THE

FLUID REPLACEMENT PROCESS

PRINCIPLES OF BEVERAGE FORMULATION FOR ATHLETES

LAUNCH

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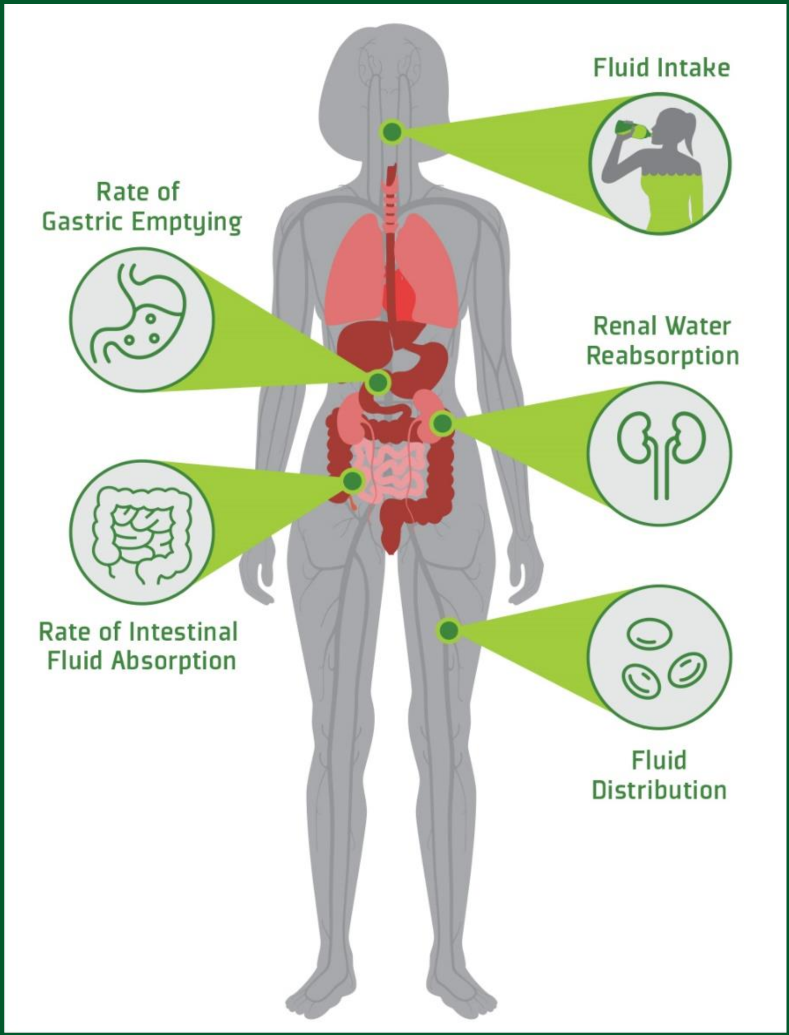


Figure 1: Factors Affecting the Fluid Replacement Process

INTRODUCTION

Substantial volumes of fluid can be lost during intense or prolonged exercise as a consequence of thermoregulatory sweating. [3]

In these situations, athletes need to drink during/after exercise to replace fluids lost to avoid the potential negative effects of dehydration. [28]

As illustrated in Figure 1, fluid replacement is a multi-step process involving a number of physiological systems.

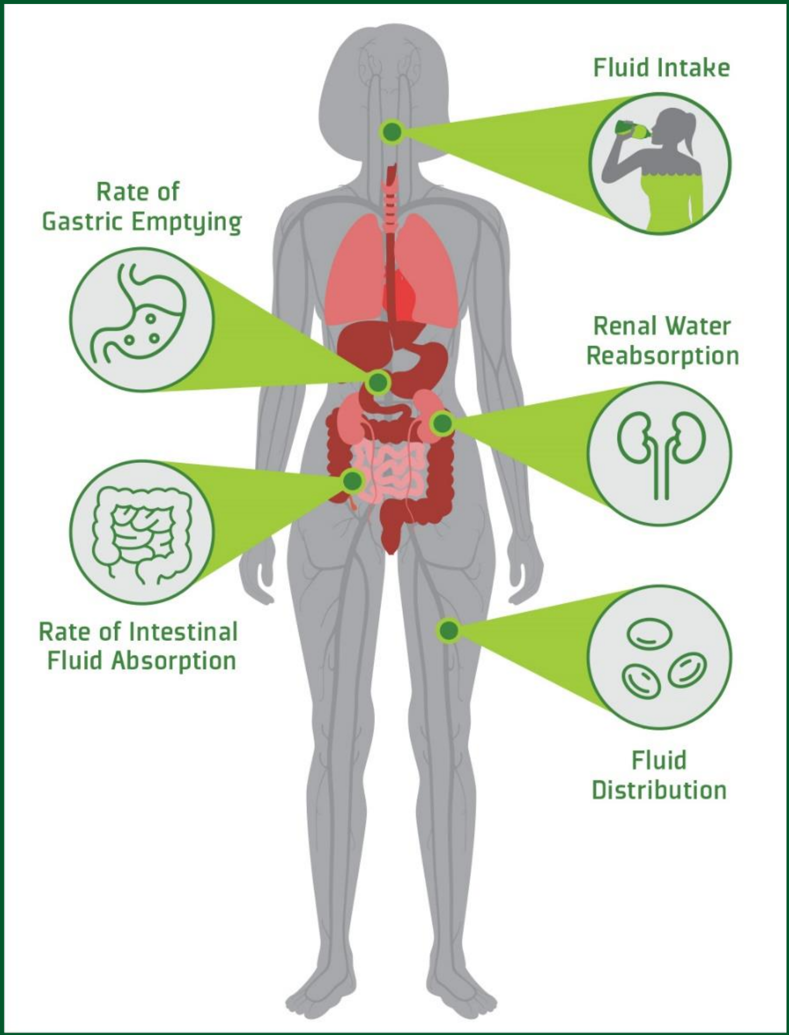


Figure 1: Factors Affecting the Fluid Replacement Process

KEY POINTS

Replacement of fluid losses during/after exercise is a process involving several steps, starting with fluid ingestion, followed by gastric emptying, and culminating in fluid absorption into the bloodstream and distribution to the intra- and extracellular fluid spaces of the body.

Adequate fluid replacement is influenced in part by beverage composition, as the presence of certain ingredients (and the types/amounts) can facilitate or hinder the rehydration process.

Beverage palatability has a substantial impact on voluntary fluid intake. In general, cool (~15°C) fluids with flavoring, electrolytes, and light sweetening are preferred by athletes and lead to increased fluid intake.

The presence of sodium in a beverage can promote fluid intake (thirst and drink palatability), whole-body fluid retention (renal water reabsorption), and fluid distribution into the extracellular space (plasma volume maintenance).

A small amount of carbohydrate (e.g., 1 – 3%) in a sports drink promotes intestinal fluid absorption. Highly concentrated carbohydrate drinks (≥ 8%) can delay fluid delivery. However, formulating with multiple transportable carbohydrates (e.g., glucose and fructose) can increase the rate of gastric emptying and intestinal fluid absorption of beverages with high carbohydrate concentrations.

During post-exercise rehydration, slowing the appearance of the ingested fluid into the circulation via increased beverage energy density (e.g., fluids with carbohydrate, protein; or drinking water with meals) attenuates diuresis and promotes fluid retention.

FLUID INTAKE

Physiological (or regulatory) thirst is stimulated in response to cellular dehydration (hyperosmolality) and extracellular hypohydration (hypovolemia).

However, ad libitum or voluntary fluid intake is also influenced by a complex interaction of numerous other non-regulatory factors.

These include perceived thirst, social influences, cultural preferences, and beverage-related factors.[2, 37]

FLUID INTAKE

The first step in rehydration is the act of drinking water or other fluids. This may sound simple, but as shown in Figure 2, fluid intake is actually very complex and dictated by multiple mechanisms. [1]

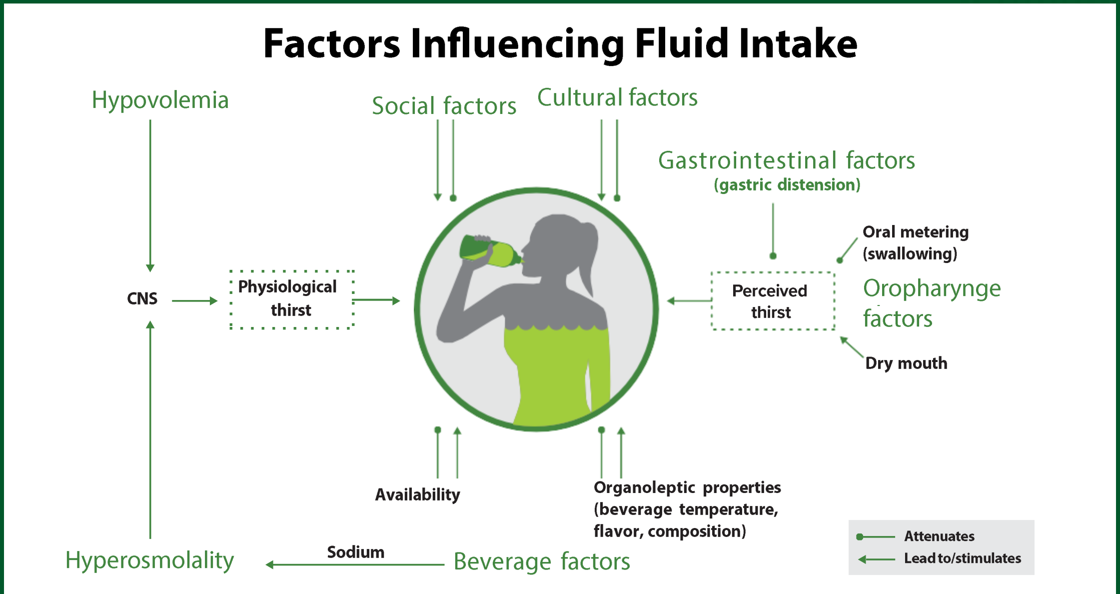


Figure 2: Factors Influencing Fluid Intake

Beverage Palatability

Electrolytes

Click each topic to learn more.

FLUID INTAKE

Beverage Palatability

Flavoring, sweetness, and electrolytes can help improve beverage palatability (i.e., liking and acceptability) and increase ad libitum fluid intake during exercise compared with water. This has been demonstrated in youth and adults, male and female subjects, and in the field during training sessions as well as in controlled laboratory conditions. [29, 38, 39, 43, 50]

It is also important to note that the perception and acceptability of beverage flavor, sweetness, tartness, mouthfeel, and aftertaste are modified by physical activity, [30] as certain flavors or attributes may be more acceptable during exercise than at rest. [38]

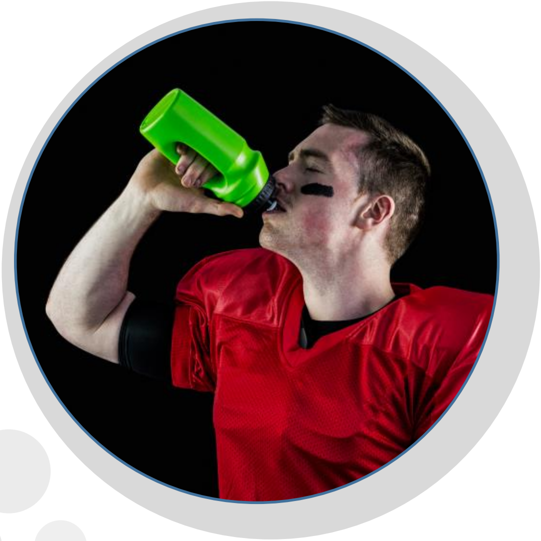
During exercise in temperate to hot conditions palatability and fluid intake seem to be maximized when beverage temperature is cool (15°C), followed by cold (0 – 7°C), then temperate (22°C); while warm-hot beverages are the least palatable (32 – 46°C). [6]

FLUID INTAKE

Electrolytes

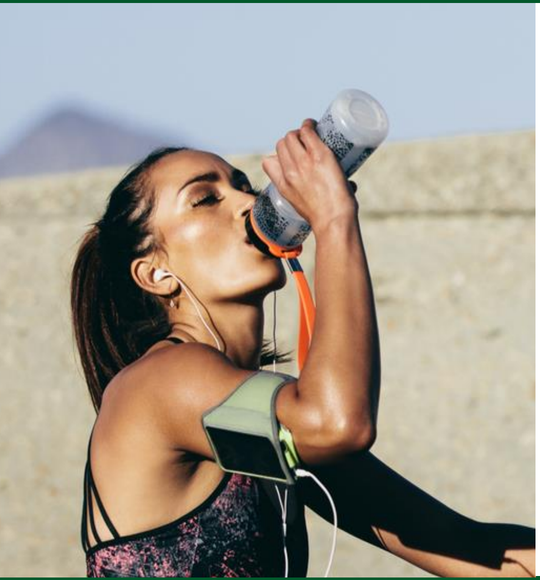
In addition to their effects on beverage palatability, electrolytes (particularly sodium) stimulate the physiological drive to drink.[35] This is because ingestion of sodium increases plasma sodium concentration and in turn plasma osmolality. The sensory information from the osmoreceptors regarding plasma tonicity feeds into higher brain regions to stimulate thirst.

The presence of low to moderate amounts of sodium (e.g., 18 – 40 mmol/L) improves beverage palatability and increases ad libitum fluid intake.[7, 37, 49] On the other hand, consumption of plain water decreases plasma osmolality and sodium concentration, which reduces the drive to drink.[35]



FLUID DELIVERY

The second major step in rehydration is the delivery of fluid into the bloodstream. This process involves both the emptying of fluid from the stomach and the transport of water across the intestinal epithelium (Figure 3). Gastric emptying of fluids is regulated by the interaction of gastric volume and feedback inhibition related to the nutrient content of the small intestine.



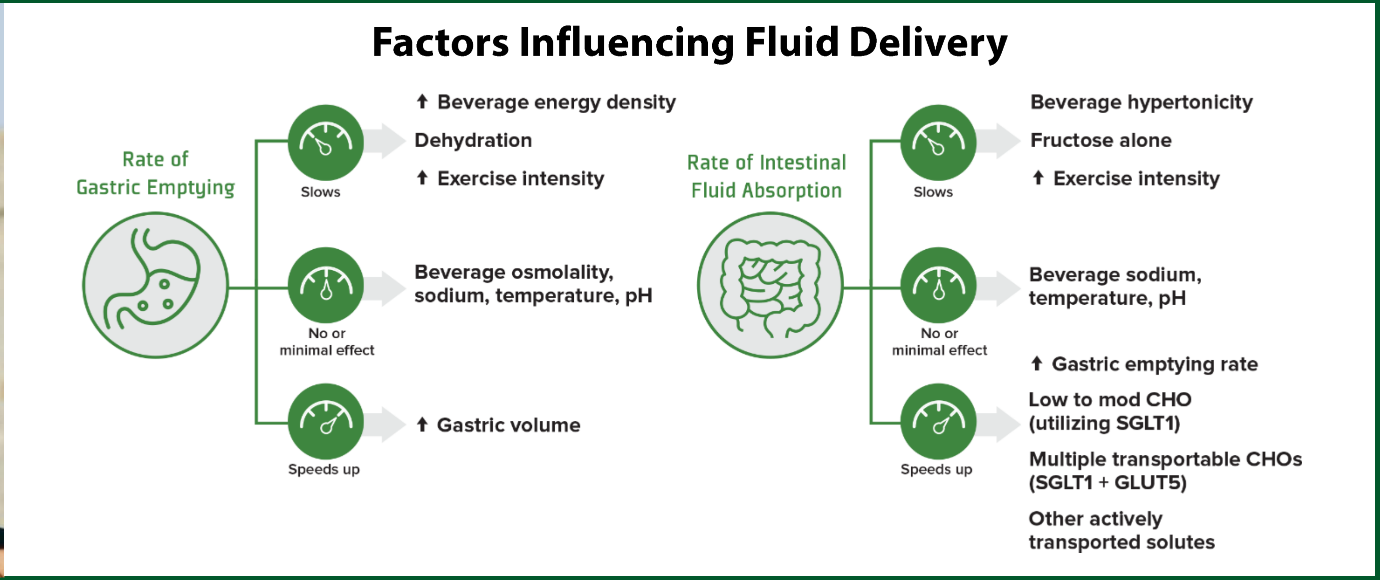


Figure 3: Factors Influencing Fluid Delivery. CHO, carbohydrate; SGLT1, sodium-glucose link transporter1; GLUT5, glucose transporter 5

FLUID DELIVERY

As such, gastric emptying can occur at a maximal rate of up to ~15 – 20 mL/min (~1 L/h) by maintaining a high gastric volume with ingestion of either water or a dilute carbohydrate solution. [8, 22]

After leaving the stomach, absorption of water and solutes occurs primarily in the proximal small intestine (duodenum and jejunum). Absorption of solute (e.g., carbohydrate and sodium) from the intestinal lumen occurs by diffusion along electrochemical gradients and by specific transport mechanisms in the brush border membrane of intestinal epithelial cells. On the other hand, water uptake is a passive process, dependent on an osmotic gradient which is created by absorption of solutes – i.e., water follows solute. [31]

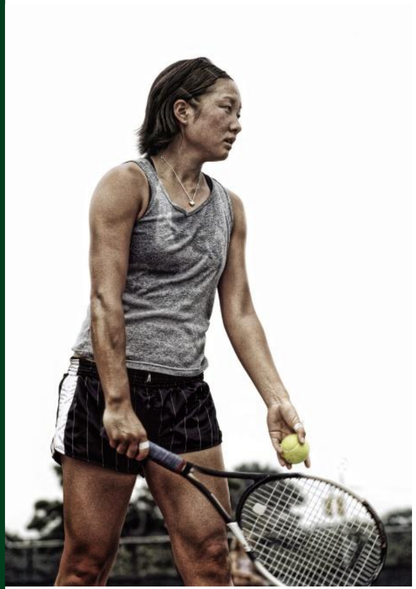
The rates of gastric emptying and intestinal fluid absorption are impacted by various types of stressors. For example, ≥ 3% dehydration and heat stress impair gastric emptying [33, 41] and exercise intensities greater than ~70 – 75% VO2max decrease gastric emptying and intestinal water absorption. [8]

Click each topic to learn more.

- **Carbohydrates**
- **Electrolytes**
- **Protein**
- **Amino Acids**
- **Other Beverage Characteristics**

FLUID INTAKE

Carbohydrates



Since water follows solute, the presence of solute (particularly carbohydrate), is important to stimulate water absorption.

Although carbohydrate plays an important role in stimulating water absorption, the presence of carbohydrates in high concentrations can lead to diminishing returns. In general, beverages with high energy density result in a slower rate of gastric emptying and fluid delivery. [5, 12, 20] For example, beverages with ≥ 8% carbohydrate solution have been found to decrease the gastric emptying rate and increase gastrointestinal discomfort compared with water. [32, 42, 45]

The type of carbohydrate in a sports drink impacts the rate of intestinal fluid and solute absorption because individual carbohydrate types are transported across enterocytes via different mechanisms. For example, a solution containing only glucose (actively transported via SGLT1 transporter) is absorbed faster than a fructose-only (facilitated diffusion via glucose transporter 5 (GLUT-5)) solution. However, a drink with multiple transportable carbohydrates (e.g., glucose and fructose) increases solute and water absorption compared with solutions with a single transportable carbohydrate. [18, 44] Sucrose can either be hydrolyzed into glucose and fructose or utilize its own disaccharide/sucrose transporter (SCRT). [14]

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FLUID DELIVERY

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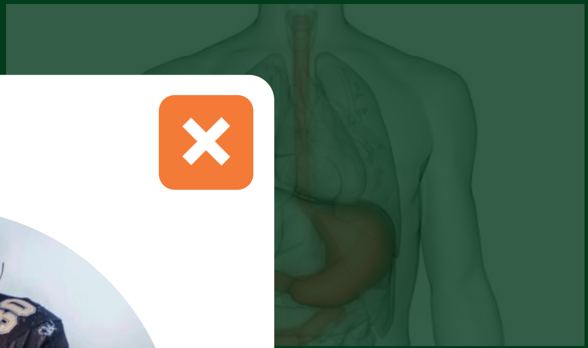

Electrolytes

Although it is well established that sodium is important for SGLT1 transport of substrate and water flux across enterocytes, beverage sodium has been found to play only a minor role in intestinal fluid absorption. This is likely because sodium is readily available through intestinal secretions.[15]

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Other Beverage Characteristics

FLUID DELIVERY

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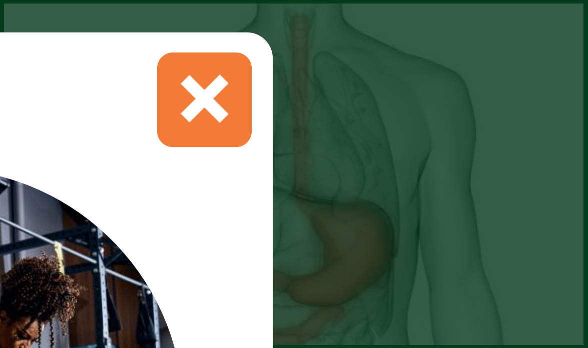

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- Other Beverage Characteristics

Protein

While the inclusion of protein reduces the rate of gastric emptying and intestinal fluid absorption, this delay in the delivery of fluid into the circulation may be advantageous for fluid retention during post-exercise rehydration.

FLUID DELIVERY

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Amino Acids

Most studies to date have found no advantage of amino acid-based ORS over glucose-based ORS in rehydrating patients with diarrhea,[4,17] although this is an area of continued research.[10] Moreover, no studies have measured the efficacy of amino acid-based solutions on intestinal fluid absorption rates in healthy humans during/after exercise.

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- Other Beverage Characteristics

FLUID DELIVERY

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Other Beverage Characteristics

There is no effect of beverage temperature on overall gastric emptying rates or intestinal fluid absorption. This is likely because intragastric temperature rapidly equilibrates with core body temperature after fluid ingestion.

Similarly, the pH of the stomach and intestinal luminal contents are minimally affected by the levels of acidity present in most beverages and thus beverage pH is unlikely to influence fluid delivery.[23]

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• Other Beverage Characteristics

FLUID DISTRIBUTION & RETENTION

Once the ingested fluid is absorbed into the circulation, it is distributed to the intracellular and extracellular fluid compartments according to osmotic gradients. The maintenance of extracellular volume, particularly plasma volume, is important for cardiovascular and thermoregulatory function. To maintain plasma volume and overall whole-body fluid balance, it is important that ingested fluid is retained in the body instead of losing it through urination.

There are two main ways to attenuate diuresis and promote fluid retention: 1) by stimulating renal water reabsorption (e.g., via sodium) and/or 2) by slowing the appearance of the ingested fluid into the circulation (e.g., via increased beverage energy density).[2] Beverage composition can have a significant effect on fluid distribution and fluid retention (Figure 4) during exercise and especially at rest.

During moderate to heavy dynamic exercise, urine output decreases by 50 – 70% due to decreases in the glomerular filtration rate and renal blood flow mediated by an increase in renal vasoconstriction.[51]

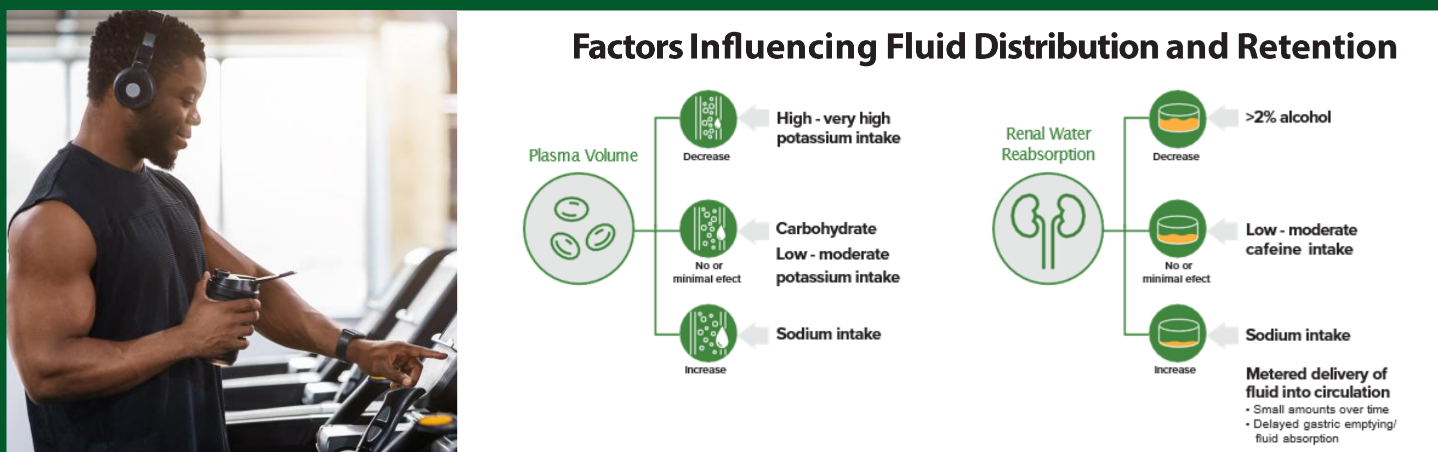

Figure 4: Factors Influencing Fluid Distribution and Retention

FLUID DISTRIBUTION & RETENTION

Before exercise, the goal is to begin the workout in a euhydrated state. After exercise in which the athlete has incurred a body mass deficit, the goal is to drink to replace sweat losses and restore body fluid balance.

Rapid and complete rehydration after exercise is important if the athlete is participating in a practice session or game within the same day or in < 24 h. When there are ≥ 24 h between exercise sessions, adequate fluid can usually be consumed with normal eating and drinking practices (i.e., ad libitum). [47]

Click each topic to learn more.

Carbohydrates **Electrolytes** **Protein**

FLUID DISTRIBUTION & RETENTION

Carbohydrates

Carbohydrate solutions ranging from 6% to 12% have been shown to promote greater fluid retention compared with electrolyte-matched, carbohydrate-free placebo solutions in a rested euhydrated state [27] as well as post-exercise rehydration. [11, 21, 36]

Highly concentrated carbohydrate solutions (e.g., 10 – 12%) could affect fluid retention by delaying gastric emptying or intestinal absorption (from the increased energy density and/or osmolality of the higher carbohydrate beverages), which would effectively delay the appearance of fluid in circulation. The delayed absorption of fluid and/or the higher plasma osmolality elicited by the carbohydrate drink would attenuate renal water excretion. [2]

Other proposed mechanisms, particularly regarding the fluid retention benefits of less concentrated carbohydrate solutions (e.g., 6%), include an insulin-mediated increase in renal sodium and water reabsorption. [21] However, more work is needed to elucidate the exact mechanisms involved and their relative contributions to enhanced fluid retention.

FLUID DISTRIBUTION & RETENTION

Electrolytes

The most osmotically active ions in the intracellular and extracellular fluid compartments are potassium and sodium, respectively.

Since extracellular fluid is the precursor for sweat gland secretions, sweat is comprised mostly of salt water (sodium and chloride concentrations of ~10 – 90 mmol/L) while potassium concentrations are much lower (~2 – 6 mmol/L).[3] Sodium and potassium are often included in sports drinks to help replace losses due to sweating.

There is no debate that inclusion of sodium can have a significant impact on fluid distribution and fluid retention. The increase in blood sodium concentration and osmolality with sodium ingestion stimulates renal water reabsorption and thus decreases urine output. Most studies suggest that fluid retention is significantly improved by drinking a beverage with a sodium concentration of ≥ ~20 – 30 mmol/L compared with no or very low sodium drinks.[16, 24, 27, 40] Furthermore, some studies have found a direct linear relation between beverage sodium concentration and fluid retention.[24, 46]

Since potassium is an intracellular osmolyte it is thought that its ingestion can promote overall water retention by regulating the level of intracellular fluid. However, studies investigating the effects of potassium-containing drinks on fluid retention have found mixed results.

Importantly, several studies have shown that the rate of recovery of the plasma volume during post-exercise rehydration is slower with sodium-free, high-potassium drinks (25 – 51 mmol/L) than control drinks. This observation suggests that restoration of intracellular volume occurs at the expense of the extracellular space when high potassium-containing drinks are consumed without sodium.[25, 34, 48] A slower restoration of plasma volume could have significant cardiovascular/thermoregulatory implications for athletes whose next practice or competition is within the same day, especially if exercising in a hot environment.

FLUID DISTRIBUTION & RETENTION

Protein

Research suggests that protein, especially milk protein, may also play a role in enhancing fluid retention in euhydrated individuals at rest [26] or during post-exercise rehydration. [13]

As discussed above, potential mechanisms by which protein-containing drinks may impact fluid retention seem to be related to a slowing of the overall rate of fluid delivery into the circulation. A delay in fluid entering the bloodstream would consequently slow the reduction in serum osmolality and therefore prolong the stimulus for renal water reabsorption. [13]

SUMMARY & PRACTICAL APPLICATIONS

Replacement of fluid losses during/after exercise is a process involving several steps, starting with fluid ingestion, and culminating in fluid absorption into the bloodstream where it is eventually distributed into the intra- and extracellular fluid spaces of the body. Adequate fluid replacement is influenced in part by beverage composition, as the presence of certain ingredients (and the types/amounts) can facilitate or hinder the rehydration process. Aside from water, the most important ingredients to consider in a rehydration drink are carbohydrates, electrolytes, and flavor. In addition, the timing of fluid intake, as well as other nutritional goals (e.g., energy provision during exercise or protein synthesis after exercise), are important factors to consider when determining the appropriate fluid replacement beverage for athletes.

Click each topic to learn more.

During Exercise **Before/After Exercise**

SUMMARY & PRACTICAL

During Exercise

When rehydration is the priority, lower carbohydrate and osmolality formulations are preferred for the rapid delivery of fluid into the circulation.

When both energy provision and fluid replacement are important, the optimal beverage would be formulated to deliver nutrients to the body without impeding gastric emptying and intestinal absorption of water.

However, when sweat rates are low (e.g., cool weather) or high rates of carbohydrate delivery are necessary (e.g., > 2 h of exercise) more concentrated beverages may be acceptable.[19] The reader is referred to other reviews that discuss the idea of potential trade-offs between carbohydrate and fluid ingestion during exercise.[9]

Before/After Exercise

The two main ways that beverage composition can attenuate diuresis and promote fluid retention are by stimulating renal water reabsorption (e.g., via sodium) and/or by slowing the appearance of the ingested fluid into circulation (e.g., via increased beverage energy density). However, athletes should consider the duration between exercise bouts when deciding the most appropriate composition of a fluid replacement beverage.

If the athlete is significantly dehydrated and the next training session or game is within a few hours, rapid rehydration is needed. In these situations, athletes should drink sodium-containing fluid (with relatively low energy density) to promote fluid retention and plasma volume restoration without delaying fluid delivery to the circulation. Energy-dense fluids may not be suitable when rapid rehydration is needed, since delayed gastric emptying could cause gastrointestinal distress during subsequent exercise.

Milk or other energy-dense carbohydrate/protein-based drinks are effective rehydration beverages when there are several hours between exercise bouts. Another practical way to help attenuate diuresis during rehydration is by drinking water in combination with food, if there is sufficient time to digest a snack/meal before the next exercise session. [13]

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