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WATER AND MINERAL BALANCE DURING EXERCISE

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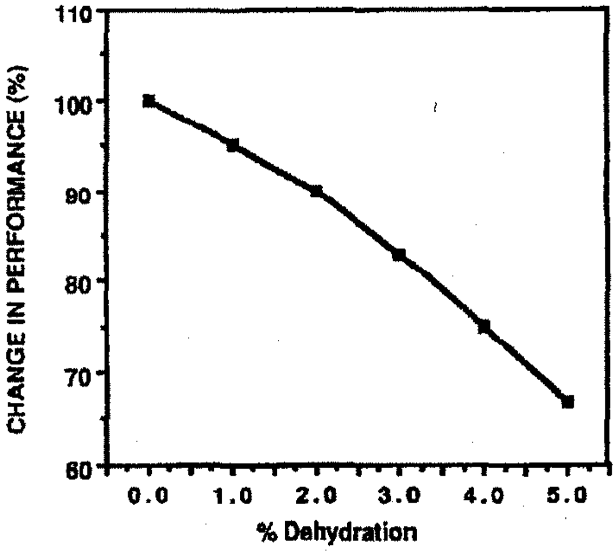
Summary

The ability to lose body heat during exercise depends, for the most part, on the formation and evaporation of sweat. The amount of sweat lost during exercise, in turn, is dictated by exercise intensity, body size, and environmental heat stress. Exercising in warm weather may evoke sweat losses in excess of two quarts per hour (Nielsen 1938; Costill et al. 1980). Despite efforts to drink fluids during an event such as the marathon, sweating and the loss of water in the air we breath may reduce body water content by 13 to 14 percent.

I. INTRODUCTION

It has been shown that the water and electrolytes in sweat come initially from extracellular sources (i.e., plasma and interstitial fluids), though the losses are subsequently distributed evenly between the intracellular and extracellular compartments. Despite the gradual decline in total body water during prolonged periods of effort in the heat, plasma water is relatively well maintained (Kozlowski and Saltin 1964). As a consequence of the loss of body water via sweating, subjects experience a pronounced decline in exercise tolerance during long term activity. Incomplete replacement of water losses can lead to a rise in body temperature and an elevated pulse rate (Claremont et al. 1976; Saltin 1964). This occurs when fluid loss corresponds to about 2% or more of body weight. If the loss increases to 4 or 5% of body weight, the capacity for intense muscular work will decline by 20 to 30% (Figure 1).

Figure 1. Relationship between dehydration and exercise performance (Saltin and Costill 1988).



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II. DEHYDRATION AND EXERCISE TOLERANCE

Studies have shown that dehydrated individuals are quite intolerant of exercise and heat stress (Armstrong et al. 1976; Claremont et al. 1985). Distance runners, for example, are forced to slow their pace by two percent for each percent of weight lost as a consequence of dehydration. This suggests that a runner capable of performing 10,000 meters in 35 minutes when normally hydrated, will be slowed by 2 minutes and 48 seconds if they attempted the run when dehydrated by 4%. However, the effects of dehydration on performance in shorter, less aerobic events does not appear to be as dramatic. In exercise bout lasts only a few seconds, where ATP is generated primarily via the ATP-PCr and glycolytic systems, performance seems to be unaffected. Although research findings are mixed on this issue, it is generally agreed that dehydration has a minimal effect on performance in events like weight lifting.

The impact of dehydration on the cardiovascular system is quite predictable. Both heart rate and body temperature are elevated during exercise when the individual is dehydrated more than two percent of body weight. There is a decrease in plasma volume that causes a reduction in blood flow to the skin and muscles. Under these circumstances, it is common for subjects to collapse, showing the usual symptoms of heat exhaustion. In addition to the body water lost during endurance events, many nutrients are known to escape with sweat. The following discussion will examine the effects of heavy sweating on body water and the mineral composition of body tissues.

Human sweat has been described as a "filtrate of plasma," since it contains many of the items present in the water portion of blood, including sodium, chloride, potassium, magnesium, and calcium. However, sweat actually contains far fewer minerals than do body fluids. Sweat is considered hypotonic, meaning it is a very dilute version of body fluids.

Sodium (Na^+) and chloride (Cl^-) are the dominant ions of sweat and blood. Table 1 shows that the concentrations of sodium and chloride in sweat are roughly one-third those found in plasma and five times those found in muscle. The mineral concentration of sweat may vary considerably between individuals and is strongly influenced by the rate of sweating and the individual's state of fitness and heat acclimatization.

Table 1. Electrolyte concentrations and osmolarity in sweat, plasma, and muscle of men following 2 hours of exercise in the heat.

	Electrolytes (mEq/litre)				Osmolality
	Na^+	Cl^-	K^+	Mg^{++}	(mOsm/litre)
SWEAT	40 - 60	30 - 50	4 - 5	1.5 - 5	80 - 185
PLASMA	140	101	4	1.5	302
MUSCLE	9	6	162	31	302

At the high rates of sweating reported during endurance events, sweat contains relatively high levels of sodium and chloride, but little potassium, calcium, and magnesium. A sweat loss of nearly nine pounds (4 litres), representing a 5.8 percent reduction in body weight, resulted in Na^+, potassium (K^+), Cl^-, and magnesium (Mg^{++}) losses of 155, 16, 137, and 13 mEq, respectively. Based on estimates of the body's mineral contents, such losses would only lower the body's Na^+ and Cl^- content by roughly 5 to 7 percent. At the same time, total body levels of K^+ and Mg^{++}, two ions (i.e., electrically charged particles) principally confined to the inside of the cells, would decrease by about one percent.

At the same time that minerals are lost from the body in sweat, there is a redistribution of the remaining ions among various tissues and organs. One such example is K^+, which leaves contracting muscle fibers and contributes to the plasma K^+ pool during exercise (Sjogaard 1989). However, the elevation in extracellular K^+ content is less than the K^+ released from active muscles,because inactive muscles and other tissues take up K^+. During recovery following exercise, normalization of intracellular K^+ appears to occur rather rapidly. There have been some suggestions that these disturbances in muscle K^+ may contribute to the factors of fatigue during exercise.

The other major source of mineral loss is routine urine production. In addition to clearing the blood of cellular waste products, the kidneys also control the body's water and electrolyte content. Under normal conditions, the kidneys excrete about 50-60 ml of water per hour. During exercise, however, blood flow to the kidneys decreases, and urine production drops to near zero. Consequently, electrolyte losses by this avenue are minimal during exercise.

There is another facet of the kidneys' management of electrolytes. If an individual eats 250 mEq of sodium and chloride per day, normally the kidneys will excrete an equal amount of those electrolytes to keep the body's content constant. Heavy sweating and dehydration, however, cause the release of aldosterone from the adrenal cortex that stimulates the kidneys to reabsorb sodium. As a result, the body tends to retain more than a normal amount of sodium in the hours and days after a prolonged exercise bout, thereby elevating the total body content of Na+, which is accompanied by an expansion of body water. Consequently, repeated days of exercise in the heat have been shown to produce a 10 to 15% increase in plasma volume (Costill 1977). This expansion of the extracellular compartment appears to be only temporary, returning to normal within 48 to 72 hours after the cessation of exercise and heat exposure.

III. REPLACEMENT OF BODY FLUIDS

Since the body loses more water than electrolytes during heavy sweating, the concentration of the minerals in the body fluids rises. This means that instead of showing a decline in plasma electrolytes, most of these dissolved minerals show an increase in concentration. Although this may seem confusing, the point is that during periods of heavy sweating, the need to replace body water is greater than the need for electrolytes.

There are obvious benefits in drinking fluids during prolonged exercise, especially during hot weather. Water intake will minimize dehydration, lessen the rise in internal body temperature, and reduces the stress placed on the circulatory system (Figure 2). Even warm fluids, near body temperature, provide some protection against overheating, but cold fluids seem to enhance body cooling, taking some of the deep body heat to warm a cold drink to body temperature.

One might wonder if the intake of too much water could dilute the blood electrolytes, leading to a body deficit? In the last few years, several cases of symptomatic hyponatremia have been reported in endurance athletes (Noakes et al. 1985; Frizzell et al.1986; Hiller et al. 1987). From a clinical point of view, hyponatremia is defined as a blood Na^+ level below the normal range of 136-143 mmol/litre. Some experts have suggested that during ultra-marathon (50 miles or more) running, some individuals may experience unusually low blood sodium levels as a consequence of drinking water in excess of body water losses. A case study of two runners who collapsed after after an ultra-marathon race in 1983 revealed that they had blood sodium values of 123 and 118 mEq/litre. One of the runners experienced a grand mal seizure, whereas the other man became disoriented and confused.

Although the cause of these effects is unclear, the initial diagnosis tends to implicate the lack of body sodium. An examination of the runners' fluid intake (21 to 24 litres) and estimates of their sodium intake (224 to 145 mEq) during the run suggested that they diluted their body sodium levels by consuming fluids that contained little sodium. Recent studies by Barr, et.al. (1991), however, have shown that when subjects consume more than 7 litres (~2 gallons) of plain water during six hours of exercise in the heat, their plasma concentrations only declined by about 3.9 mmoles/litre. Sports drinks that contain 25 mmol/litre were found to have no notable effect on plasma Na^+. The precise causes of the observed exercise hyponatremia remains unclear, and has been reported only in a small number of cases. Thus, it is probably inappropriate to draw generalizations from this information in designing a fluid therapy for individuals who must exercise for long periods in the heat.

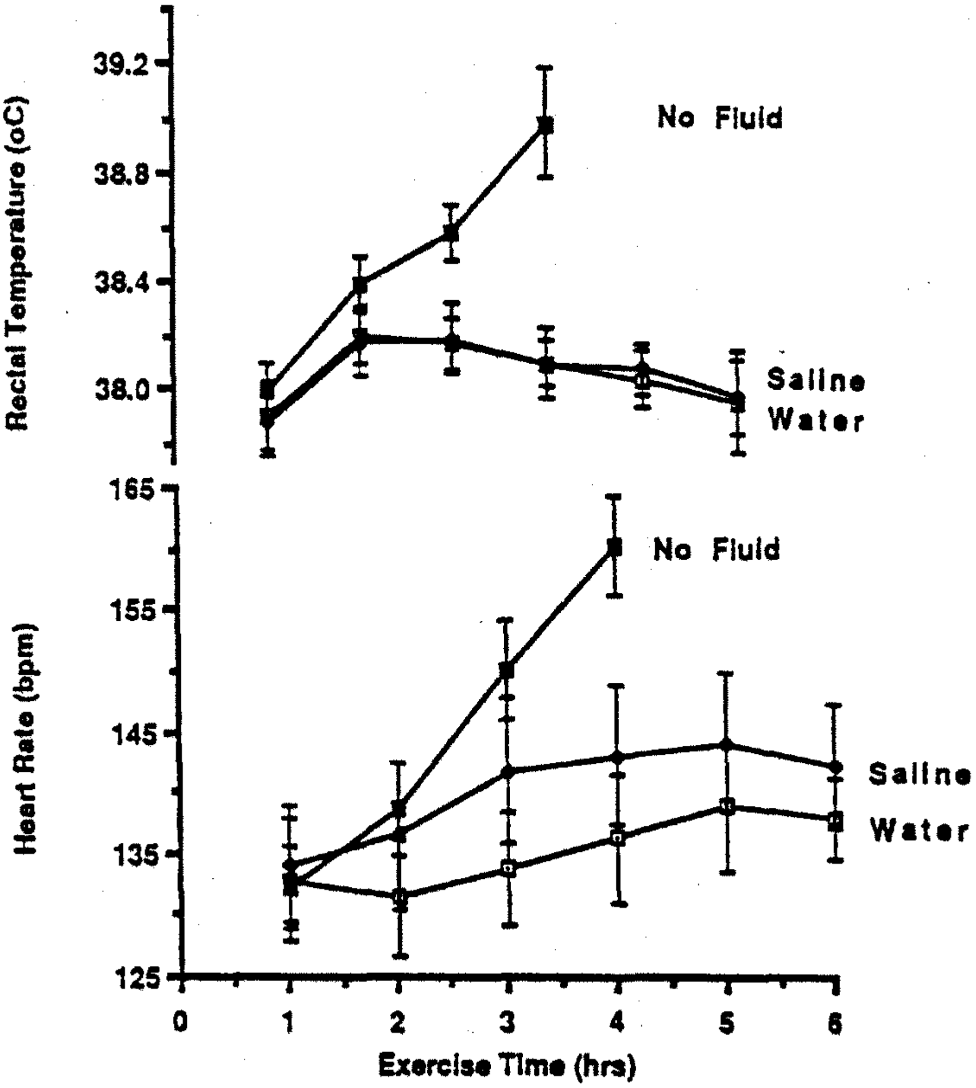

Figure 2. Effects of water intake during six hours of exercise in the heat on heart rate and rectal temperature (modified from Barr et al.1991).

IV. GASTROINTESTINAL ABSORPTION DURING EXERCISE

One's capacity to replace body fluids is influenced, in part, by the rate of gastrointestinal absorption. Since little exchange of water occurs directly from the stomach, the food and fluids we ingest must reach the intestine before they can be absorbed. Many factors affect the rate at which the stomach will empty, including its volume, temperature, acidity, and the number of particles it contains (osmolality). There are a number of review articles available that thoroughly describe the past century of research on the regulation of gastric emptying during rest and exercise (Costill 1990; Thomas 1957; Hunt and Knox 1969).

Gastric emptying is slowed significantly during intense exercise. However, most studies have shown that when the level of activity is maintained at less than 70 to 80% of the subject's aerobic capacity ($V0_2$ max), the rate of gastric emptying of various solutions is not different from resting conditions (Costill and Saltin 1974; Neufer et al. 1986). Thus, it can be assumed that the physiological mechanisms that regulate gastric emptying are similar at rest and during light to moderate activity.

Fat in any digestible form (triglycerides or phospholipids) in the presence of bile and pancreatic juice is the most powerful of the chemical agents that slow gastric motility. In the first 15 min after ingesting a meal containing 100 g of fat, strong antral contractions are entirely absent, and thereafter their frequency and strength are about half those observed after a carbohydrate feeding. If the fatty meal is removed from the stomach, its inhibitory influence disappears in 3 to 5 minutes.

Although the nervous and hormonal regulation of gastric emptying is not fully understood, it is clear that there are a wide variety of stimuli which control the rate at which materials pass through the stomach. Through feedback mechanisms the receptors in the duodenum exert considerable control on the composition of the effluent from the stomach. By slowing gastric emptying, materials in the stomach are diluted by gastric secretions, which add water and minerals to the stomach's contents. The importance of these changes should not be overlooked, since they can drastically alter the composition of ingested materials. Consequently, all solutions and/or solid feedings are modified by the stomach before being delivered to the intestine for absorption.

The volume of solids and liquids in the stomach is one of the strongest regulators of gastric emptying. The greater the volume of the contents, the greater the rate of emptying. Distending the stomach with 250 ml of air after putting 250 ml of water in the stomach increased the rate of emptying to the same level as if the subject had consumed 500 ml of water, demonstrating that the stimulus was distention rather than the weight of the stomach's contents. Subsequent studies have shown that receptors in the gastric musculature respond to increasing distension and pressure by increasing the rate of emptying (Hunt and MacDonald 1954; Minaim and McCallum 1984). Though this suggests that it is important to maintain a sizeable volume of fluid in the stomach (e.g. 400 - 600 ml) in order to promote gastric emptying, excessive distension may retard emptying.

It is generally agreed that carbohydrate solutions empty more slowly from the stomach than water or a weak sodium chloride solution (Coyle et al. 1978; Fordtran and Saltin 1967; Costill and Saltin 1974). The rate of gastric emptying is inversely related to the glucose concentration of the test solution. However, there is no significant difference between the emptying rate for water and a 139 mmol/l (2.5 g/100 ml) glucose solution. Likewise, when gastric emptying was studied at various times (5 to 120 min) after the ingestion of solutions containing 139 to 834 mmol of glucose per litre, nearly all of the 139 mmol/l solution was emptied from the stomach within 20 min, whereas the 834 mmol/l solution took nearly 120 min to empty from the stomach (Costill and Saltin 1974). Similar findings have been reported by Brener et al. (1983) who examined the gastric emptying rates of 400 ml of isotonic saline, and 5.0, 12.5, and 25 g/100 ml glucose solutions. Although the gastric emptying rate is inversely related to the glucose concentration of the drinks, the rate at which calories are emptied from the stomach (kcal/min) was similar (2.13 kcal/min) for all of the glucose solutions.

It should be noted that the factors listed in this section are not the only ones capable of influencing the stomach's function. A limited amount of data are available which suggest that caffeine, emotional distress, diurnal variations, environmental conditions, form of carbohydrate, and the menstrual cycle may also influence gastric emptying (Costill 1990).

As early as 1833, Beaumont noted that severe and fatiguing exercise retarded digestion. Moderate exercise such as running two or three miles after a light meal will slow gastric emptying, while reducing gastric secretion. Lighter activity such as walking, however, did not effectively delay gastric secretion, but increased the rate of emptying. The level of exercise needed to impair gastric emptying has been suggested to vary in accordance with the subjects fitness. Thus, in one subject walking quickly was enough to slow emptying, whereas in another man who trained regularly, running two miles had no effect on gastric function. Studies by Costill and Saltin (1974) reported that exercise had no effect on gastric emptying (~13 ml/min) until the working intensity exceeded 65-80% of the subjects' maximal oxygen uptake ($V0_2$ max). In addition, Costill and Saltin (1974) examined the rate of gastric emptying at four intervals during two hours of cycling to determine the effects of exercise duration. Despite the fatiguing effects of the exercise, there was no change in the rate of gastric emptying from the beginning of the activity (0-30 min) until the end (90-120 min). As a consequence of these studies, it has been assumed that data on gastric emptying measured at rest would be applicable during prolonged activities (e.g. > 2 hr), which are generally performed at intensities below 80% $V0_2$ max.

On the other hand, recent studies by Neufer et al. (1986) have observed that mild to moderate exercise (i.e., walking and slow running) may accelerate the rate of gastric emptying. It has been shown that water and carbohydrate (5 and 7% carbohydrate) solutions empty 38% faster during treadmill exercise (15 min at 50 and 70% $V0_2$ max) than when the subjects remained inactive (i.e., seated) for 20 min after the feeding (Neufer et al. 1986). Submaximal cycling may also increase the rate of gastric emptying, though the findings of recent investigations have often presented conflicting results (Costill 1990; Mitchell et al. 1989; Neufer et al. 1986).

Once foods and fluids leave the stomach, they are not all absorbed at the same rate or via the same mechanisms. A more complete review of this topic is provided by Gisolfi et al. (1990). Normally, about 9 litres of fluid are presented to the intestines each day, 2 litres from ingested fluid, 1.5 litres from saliva, and 5.5 litres from gastrointestinal secretions (Gisolfi et al. 1990). Of this amount, approximately 60% is absorbed by the duodenojejunum, 20% by the ileum, and 15% by the colon. Though a number of methods have been used to measure the rate and quantity of diffusion and absorption in the small intestine, the most widely used technique involves the insertion of a triple-lumen catheter into the duodenum by way of the nasal passage, oesophagus, and stomach. Since this method has been used to a limited degree to study intestinal absorption during exercise, we have little information regarding its role in maintaining fluid balance during exercise and dehydration.

It is generally agreed that moderate to intense exercise will reduce blood flow to the gut, thereby reducing the opportunity for intestinal fluid/food absorption. Fordtran and Saltin (1967), however, found that exercise at 75% $V0_2$ max did not impair gastrointestinal absorption of fluid containing carbohydrates and sodium chloride. Thus, it has been concluded that under most exercise situations, intestinal blood flow and normal motility do not play a major role in altering absorption. However, during highly intense effort, as in long distance running and triathlon competitions, the reported incidence of gastrointestinal distress suggests that there may be some serious alterations in intestinal function. Abdominal cramps can be indications of interruptions in normal motility and/or oxygen supply. Diarrhoea during exertion suggests that there may be abnormal absorption and/or secretion in the small and large intestine. There have even been some cases of gastrointestinal bleeding, indicative of possible ischaemic (i.e., oxygen deprivation) injury to the intestinal lining.

It has been suggested that a variety of things may affect intestinal absorption during exercise, such as the mode of exercise, environmental temperature, and the formulation of ingested solutions. Although some studies have shown a reduced rate of water, Na^+, K^+, and Cl^-

absorption during exercise, most studies have concluded that exercise does not influence intestinal absorption (Gisolfi et al. 1990; Fordtran and Saltin 1967). There have been some indications that the addition of glucose to rehydrative beverages may stimulate both water and Na^+ absorption. It has also been noted that Na^+ is required for glucose transport, information that has been used to justify the addition of Na^+ to sports drinks. This interacting roles of glucose and Na^+ are still unconfirmed, thus it is difficult to extrapolate from laboratory studies that use a triple-lumen tube to normal gastrointestinal function. It should be remembered that these studies use a tube that by-passes the stomach, thereby ignoring the normal contributions of Na^+ and other ions to the ingested solutions.

It has also been suggested that the addition of amino acids to a glucose-electrolyte solution may enhance its absorption. Clearly, the designing the "best" drink for rehydration is still debatable. Though a good case can be made for plane water, it is generally agreed that there are definite nutritional benefits to be gained by adding carbohydrates to the solution. Studies have shown that a drink containing 7 to 10 grams of carbohydrate will empty from the stomach, and is probably absorbed without complication. In light of the commercial competition surrounding "sports drinks," the debate over the "ideal" drink for exercise will probably continue for some time.

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