 30 minutes at 72% VO2max in a warm environment. After 20 minutes, the core temperature of subjects in the 3.0% and 4.2% trials were significantly greater than the euhydrated trial and the core temperature for all three dehydrated conditions were significantly elevated above euhydrated levels at 25 and 30 minutes. Core temperature remains significantly lower when exercise is started closer to euhydration.

Plasma volume is fundamental to cardiovascular function and may impact temperature regulation and subsequent work capacity. Ray et al. (51) demonstrated that chicken noodle soup and chicken broth are more effective in restoring plasma volume than a carbohydrate electrolyte beverage or water. At the end of a two hour rehydration period, the plasma volume of subjects ingesting either chicken noodle soup or chicken broth was not different from baseline. On the other hand, the plasma volume of subjects ingesting a carbohydrate electrolyte beverage or water was significantly below initial values.

There is ample evidence demonstrating improvements in subsequent exercise performance following carbohydrate ingestion (4, 16, 66). Blizon et al. (5) demonstrated that consuming 55 grams of carbohydrate in a recovery drink was as effective as consuming 220 grams in conferring a performance benefit in a subsequent exercise bout. In the rehydration protocol utilized by Ray et al. (51) chicken noodle soup provided 33.0 grams of carbohydrate, thereby promoting carbohydrate availability and possibly conferring performance benefits. Chicken noodle soup is a commercially available whole food suitable to meet the recovery needs of both fluid and carbohydrate because it contains ample amounts of sodium (118.4 mmol/l) and adequate carbohydrate (93.0 g/l) to promote
restoration of body fluid balance and glycogen resynthesis. The purpose of this investigation is to assess whether a whole food (chicken noodle soup) with a high sodium content consumed during the initial stages of recovery from exercise in the heat improves subsequent temperature regulation and exercise performance.
CHAPTER 3. METHODS

3.1 Subject Characteristics

Ten college-aged males capable of performing ≥ 60 min of cycling at 70% of VO₂peak were recruited to participate in this study. Informed consent was obtained from the subjects in accordance with the guidelines established by the Human Subjects Review Board of Iowa State University. All subjects were physically active at least 3-4 days/wk and were without any serious health problems. Their age, height, body mass, and VO₂peak were 23.0 ± 4.2 yr, 179.8 ± 8.3 cm, 75.9 ± 10.6 kg, and 58.1 ± 5.9 ml/kg/min respectively.

One week prior to the first trial, each subject participated in a graded cycle ergometer test for determination of VO₂peak and subsequent submaximal workloads. Each participant was then subjected to two rehydration conditions conducted in a randomized counterbalanced design with each trial separated by ≥ 1 wk. Well trained athletes are well aware that a carbohydrate electrolyte beverage will enhance endurance performance compared to drinking water alone. Therefore, the water placebo was disguised as a “sports beverage” to eliminate bias for the chicken noodle soup.

3.2 Beverage Composition

The Placebo and Soup were analyzed for electrolytes (Na⁺, K⁺, and Cl⁻; Medica EasyLyte Bedford, MA) and osmolality (model 5500, Wescor, Logan, UT). The Placebo used in the present study was fruit punch flavored sugar free Kool Aid® (14.4 mmol/l Na⁺, 1.6 mmol/l K⁺; 31 mosmol/kgH₂O), the soup was Campbell’s Chicken Noodle Soup® (161.0 mmol/l Na⁺, 5.3 mmol/l K⁺; 338 mosmol/kgH₂O), and the water used in the making of the soup and Kool Aid® was tap water (Ames, IA) (Table 4).
Table 4. Composition of Rehydration Beverages

<table>
<thead>
<tr>
<th></th>
<th>Soup</th>
<th>Placebo</th>
<th>Water</th>
</tr>
</thead>
<tbody>
<tr>
<td>Osm (mosmol/kgH₂O)</td>
<td>338</td>
<td>31</td>
<td>4</td>
</tr>
<tr>
<td>Na⁺ (mmol/l)</td>
<td>161.0</td>
<td>14.4</td>
<td>3.0</td>
</tr>
<tr>
<td>K⁺ (mmol/l)</td>
<td>5.3</td>
<td>1.6</td>
<td>0</td>
</tr>
<tr>
<td>CHO (total g)</td>
<td>~30</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Each trial consisted of a dehydration period (70 - 150 min), a 30 min transition period, a 120 min rehydration period, 30 min of steady state exercise, and a (~ 30 min) time trial (Figure 2).

Figure 2. Timeline of Study Periods and Measurements
3.3 Dehydration

On two occasions subjects entered the laboratory following an overnight fast. Subjects emptied their bladders and were fitted with a rectal thermistor inserted to a depth of 10 cm past the anal sphincter for measurement of core body temperature. After being fitted with a heart rate monitor (Polar Electro, Finland), nude body mass was obtained on a digital scale accurate to the nearest 0.1 kg. A blood sample (10 ml) was collected by venipuncture without stasis after which subjects entered the environmental chamber.

Subjects rode a cycle ergometer at 30% VO_2peak in hot and humid conditions (40°C and 60% relative humidity) until 2.5 - 3.0% of initial body mass was lost (70 - 150 min). Subjects were weighed at 30 and 60 min. Thereafter a body mass was obtained at 10 min intervals until 2.5 - 3.0% of initial body mass was lost.

3.4 Rehydration

Immediately following dehydration, subjects changed into dry clothes and rested for 30 min in a thermoneutral environment (20°C) to allow body fluid compartments to stabilize (44). During this time, a small flexible Teflon catheter was inserted into an antecubital vein and a blood sample (10 ml) was taken at 30 min of the transition period. At this time subjects began the 120 min rehydration period in which either Placebo or Soup was consumed (Figure 2). The Placebo and Soup were administered at room temperature and ~50°C respectively. One-hundred seventy-five milliliters of the respective beverage was consumed at the beginning of the rehydration period (min 0), and 175 ml 20 min later (min 20). For the remainder of the rehydration period, participants ingested an equal volume of H_2O every 20 min (4 feedings) to match the total volume of water lost during dehydration.
(100% body mass). Blood samples were taken at the start of rehydration (min 0) and every 20 min thereafter.

3.5 Subsequent Exercise

After 120 min of rehydration, subjects entered the environmental chamber and performed 30 min of steady state exercise at 70% of VO₂peak. Following steady state exercise subjects were asked to complete the same amount of work produced in 30 min at 70% of VO₂peak as fast as possible during a time trial. The steady state bout and time trial were completed in a themoneutral environment (25°C and 40% RH). Blood samples, rectal temperature, heart rate, ratings of perceived exertion, and respiratory exchange measurements were recorded every 10 min during steady state exercise and time trial. Sweat rate was calculated during steady state exercise by subtracting urine output during steady state exercise (urine collected post time trial/2) from body mass lost during steady state exercise. The volume of metabolic water produced during cellular metabolism (~0.13 g/kcal) is approximately equal to respiratory water losses (~0.12 g/kcal) (38). Therefore ventilatory water losses were not considered in sweat rate calculations.

3.6 Blood and Fluid Analyses

Blood samples were taken from an antecubital vein after fluid in the dead space of the catheter was removed and discarded. The catheter was kept patent with 3 ml of 0.9% sodium chloride after each blood draw. Whole blood samples were immediately transferred into tubes containing lithium heparin and analyzed for hematocrit and hemoglobin in triplicate by use of microcapillary tubes and cyanmethemoglobin methods, respectively. Hematocrit measurements were corrected for plasma trapped within the packed red blood cells (0.96) and for venous-to-total body hematocrit ratio (0.91) (9). Percent changes in plasma volume from
dehydrated values were calculated using hematocrit and Hb concentrations according to Dill and Costill (14). Plasma was separated from blood cells by centrifugation at 2000 rpm for 10 min and analyzed for osmolality using a vapor pressure osmometer (model 5500, Wescor, Logan, UT), and electrolytes (Na⁺, K⁺, and Cl⁻; Medica EasyLyte Bedford, MA). Urine samples were obtained post-dehydration, post-rehydration, and time trial end; and analyzed for volume, osmolality, electrolytes, and specific gravity.

3.7 Dietary and Exercise Control

A 3 day diet record (food and fluid) and 3 day exercise diary were completed before the first trial and replicated prior to the second. To ensure proper hydration on testing days, participants were instructed to drink an additional liter of water the day before each trial.

3.8 Statistical Analysis

Values are means ± SE. All blood, urine, heart rate, rectal temperature, ratings of perceived exertion, and body mass measurements were analyzed using two-way repeated measures ANOVA. Holm-Sidak post hoc tests were used when appropriate. Differences among treatments were accepted as being significant when P < 0.05 was obtained.
CHAPTER 4. RESULTS

The mean body mass loss due to dehydration was $2.1 \pm 0.1$ kg (both trials pooled), corresponding to a percent body mass loss of $2.7 \pm 0.1\%$. There were no significant differences between treatments in body mass lost during dehydration nor were there significant differences between treatments in body mass regained after rehydration. A statistical analysis suggested significantly more body mass was lost during steady state exercise in the Placebo trial when expressed in kilograms ($1.1 \pm 0.1$ Placebo) ($P = 0.05$, Figure 3), although the quantity of fluid loss during steady state exercise was not different ($P = 0.59$).

During the rehydration period subjects drank an average of $310 \pm 23$ ml of $H_2O$ every 20 min between min 40 and 100 of the rehydration period for a total volume of $1590 \pm 92$ ml; there were no significant differences in drink volume with respect to trial.

Table 5. Percentage of Body Mass Lost.

<table>
<thead>
<tr>
<th></th>
<th>Soup (% BM Loss)</th>
<th>Placebo (% BM Loss)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dehydration</td>
<td>$2.7 \pm 0.1$</td>
<td>$2.7 \pm 0.1$</td>
</tr>
<tr>
<td>Rehydration</td>
<td>$0.6 \pm 0.1$</td>
<td>$0.7 \pm 0.1$</td>
</tr>
<tr>
<td>Steady State Exercise</td>
<td>$1.3 \pm 0.1$</td>
<td>$1.4 \pm 0.1$</td>
</tr>
</tbody>
</table>

4.1 Percent Rehydration

Body mass regained after the 2 hour rehydration period was not different between trials ($75.9 \pm 1.6\%$ Soup, $74.8 \pm 2.0\%$ Placebo). After rehydration body mass remained significantly reduced from baseline ($P < 0.001$) in each trial. Sweat rates were similar among treatments ($1.0 \pm 0.07$ l/h Soup, $1.0 \pm 0.05$ l/h Placebo) during steady state exercise.
There were no significant differences between treatments in hemoglobin, hematocrit (Table 6) or plasma volume measurements at any time during the rehydration period.

**Table 6.** Hemoglobin and Hematocrit Values during the 120 min Rehydration Period

<table>
<thead>
<tr>
<th></th>
<th>0</th>
<th>20</th>
<th>40</th>
<th>60</th>
<th>80</th>
<th>100</th>
<th>120</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Hb, g/100 ml</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><em>Soup</em></td>
<td>13.5 ± 0.3</td>
<td>13.5 ± 0.3</td>
<td>13.3 ± 0.3</td>
<td>13.3 ± 0.3</td>
<td>13.2 ± 0.3</td>
<td>13.6 ± 0.3</td>
<td>13.9 ± 0.3</td>
</tr>
<tr>
<td><em>Placebo</em></td>
<td>13.7 ± 0.2</td>
<td>13.4 ± 0.1</td>
<td>13.1 ± 0.2</td>
<td>13.2 ± 0.2</td>
<td>13.2 ± 0.1</td>
<td>13.5 ± 0.1</td>
<td>13.7 ± 0.1</td>
</tr>
<tr>
<td><strong>Hct, %</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><em>Soup</em></td>
<td>42.5 ± 0.9</td>
<td>42.0 ± 1.0</td>
<td>42.1 ± 0.9</td>
<td>41.7 ± 0.8</td>
<td>41.7 ± 0.9</td>
<td>41.7 ± 0.9</td>
<td>42.9 ± 0.8</td>
</tr>
<tr>
<td><em>Placebo</em></td>
<td>42.2 ± 0.6</td>
<td>41.7 ± 0.6</td>
<td>41.9 ± 0.6</td>
<td>41.9 ± 0.8</td>
<td>42.3 ± 0.6</td>
<td>42.6 ± 0.6</td>
<td>43.6 ± 0.6</td>
</tr>
</tbody>
</table>

At the end of the rehydration period plasma volume was not significantly different from baseline in either trial (*Soup*, -3.5 ± 1.2% and *Placebo*, -1.4 ± 2.0%) (Figure 4). Plasma
volume recovered to similar levels by min 80 in each trial before dropping below baseline
during the second half of the rehydration period.

Figure 4. Time Course of Plasma Volume Recovery during Rehydration.

4.3 Urine Volume, Specific Gravity, Osmolality, and Electrolytes

A trend towards greater urine production during rehydration ($P = 0.06$) as well as
accumulated urine output (post-rehydration and time-trial end) during the Placebo trial (222
± 24 ml Soup, 318 ± 58 ml Placebo) ($P = 0.07$) was observed (Figure 5). Urine volume
during rehydration was significantly greater in the Placebo trial ($P < 0.04$) when data was
normalized using a Wilcoxon signed rank test.

Urinary sodium (Table 7) was significantly lower in the Soup trial post-dehydration
($P < 0.05$) whereas there were no differences in urinary potassium, osmolality, or urine
specific gravity post-dehydration between treatments. There were also no differences in
urine sodium, osmolality, or urine specific gravity post-rehydration between treatments.
Table 7. Urinary Markers of Hydration Status. *Urine specific gravity in the Soup trial Post-TT was significantly greater compared to the Placebo trial (P = 0.02).

<table>
<thead>
<tr>
<th></th>
<th>Soup Post-D</th>
<th>Placebo Post-D</th>
<th>Soup Post-R</th>
<th>Placebo Post-R</th>
<th>Soup Post-TT</th>
<th>Placebo Post-TT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume (ml)</td>
<td>55 ± 7</td>
<td>61 ± 13</td>
<td>128 ± 57</td>
<td>180 ± 18</td>
<td>94 ± 22</td>
<td>138 ± 35</td>
</tr>
<tr>
<td>Specific Gravity</td>
<td>1.021 ± 0.002</td>
<td>1.019 ± 0.002</td>
<td>1.016 ± 0.002</td>
<td>1.01 ± 0.002</td>
<td>1.006 ± 0.001</td>
<td></td>
</tr>
<tr>
<td>Osmolality (mosmol/kgH_2O)</td>
<td>714 ± 66</td>
<td>817 ± 70</td>
<td>681 ± 48</td>
<td>625 ± 53</td>
<td>366 ± 81</td>
<td>241 ± 46</td>
</tr>
<tr>
<td>[Na⁺] (mmol/l)</td>
<td>86.1 ± 10.2 *</td>
<td>115.6 ± 12.1</td>
<td>104.4 ± 10.8</td>
<td>102.3 ± 16.3</td>
<td>51.1 ± 14.5</td>
<td>34.3 ± 11.3</td>
</tr>
<tr>
<td>[K⁺] (mmol/l)</td>
<td>74.9 ± 8.0</td>
<td>75.49 ± 7.1</td>
<td>87.7 ± 12.0</td>
<td>65.4 ± 8.0</td>
<td>53.0 ± 12.7</td>
<td>29.8 ± 7.5</td>
</tr>
</tbody>
</table>

Post-D = post-dehydration; Post-R = post-rehydration; Post-TT = time trial end

Urinary potassium approached significance in the Soup trial post-rehydration (P = 0.07) and time trial (P = 0.06). Urine specific gravity was significantly greater (P = 0.02) in the Soup trial post-time trial while urine osmolality tended to be greater in the Soup trial post-time trial (P = 0.054) (Table 7).

4.4 Plasma Osmolality and Electrolytes

Plasma osmolality (main effect P < 0.02) and plasma sodium (main effect P < 0.02) were significantly greater throughout the rehydration period of the Soup trial (Figure 6). There were no significant differences in potassium concentration between treatments during the rehydration period.

4.5 Heart Rate, Rectal Temperature, and Ratings of Perceived Exertion

There were no significant differences in heart rate or ratings of perceived exertion at any time during steady state exercise. Rectal temperature was significantly elevated at min 10 during steady state exercise in the Soup trial (P = 0.04) but not at any other time.
Figure 5. Differences in Urine Volume among Treatments. A trend towards increased urine production post-rehydration was observed during the Placebo trial ($P = 0.06$).

Figure 6. Differences in Plasma Osmolality ($P_{\text{osm}}$) between Treatments. During the rehydration period there was a significant main effect for $P_{\text{osm}}$ to be greater during the Soup trial ($P < 0.02$).
4.6 Steady State Exercise and Time Trial

The mean VO$_2$ during steady state exercise was 73 ± 2%. There were no differences in VO$_2$ during steady state exercise between trials. There was a trend (P = 0.13) for
increased performance in the Soup trial during the time trial (Soup 30.6 ± 0.9 min; Placebo 32.2 ± 1.5 min). A strong order effect was also observed among the trials (P = 0.04) with performance increasing during the second trial regardless of treatment (first trial 32.4 ± 1.4, second trial 30.3 ± 1.0 min).

**Figure 8.** Time Needed to Complete a Fixed Amount of Work
CHAPTER 5. DISCUSSION

The purpose of this investigation was to assess whether a food (chicken noodle soup) consumed during the initial stages of recovery from exercise in the heat would improve subsequent thermoregulatory capacity and exercise performance by improving fluid retention and restoring plasma volume closer to euhydrated levels.

Plasma volume recovery in the present study conflicts with previous reports (34, 36, 51) and is likely due to experimental error. Plasma volume change was calculated using minute zero of the rehydration period as the reference point. The baseline blood sample obtained from subjects immediately upon entering the lab was not used as a reference point due to unusually elevated hematocrit values.

The abnormal hematocrit values during the initial blood draw were likely the result of leaving the tourniquet on the arm while taking the blood sample. The pressure created by the tourniquet may have caused some of the fluid in the vascular beds to seep into the interstitial space thereby reducing the ratio of red blood cells to fluid and inflating the hematocrit values. Therefore, the percentage change in plasma volume was calculated with minute zero of the rehydration period as the reference point.

In this and previous studies (51) plasma volume change was calculated using hemoglobin (Hb) and hematocrit (Hct) measurements. In the present study there were no significant differences in Hb or Hct between treatments at any time during the rehydration period. Abnormalities in Hb or Hct measurements would have been reflected in the calculated plasma volumes. Therefore Hb and Hct values appear to be valid.

In the present study plasma volume recovery was expected to increase throughout the rehydration period and plateau near rehydration end (37, 46). An analysis of both Hb and
Hct revealed a progressive hemo-dilution effect through ~80 minutes followed by a decline below baseline levels thereafter. Calculation of plasma volume from these data therefore indicates the expected pattern of plasma volume restoration during the first 80 minutes. This was however, followed by declining plasma volumes despite continued drinking (Figure 4).

The plasma volume pattern during the last 30 minutes of the rehydration period in the present study is likely due to experimental error. However, increases in urine production or changes in water distribution among body fluid compartments may also account for the observed decline in plasma volume. Urine production increased during the rehydration period of the Placebo trial (P = 0.06). Plasma osmolality (P < 0.02) and plasma sodium (P < 0.02) were significantly elevated during the rehydration period of the Soup trial. Both of these factors stimulate the release of arginine vasopressin (26) which likely explains the trend for less urine to be produced during the Soup trial.

Despite differences in urine production between trials plasma volume decreased in a similar manner. Therefore, it seems likely that fluid redistribution among body compartments rather than increased urine production may have caused the decline in plasma volumes. However, it is not possible to determine the cause of the decline in plasma volumes from this set of data.

The rehydration protocol employed in the present study was identical to a method previously used in our laboratory (51). Ray et al. found that plasma volume was restored to the greatest extent using either chicken noodle soup (Soup) or chicken broth (CB) as a rehydration beverage (-1.6 ± 1.1%, -1.4 ± 0.9% CB and Soup respectively). Plasma volume was not different from baseline in the CB and Soup trials whereas when a carbohydrate electrolyte beverage (CE) or water were used plasma volumes were significantly below
baseline (-4.2 ± 1.0% and -5.6 ± 1.1% respectively). In the present study plasma volumes were in a net negative balance at rehydration end (Soup -3.5 ± 1.2%, Placebo -1.4 ± 2.0%).

Due to differences in the baseline used for calculating plasma volumes, a direct comparison of plasma volume recovery between studies is not allowed. However, plasma volume recovery in the Ray et al. study may have followed a pattern similar to the present study (Figure 4). Plasma volume was measured at baseline and at rehydration end. Plasma volume may have recovered to the greatest extent (a positive value) midway through the rehydration period before returning closer to baseline levels. However, a direct comparison cannot be made due to measurement timing.

Beverage content may also account for the divergence in plasma volume recovery between studies. Well trained athletes are aware that a drink containing carbohydrates and electrolytes will likely improve performance. In the present study the water treatment (Placebo) was disguised as a “sports beverage” (sugar free fruit punch flavored Kool Aid®) to control for subjects’ possible expectations of favorable experimental effects. Disguising the water treatment as a sports beverage altered the electrolyte content. The composition of sugar free Kool Aid® is similar to the carbohydrate electrolyte (CE) beverage used in the Ray et al. study (14.4 mmol/l Na⁺, 1.6 mmol/l K⁺ Kool Aid®; 16 mmol/l Na⁺, 3.3 mmol/l K⁺ Gatorade) which may have caused greater retention of the ingested fluid than water alone. However, the similarity between Kool Aid® and the CE beverage does not explain the trend in plasma volume recovery observed between the two experimental beverages (-1.4 ± 2.0% Kool Aid® and -4.2 ± 1.0% CE Ray et al. study). However, due to the methodological differences it is not possible to determine cause and effect from these sets of data.
The percentage of fluid retained from both treatments was nearly identical (75.9 ± 1.6% Soup, 74.8 ± 2.0% Placebo) which is in conflict with previous reports (48) but not others (20, 51). During a 3 hour rehydration period Nose et al. (48) had subjects ingest water along with capsules containing either a sugar placebo or NaCl. Subjects consuming the sugar placebo retained 51% of the fluid consumed compared to 71% for those ingesting the NaCl. A “true” Water trial would have likely yielded results similar to Nose et al. However, the electrolyte content of the sports beverage used in the present study was similar to the content of a CE beverage which may (20, 51, 62) have contributed to amount of fluid retained in this study. Body fluid balance at the end of the rehydration period was similar (-0.6 ± 0.1% Soup, -0.7 ± 0.1% Placebo) between treatments and agrees with previous findings (51).

Starting an exercise bout closer to euhydration may maintain sweat rate and blunt an exaggerated rise in body temperature (22, 40). Sweat sensitivity and sweat rate decline with graded levels of dehydration thereby mediating an increase in core temperature (57). The difference in the level of dehydration between treatments at the start of steady state exercise was not enough to illicit a difference in sweat rate or body mass lost during steady state exercise.

Core temperature in the Soup trial started out higher and remained elevated throughout steady state exercise despite similar sweat rates (1.0 ± 0.07 l/h Soup, 1.0 ± 0.05 l/h Placebo). Core temperature was significantly elevated at 10 min during steady state exercise (P < 0.04) in the Soup trial. This effect may have been due to the temperature of the liquid (50°C) ingested at the start of the rehydration period; however, this effect is unlikely. The volume of soup ingested was 350 ml (~20% of the total fluid consumed) and was
ingested at minutes 0 and 20 of the rehydration period leaving 100 min for core body
temperature to normalize (51).

The rate of core temperature increase was also similar among trials which suggests
that the elevated core temperatures observed in the Soup trial were the result of starting
steady state exercise at a higher temperature rather than the temperature of the ingested fluid.

Physical work capacity decreases when body water losses reach 1% in both temperate
and hot environments (50, 53). The level of dehydration after steady state exercise in the
present study was greater than 1% (1.3 ± 0.1% Soup and 1.4 ± 0.1% Placebo*) therefore,
dehydration likely had some effect on time trial performance. The significant difference in
fluid balance between trials after steady state exercise may have been due to small
differences in fluid balance before steady state exercise. Fluid balance in the Placebo trial
post-rehydration was already slightly reduced compared to the Soup trial which may have led
to the significant difference observed among the trials after steady state exercise. However,
the similar level of dehydration observed after steady state exercise between treatments
negates any temperature regulation advantages of the respective beverages.

A trend for performance to increase during the time trial of the Soup treatment (P =
0.13) was observed (Figure 8). The similar levels of dehydration accrued before the time
trial as well as comparable sweat rates and core temperatures demonstrate that the
discrepancies observed in performance were not due to differences in fluid balance or
temperature regulation. The Soup trial provided ~30 g of carbohydrate which is likely the
cause of the trend for improved performance observed in the Soup trial. The effect of
carbohydrate availability on subsequent exercise performance is discussed in another paper.
During this study and others (48, 51) plasma osmolality (P_{osm}) increased above resting values during the rehydration period and remained elevated as a result of consuming a beverage containing high concentrations of sodium. Consuming soup during the initial stages of the rehydration period significantly elevated P_{osm} (P < 0.02) and plasma sodium (P < 0.02) above Placebo. It is well established that elevations in plasma osmolality and plasma sodium are potent stimuli of dipsogenic drive (48, 64).

On the other hand, Nose and colleagues (48) demonstrated that ingestion of water after exercise results in a decrease in serum sodium concentration [Na^+] and plasma osmolality. Both of these factors diminish the drive to drink resulting in a delayed or incomplete fluid restoration.

A limitation of our study was that fluid intake was fixed during rehydration and restricted during steady state exercise and time trial. In real world settings where athletes and workers have free access to fluids, consuming a sodium containing beverage (soup) at the onset of rehydration may help to rapidly restore plasma volume closer to euhydration (48) and increase physical work capacity.

Consuming larger quantities of sodium early in the rehydration period and a more palatable drink with more dilute amounts of sodium later in the rehydration period may be beneficial to subsequent exercise capacity. The large amount of sodium on the front end of the rehydration period causes P_{osm} and [Na^+] to rise and remain elevated throughout the rehydration period maintaining the osmotic stimulus to drink. Consuming a beverage lower in sodium later in the rehydration period may help to avoid the palatability issues drinks containing larger quantities of sodium may have (64).
In conclusion evidence from the present study suggests that consuming a whole food (chicken noodle soup) with a high sodium content during the initial stages of recovery from exercise in the heat improves subsequent exercise performance. The improved performance observed in the present study was likely due to carbohydrate availability rather than improved thermoregulation. There was no difference in plasma volume recovery or the amount of fluid retained between trials; therefore the degree of dehydration, sweat rate, and rate of core temperature increase appeared to be similar between treatments. Consuming soup during the initial stages of the rehydration period increased $P_{\text{osm}}$ and $[\text{Na}^+]$ which have been shown to be potent thirst stimuli. Further research is needed to test the ability of soup consumed at the beginning of the rehydration period to stimulate thirst during ad libitum rehydration and subsequent exercise thereby increasing fluid consumption and body fluid balance while also improving subsequent exercise thermoregulation and augmenting exercise performance.
BIBLIOGRAPHY


