

# FLUID REQUIREMENTS OF ENDURANCE ATHLETES

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# **1 Literature Review**

## **1.1 Introduction**

This literature review addresses the physiological and nutritional challenges faced by athletes competing in the ironman triathlon. Particular focus will be on fluid requirements, with discussion of the latest research into the optimal composition of carbohydrate electrolyte drinks for maintaining maximal hydration and performance.

It is very common for athletes to experience symptoms of dehydration or heat stress from lack of adequate fluid intake during endurance events. Therefore a review of some of the factors contributing to dehydration, mainly gastrointestinal discomfort, delayed gastric emptying and absorption and fluid palatability will be discussed. These factors may be barriers to the consumption of adequate volumes of fluid during endurance events.

## **1.2 The Ironman Distance Triathlon**

The Ironman Triathlon is regarded as one of the most physically challenging one-day endurance events in sport, with competitors required to swim 3.8 km, ride 180 km and then run a 42.2 km marathon. The average time for completion of the event is between 11 and 12 hours. Elite male competitors generally complete the event in a time between 8 and 9 hours depending on the course and the conditions of the race. Elite female winning times are usually between 9 and 10 hours. The event is not limited to elite athletes with some competitors competing in the race with one common goal, to make it to the finish line. Age is not a barrier with people in all age categories right up to 70-75 years. The first triathlon was completed in 1974 in San Diego USA where only 15 athletes competed, during the 30 years since then, interest in the sport of triathlon has risen steadily [1]. Today at the ironman triathlon world championship held in Hawaii in October of each year, 1500 competitors are involved with around 8000 spectators. The field is restricted to 1500 and entry is through a very competitive qualification process.

## **1.3 Physiological Considerations for Success in Ironman Distance Triathlon**

Ironman triathlon is one of the most gruelling one-day endurance events in sport. The primary determinant of success in ironman triathlon racing is the ability to produce and efficiently utilise large amounts of energy over a long period of time [1]. For this to occur there must be training induced physiological adaptations to the cardiovascular, metabolic, thermal and musculoskeletal systems of the body. In order for a high rate of energy expenditure to occur without creating fatigue, these systems must be working at their

optimal capacity in order to maintain homeostasis [1]. Researchers have found key physiological variables correlate with endurance performance. These include maximal oxygen uptake (VO<sub>2</sub> max), economy of motion and the fractional utilisation of oxygen uptake (VO<sub>2</sub>) [2]. These measures become less relevant for events lasting in excess of 4 hours where the physiological demands of the event become extremely high. Factors such as fluid and electrolyte balance and hydration and glycogen status play a significant role in determining performance outcomes. These external variables can have a greater effect on performance in endurance events than other physiological measures such as VO<sub>2</sub> max or submaximal VO<sub>2</sub> [3].

This review will discuss the nutritional challenges that face the ironman triathlete.

## **1.4 Nutritional Demands of Ironman Triathlon**

Maintaining energy and fluid and electrolyte balance are important areas for consideration in ultra endurance exercise [2]. The main causes of fatigue in an ironman triathlon are energy depletion and dehydration, with both factors playing a significant role in the overall success of an athlete. Competing in an event such as this puts more demand on the fluid and energy balance of the body than any other form of exercise [4]. Understanding the effects that an ultra endurance event such as ironman triathlon has on all of the physiological systems of the body is something that has intrigued sports scientists since its development [1]. The focus in the literature has mainly been on the physiological adaptations needed for success in an ironman triathlon, however performance detriments can occur due to energy depletion and fluid and electrolyte balance, this area, however, has not been well researched [1].

Energy expenditure in an ironman event can range from 35 000 to 48 000 KJ, and sweat rates can be as high as 2-3L/hr in the heat [5, 6]. Knowledge in the area of nutrition appropriate for ultra endurance events has developed greatly over the last two decades. Practical recommendations for fluid and fuel intake during exercise have been based upon interpretation of scientific literature both in the laboratory setting and in the field.

### **1.4.1 Energy Requirements During Exercise**

The ingestion of a carbohydrate source during exercise has been shown to improve endurance capacity by maintaining blood glucose concentrations [7, 8]. In both cycling and running the point of fatigue closely coincides with the rate of glycogen depletion, therefore, increasing muscle glycogen stores prior to prolonged exercise can improve performance [9].

A recent study by Kimber et al [10] looked at the carbohydrate consumption in a group of ironman triathletes and correlated the amount consumed with finishing times. In the male group the amount of carbohydrate consumed throughout the ironman race positively correlated with finishing time [10]. Similar findings have been reported by Below et al [8] who studied the performance of a group of cyclists in a time trial performed at the end of a 50 minute cycling effort at moderate intensity. The subjects undertook four separate trials involving the replacement of fluid and or carbohydrate during the one-hour of cycling. The

replacement of fluid resulted in a 6% improvement in performance; similarly the replacement of carbohydrate resulted in the same 6% improvement. However the combination of both strategies resulted in a 12% performance increase [8]. This study highlights the need for the consumption of both fluid and carbohydrate in order to maximise performance. A further study by Carter et al [11] showed a performance improvement in a one hour cycling time trial in 9 endurance cyclists when a carbohydrate solution was rinsed around the mouth without swallowing, compared to a water placebo [11]. The carbohydrate drink was made up of 6.5% maltodextrin. Maltodextrin is a partially hydrolysed starch that when dissolved in water is colourless and nonsweet. Because of this the subjects were not aware of which solution they had received in order to eliminate any placebo effect. The mechanism responsible for the performance improvement is unknown but may involve the carbohydrate receptors in the mouth stimulating central pathways associated with motivation.

Endurance exercise of longer duration than 4 hours will cause depletion of muscle glycogen. Therefore, it is no surprise that when carbohydrate is supplied to athletes there are performance improvements compared to when only water is given [12].

Based on the feeding protocols used in studies which have noted significant performance improvements, it has been suggested that athletes ingest carbohydrate at a rate of 30-60g per hour [13]. There is, however, no conclusive evidence as to the most appropriate level of carbohydrate to consume per hour during endurance exercise.

For an ironman athlete, practical considerations also dictate the timing and frequency of carbohydrate intake during the event. The study mentioned above by Kimber et al [10] showed that more than half of the carbohydrate intake during the triathlon event was consumed during the cycle leg. Based on this information it is important to consider the practicality of the nutrition recommendations that are given to ironman triathletes and the possible need for a slightly increased intake of energy during the cycle leg in preparation for the marathon finish.

## **1.4.2 Fluid Intake Recommendations**

### **1.4.2.1 Sports Medicine Australia Hydration Guidelines**

- 1) The sweat rate of an athlete should govern how much they drink during exercise. An athlete with a high sweat rate should drink more than an athlete who does not lose as much fluid through sweat.
- 2) To diminish the risk of heat illness fluids should be consumed before, during and after sport.
- 3) It is recommended that athletes drink at least 7-8ml/kg of fluid per kilogram of body weight 2 hours before exercise.

- 4) During exercise athletes should drink at least 3ml/kg of body weight every 15-20 minutes.
- 5) Water is considered adequate for activities lasting up to 1 hour in duration, athletes participating in exercise for longer than 1 hour or in hot conditions should consume a sports drink to replace both carbohydrate and electrolytes lost in sweat [14].

The sport of triathlon poses greater nutritional challenges than any single event sport. Because of the lengthy competition time the prevention of hypohydration is extremely important, not only in terms of performance but also in order to avoid serious physiological disturbances [3]. Fluid intake during both the swim and the run leg poses unique challenges for the athlete. Consumption of fluid during the swim leg is impossible due to the nature of the activity. Apart from the practical issues such as carrying and drinking fluids while running, the gastrointestinal disturbances often-accompanying high fluid intakes during the run leg also pose problems. Therefore during competition, cycling provides the best opportunity for the athletes to ingest fluids [3]. Fluids during this leg are readily available at aid stations so consuming and replenishing supplies has minimal negative performance effects.

In the 1960's the scientific literature suggested that the dehydration caused by a 3-4% decrease in body weight was insignificant and it was only until greater than 4% of body weight was lost that there was a danger to health [15]. Today it is well acknowledged that a fluid deficit of this kind is not only detrimental to performance but also a hazard to health.

In its most recent position stand [13], the Australian College of Sports Medicine recommends that 'During exercise, athletes should start drinking early and at regular intervals in an attempt to consume fluids at a rate sufficient to replace all the water lost through sweating'. In 2000, the National Athletic Trainers Association also published a position statement that aimed to 'provide useful recommendations to optimise fluid replacement for athletes'. The statement identified individual variation in fluid intakes due to differences in sweating rates, environmental conditions, exercise duration, exercise intensity as well as the sport dynamics [16]. Further recommendations from the statement were that 'fluid replacement should approximate sweat and urine losses, and at least maintain hydration at less than 2% body weight reduction' [16]. This highlights the evolution of scientific findings in the last 30 years in this area, and the challenges in developing practical individual guidelines for ultra endurance athletes.

## **1.5 Fluid Imbalance: Dehydration and Heat Stress**

### **1.5.1 Physiological Disturbances**

All physiological systems in the body are affected by dehydration [17]. The degree to which a person is dehydrated dictates the compromise to each of the major systems of the body.

When a person begins exercising in the heat, there is an associated rise in core body temperature. The body attempts to offset this increase in temperature by heat dissipation via conduction, convection, radiation and most effectively through evaporation [18]. Heat dissipation through the evaporation of sweat is the most effective means of regulating temperature during exercise. In hot and dry conditions evaporation may account for 98% of cooling [18]. If adequate fluid is not consumed to offset what is lost through sweating, progressive dehydration will occur.

Aerobic exercise can produce a regional change in blood flow distribution [18]. Muscular endurance exercise requires an increased level of blood flow to the working muscles and an associated decrease in flow to non-exercising muscles (splanchnic area and the skin). As dehydration progressively occurs there is competition for blood circulation between active muscles for metabolism and the skin for heat dissipation [18]. Because of the reduction in skin blood flow, causing reduction in the ability to thermo regulate through sweat evaporation, body temperature progressively increases. During endurance exercise in the heat, there is an increase in core body temperature of 0.2 degrees for every 1% of body weight that is lost [19].

Along with the decreased ability to thermo regulate, there is an associated increase in cardiovascular strain. This is characterised by an increase in heart rate and decreased stroke volume and cardiac output [19, 20]. Montain and Coyle [21] demonstrated that the amount of dehydration induced (between 1% and 4% of body weight) was in direct proportion to the increase in heart rate and decrease in stroke volume that was observed. Similarly Sanders et al [22] reported an increase in heart rate of approximately 10 beats per minute over a 90 minute cycling effort.

There are also psychological changes associated with dehydration that should be considered. Dehydration has been shown to increase the perceived rate of exertion as well as impairing mental functioning [19]. Motivation to exercise and perform is an important requirement of elite endurance athletes. Dehydration reduces both the motivation to exercise along with the time to exhaustion.

### **1.5.2 Effects on Performance**

The effects of dehydration on endurance exercise performance has been studied by either inducing a certain degree of body water loss before exercise, or by allowing dehydration to develop during exercise (Shirreffs 2005). The experimental findings of research is therefore different depending on the approach taken. It is clear from review of the current published literature that dehydration does have a marked effect on endurance performance. Consequences of dehydration in the athlete include reduced training capacity, and sports performance, along with compromised ability to thermoregulate [23]. Any level of dehydration will greatly affect events that rely heavily on the cardiovascular system. When body water content is decreased, cardiovascular strain is seen through an increase in heart rate and decrease in stroke volume (Shirreffs 2005). When exercise is performed in a hot and humid environment, dehydration of as little as 2% of body mass, has consistently been shown to decrease endurance exercise performance (Below et al, Walsh et al, Barr et al).

A recent study performed on endurance cyclists indicated that dehydration resulted in a decreased ability to maintain maximal exertion during a cycling effort. In this study the cyclists were to perform a time trial at 90% of VO<sub>2</sub> max for as long as they were able, directly after a 60 minute cycle at 70% of peak VO<sub>2</sub>. It was noted that a 2% reduction in body weight prior to the start of exercise decreased the maximum cycling time at high intensity by approximately 34%, when compared with the hydrated group [24]. Furthermore a review by Sawka et al [25] indicated that small (2% body weight) to moderate (4% body weight) water deficits were shown to significantly decrease exercise performance, primarily due to a significant reduction in maximal oxygen uptake in a hot environment [25].

The current research indicates that dehydration causes premature fatigue in athletes competing in endurance sport in the heat. This is mainly due to the effects on circulation, which makes hyperthermia more difficult to deal with, causing a further increase in core body temperature, heart rate and ratings of perceived exertion.

## **1.6 Composition of Commercially Available Sports Drinks**

The production and sale of sports drinks is a very competitive industry [12]. The market is growing rapidly with a variety of products claiming that their product is superior to rival beverages. As a result of the immense number of drinks on the market, selecting an appropriate sports drink can be overwhelming for the athlete [12]. Table 1 lists a small percentage of the sports drinks available on the market; the table also demonstrates the variation that exists between products in terms of their carbohydrate and electrolyte composition.

Sports drinks are designed to maximize fluid absorption and enhance performance by delivering extra calories in the form of carbohydrates while also supplying water needs.

Sports drinks are formulated to

- 1) Prevent dehydration
- 2) Provide electrolytes to replace what is lost in sweat
- 3) Provide a source of carbohydrate to replenish working muscles
- 4) Be highly palatable to encourage athletes to voluntarily hydrate throughout exercise.

**Table 1: Comparison of the contents of a selection commercially available sports drinks**

<b>Sports Drink</b>	<b>Energy (Kj/100ml)</b>	<b>Carbohydrate (g/100ml)</b>	<b>Sodium (mg/100ml)</b>	<b>Potassium (mg/100ml)</b>
<b>Powerade</b>	135	7.6	25	3
<b>Aqualyte</b>	67	3.8	28	12
<b>Gatorade</b>	262	6.0	44	0.7
<b>Endura</b>	257	6.4	80	160
<b>Staminade</b>	212	5.2	58	49
<b>PB Fluid and electrolyte replacement</b>	109	6.8	58	18
<b>Carbo Shotz</b>	115	6.8	50	19

### **1.6.1 Carbohydrate Content**

The sports drinks described in Table 1 vary in both carbohydrate and electrolyte content. Carbohydrate concentration ranges between 3.8 and 8%, while both the potassium and sodium concentrations in the drinks are extremely varied.

It has been well recognised that the consumption of a sports drink containing carbohydrates increases endurance capacity, time to exhaustion and ultimately improves performance [7, 26, 27]. The improvement in performance is thought to occur due to the sparing of muscle glycogen [15]. The rate at which sports drinks are emptied from the stomach and absorbed by the small intestine are two factors that can limit the availability of the ingested fluid [28]. The optimal concentration of carbohydrate and electrolyte that is required for maximum emptying and absorption rates is still uncertain, further research is required. Some studies report that



carbohydrate solutions with greater than 7% concentration, empty from the stomach at similar rates to water [29, 30]. Other studies have reported an inhibition of gastric emptying at comparatively low carbohydrate concentrations [31-33]. Variation in study results can be attributed to the differing methods of measuring gastric emptying, the fitness of the subjects used, the exercise completed by the subjects and the length and intensity of the exercise sessions. A more detailed comparison of these studies will be covered later in this review.

## **1.7 Rationale for Using Sports Drinks**

The topic of whether sports drinks provide a performance benefit to athletes that is superior to water has been a focus of research for many years [12]. There are a number of important factors influencing how effective a sports drink is at replacing lost fluids during endurance exercise in the heat. These factors include:

- 1) The quantity of the beverage which is ingested by athletes during exercise, this is strongly influenced by the palatability of the drink [34].
- 2) The time it takes for the beverage to be emptied from the stomach
- 3) How long the drink takes to be absorbed into the blood from the small intestine.

These factors have been the topic of extensive research. It is often difficult to draw conclusive results from this research. The drinks investigated are often not commercially available to consumers; therefore whether they are exactly equivalent to commercially available drinks is unknown. The next section of this review will discuss the effects of various compositions of carbohydrate electrolyte drinks and their effects on fluid consumption, gastric emptying, intestinal absorption and performance.

## **1.8 Carbohydrate Electrolyte Solution Vs Water for Endurance Exercise**

Plain water is not the ideal pre, during or post exercise hydration beverage particularly when considering ultra endurance exercise [35]. When exercising for prolonged periods in very hot conditions sweat losses can be as high as 2-3L/hr, this would equate to a salt loss of 10-14 grams. In this type of prolonged exercise complete restoration of fluid balance is required immediately. If this sweat loss was replaced with plain water a dilution of the plasma may occur, resulting in low plasma sodium. Therefore, in order to replace the salt lost in sweat, sodium is added to a replacement beverage. Sodium is also added to the drinks to aid in the transport of glucose and water across the intestinal wall. In addition to this, glucose is added to a sports drink in order to maintain blood glucose levels and replenish working muscles.

A study by Nielson et al [36] determined that consuming electrolyte free beverages promoted high urine flow, indicating that a minimal amount of fluid was being absorbed [36]. They also established that fluid volume was maintained more effectively when electrolytes were

included in the rehydration fluid. The marked fall in plasma osmolarity and sodium concentration that occurs also reduces the drive to drink.

## **1.9 Factors Influencing Consumption and Absorption**

### **1.9.1 Influence of Fluid Palatability on Ingestion During Exercise**

Replenishing fluids lost during prolonged exercise in the heat is important for maintaining hydration status [13]. Providing access to adequate fluid is often not enough to prevent hypohydration. A classic study by Pitts et al [37] reported that men who are working in the desert heat do not voluntarily replace all of the fluid that they lose due to sweating [37]. This voluntary dehydration has been reported in athletes [9]. The thirst mechanism is insensitive and will not stimulate an athlete to drink until between 1% and 2% of body weight loss has already occurred [9]. This is reflected in the low levels of fluid consumed by athletes during endurance competition. During a 42km marathon competition, mean fluid intake for a group of runners was  $577 \pm 46$ ml equivalent to a rate of 155ml/hr. This volume of fluid intake is well below the estimated sweat rate of between 1 and 2L/hr in these athletes [38].

The palatability of a beverage is an important factor influencing the consumption of fluid and significantly contributes to rehydration [9]. The organoleptic characteristics of fluid such as colour, odour, temperature as well as taste, affect human senses and therefore are critical to palatability and intake [34]. According to the American College of Sports Medicine's position statement on exercise and fluid replacement, enhancing the palatability of the fluid consumed during exercise can improve overall fluid consumption and, therefore, improve the match between sweat losses and fluid consumption [13]. Several factors will influence palatability and therefore the desire to drink. The addition of flavour to a drink has been shown to stimulate drinking behaviour [39, 40]. A study by Wilmore et al [41] investigated the relationship between taste preference and fluid intake during and following exercise. Two commercially available sports drinks varying in carbohydrate content were used along with water. These fluids were offered *ab libitum* during 90 min of exercise followed by 90 minutes of rest. Results showed that when a subject rated a drink highly in terms of taste they would drink significantly larger volumes of the fluid. Similarly Hubbard et al [34] found that the addition of flavouring to a fluid resulted in an increased consumption, by approximately 50% during prolonged exercise.

A further study by Bergeron et al examined the difference in ad libitum fluid intake, comparing a 6% carbohydrate electrolyte drink and water. Fourteen fit tennis players completed 120 minutes of tennis specific training in the heat on separate days. Results of the study showed that there were no significant differences between the trials with respect to fluid intake. Limitations of this study may have affected the results. It is difficult to ensure that the athletes were training at the same intensity during both of the training sessions without the recording of heart rate throughout. Temperature in this study was controlled in each of the sessions however environmental factors such as humidity and wind could have influenced fluid intake.

Electrolytes, particularly sodium, are added to sports drinks in order to replace salts that are lost in sweat. Sodium stimulates glucose and water uptake in the small intestine and aids in maintaining extracellular fluid volume [9]. A moderate sodium concentration increases the drive to drink [34], however a high sodium concentration tends to make a solution unpalatable [9]. It is very important that sports drinks are formulated to include sufficient carbohydrate and electrolyte, however, they must strike a balance between efficacy and palatability [9].

## **1.9.2 Gastric Emptying of Fluids During Exercise**

Endurance exercise lasting in excess of 4 hours places severe demands on sweat production in an effort to minimise body heat storage [42]. In addition to this, muscle glycogen depletion due to limited availability of carbohydrate is another factor contributing to severe fatigue in endurance athletes [3]. There have been a number of published studies in the literature reporting improvements in performance when the subjects were given carbohydrate throughout endurance exercise [27, 43].

The intake of fluids containing a carbohydrate source during exercise can decrease the risk of dehydration and hyperthermia as well as provide an energy source to prevent premature fatigue and improve endurance performance [42]. The replacement of water and carbohydrate during exercise is however limited by the rate of gastric emptying [31]. Gastric emptying refers to the action of the stomach contents emptying into the small intestine for absorption into the blood stream. The next section of this review will discuss the measurement of gastric emptying, the physiological controls, along with the factors which influence gastric emptying rate.

### **1.9.2.1 Measurement of Gastric Emptying**

There are a variety of techniques used to assess the rate at which solids and fluid leave the stomach [42]. These include X-ray, radioisotopic and tomographic techniques.

Radioisotopic techniques use indium to follow the movement of materials within the gastrointestinal tract. A scanner outside the body is used to measure the radiation emitted from the stomach, sensing the degree of movement of materials out of the stomach [42].

Tomography uses skin electrodes placed over the stomach, it measures changes in resistance to produce a computer-generated image of stomach contents. This technique is non invasive to the subject, however, measurements are only limited to a relative index of gastric emptying, stomach contents are not sampled [42].

The most well used technique is aspiration, which employs a French gauge tube that is passed through the nasal passage to the stomach. There are a number of studies in the literature aimed at assessing the gastric emptying rates of different fluids during exercise [30, 44, 45]. Due to methodological differences in calculation of gastric emptying rate, it is difficult to compare the results of such studies. There is also wide individual variation in rates of

gastric emptying; therefore the use of a limited number of subjects in some studies may be unreliable.

### **1.9.2.2 Physiological controls of Gastric Emptying**

There are a wide variety of stimuli that control the rate at which food and fluid pass through the stomach. It is clear that there is both a nervous and hormonal regulation of gastric emptying rate [42]. The volume of stomach contents is one of the strongest regulators of gastric emptying, so when there is a large volume of gastric contents, the rate of gastric emptying is increased. Fat is one of the most powerful inhibitors of gastric motility [42]. The major control mechanisms for gastric emptying involve duodenal gastric reflexes. The duodenum has receptors that respond to the presence of carbohydrate, fat, protein and acid. Stimulating these receptors causes a decrease in the gastric emptying rate [46]. Through feedback mechanisms the receptors in the duodenum exert control over composition of the materials moving out of the stomach.

### **1.9.2.3 Factors influencing rate of Gastric Emptying**

Gastric motor activity and consequently gastric emptying rate is controlled by neural factors governed by receptors in the gastric musculature and proximal small intestine [47]. Other factors may influence gastric emptying rate including caloric content and carbohydrate content, volume, osmolarity, temperature, PH of the fluid, and exercise.

#### **a) Carbohydrate and Caloric Content**

The rate at which carbohydrate electrolyte solutions are emptied from the stomach is primarily influenced by the volume of fluid consumed along with the carbohydrate content of the fluid [42]. The progressively more concentrated a carbohydrate solution becomes the more slowly it is emptied from the stomach. The literature is unclear as to the exact carbohydrate concentration at which the gastric emptying rate is slowed relative to water [48].

Murray et al [48] performed a study to investigate the effects of repeated ingestion of drinks containing varying concentrations of carbohydrate and osmolarity on gastric emptying during low-moderate intensity cycling [48]. Fourteen subjects participated, both male and female. The subjects cycled at 70% of peak  $\text{VO}_2$  for a period of 90 minutes in an environmental chamber set to 22.8 degrees Celsius. Gastric emptying was measured using aspiration of stomach contents. Beverages used in the investigation included water and three carbohydrate-electrolyte solutions with 4%,6% and 8% carbohydrate. The data demonstrated that the ingestion of the 8% CHO beverage significantly reduced gastric emptying rate. In support of these results Vist and Maughan [49] reported that 4% and 6% glucose solutions emptied from the stomach significantly slower than water. The double sampling method was used to assess gastric emptying rate. Similar results were reported by Costill et al [31] and Ryan et al [32] who have indicated that beverages containing above 5% carbohydrate, empty significantly slower from the stomach than water.

There are studies, however, that have reported no difference in gastric emptying rate between water and drinks containing more than 6% carbohydrate [30, 32]. The results from a study performed by Rogers, Summers et al [30] indicated that lowering the CHO concentration of a drink to below 6% does not enhance gastric emptying. Five out of 8 subjects were able to complete all trials which consisted of 85 minutes of constant cycling at 85% of  $\text{VO}_2$  max, followed by a 3 mile time trial. All trials were performed in a thermo neutral environment (22 degrees). Low subject number in this investigation significantly reduced the power of the study.

There are a number of factors that add to the difficulty in comparing gastric emptying across a range of studies. Results that are collected using gastric aspiration experience a lag from the time that the stomach contents are aspirated following drinking. [48], because of this comparison between studies using different aspiration times is difficult. Further difficulties exist due to differences in the method used to measure the gastric emptying rate, as well as the volume of fluid ingested, the frequency of ingestion along with the exercise intensity.

## **b) Solute Osmolarity**

The osmolarity of a fluid refers to the number of osmoles of solute per litre of solution. The osmolarity increases with an increase in the number of particles. The osmolarity of the ingested beverage has been shown to be of secondary importance with respect to the gastric emptying rate [12]. Data from a number of studies in the literature suggest that beverage osmolarity can significantly slow the gastric emptying rate [18, 48]. Costill et al [31] found that when the glucose concentration in a beverage exceeded 139mM, gastric emptying was significantly delayed. The ingestion of a hypertonic solution (430mM) in this study induced a marked delay in gastric emptying. Conclusions from the study were that in order to maintain an optimal rate of fluid replacement, the concentration of glucose in a solution should be minimised in order to maximise gastric emptying.

The effect of osmolarity on gastric emptying has been reviewed [42, 47, 50]. Although the results of these studies are consistent with the theory that the osmolarity of the stomach contents may influence gastric emptying, especially when hypertonic solutions are ingested, they also suggest that the carbohydrate content and calorific content may also have an effect.

The effect of osmolarity on gastric emptying however remains controversial, differences in data can be attributed to differences in the techniques of assessing gastric emptying, the composition of the fluids ingested along with the exercise time and intensity. Further studies are needed in the area to confirm the effects of varying tonicity on gastric emptying.

## **c) Exercise**

The effect of exercise on gastric emptying has been reviewed extensively [42, 47, 51]. Early studies in the area reported that even low to moderate intensity walking and jogging reduced

gastric emptying rate in a group of young men [52].

In a much more recent study by Costill et al [31] the rate of gastric emptying at 4 intervals throughout 2 hours of cycling was examined to determine differences at varying exercise times. There was no change in gastric emptying rate from the beginning of the activity until the end. It has been suggested that gastric emptying is not effected at intensities of up to about 70% of  $\text{VO}_2$  max, however, exercise at intensities higher than 70% tends to delay gastric emptying [12].

### **1.9.3 Intestinal Absorption of Fluids**

Intestinal absorption is the transport of solute and water from the gut lumen, across the intestinal epithelium, into the lymph or venous blood. Absorption can occur via three different processes:

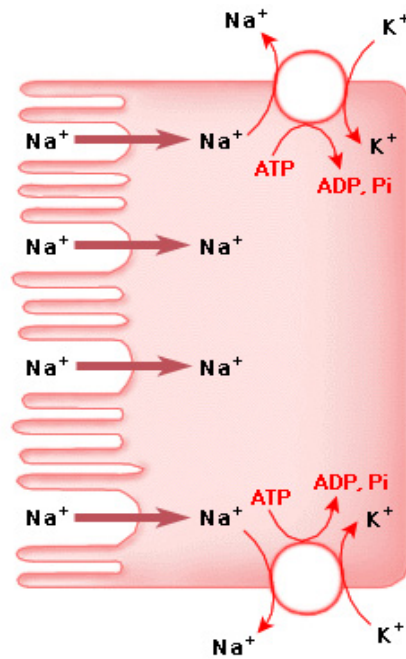
- a) Simple Diffusion: This process does not use metabolic energy and the solute is not transported against a gradient.
- b) Facilitated Diffusion: This process involves a transport protein which aids transport through the gut lumen, the process does not use metabolic energy and is not transported against a gradient.
- c) Active transport: This process involves transport proteins and demonstrates substrate specificity. This process requires metabolic energy and is against a concentration gradient [46].

#### **1.9.3.1 Generation of an Electrochemical Gradient: The Sodium/Potassium Pump**

The plasma membrane of the small intestine consists of the brushborder that faces the lumen and the basolateral membrane facing the blood. The Na-K ATPase is located on the basolateral membrane of the cell (see Figure 1). Its primary function is to pump  $\text{Na}^+$  out of the cell and  $\text{K}^+$  into the cell. This results in an electrochemical gradient across the basolateral membrane. This process requires metabolic energy in the form of ATP. It also creates a chemical gradient across the membrane, where under normal conditions the inside of the cell contains high concentrations of sodium and the extracellular fluid contains high concentrations of potassium.

**Brush  
Border**

**Basolateral  
Membrane**



**Figure 1: Generation of an Electrochemical Sodium Gradient Across Plasma Membrane of an Intestinal Cell [46].**

### 1.9.3.2 Carbohydrate Absorption

Glucose is absorbed by secondary active transport where it forms an obligatory complex with a sodium molecule in the brush border of the cell. The glucose carrier has binding sites for sodium and glucose molecules. When both of these sites are occupied the complex is actively transported into the membrane of the cell where both molecules are released into the cytoplasm [46]. The empty carrier then moves back out of the cell to the brush border to continue the process. The electrochemical gradient created by the sodium potassium pump provides the energy for the movement of glucose into the mucosal cell. The addition of glucose to an electrolyte replacement beverage can increase water absorption six fold and sodium absorption four fold (Costill 1990).

### 1.9.3.3 Electrolyte Absorption

Both active and passive solute transport occurs along the entire length of the intestine [42]. Absorptive processes occur in the epithelial cells of the villi, while secretory processes are stored in the crypt. Sodium is the most important electrolyte as it is continually lost in sweat. Potassium is also included in sports drinks in concentrations similar to those in sweat.

There is no evidence for the inclusion of any other electrolytes in sports beverages. (see Section 1.11).

#### **a) Sodium**

Sodium is the major ion in the extracellular fluid, therefore if plasma volume is to be maintained, sweat sodium losses must be replaced. Water transport and fluid homeostasis is highly dependant on the movement of sodium. Sodium can be absorbed both actively and passively. Passively it can move down its electrochemical gradient, through leaky tight junctions, into the interstitial fluid within cells [53]. The amount of passive diffusion within the intestine varies with an insignificant amount occurring in the colon. Sodium can also move through the cells in an energy dependant process that involves two carriers, either glucose or amino acids. Sodium is transported down its electrochemical gradient, providing the energy for the uphill movement of glucose into the mucosal cell. Active transport of sodium across the basolateral membrane via the Na<sup>+</sup>/K<sup>+</sup> pump conserves the sodium gradient across the the mucosal membrane. The transport of glucose and sodium via this carrier results in a transfer of positive charge across the membrane. This allows for bulk absorption of sodium while providing maximal absorption of substrate and water [46].

#### **b) Potassium Absorption**

98% of total body potassium resides in the intracellular space, with a concentration of approximately 3.8-5.0mEq/L. Potassium passively moves down its electrochemical gradient across the basolateral membrane and brush border membrane. Unlike sodium, it does not play a role in the absorption of other nutrients. Total body potassium loss during exercise is not large, however it can become significant during prolonged exercise or exercise in the heat. It may be important in achieving rehydration by aiding in the retention of water in the intracellular space(Costill 1990).

#### **1.9.3.4 Water Absorption**

The absorption of water is highly dependant upon the movement of sodium in the luminal cells of the small intestine. Sodium that is pumped into the intercellular spaces results in a concentrated area of high osmotic pressure. This induces movement of water from the lumen through the cell into the lateral space. This movement raises the hydrostatic pressure and as a result water is flushed into the interior of the villus to be picked up by the capillary network.

### **1.10 Effect of Fluid Tonicity on Gastric Emptying and Intestinal Absorption**

The osmolarity of a sports drink is affected by the concentration and type of carbohydrate used along with the electrolyte concentration. The optimal amount of carbohydrate and sodium required to maximise water absorption is not clear. Hypertonic solutions (>280mOsm/kg) tend to delay water absorption in the intestine as water flows into the



intestine to dilute the solution before water is absorbed [32, 54, 55]. There is also contention as to whether hypertonic solutions reduce the rate of gastric emptying [54]. Hypotonic and isotonic solutions (<280mOsm/kg) promote water absorption by the small intestine [56]. Rehrer et al [57] found that repeated ingestion of a hypertonic carbohydrate solution resulted in a reduced rate of gastric emptying and intestinal absorption after 20 minutes compared with an isotonic beverage during running and cycling exercise. The relationship between fluid tonicity, carbohydrate content and calorific content will be discussed further into this review.

## **1.11 Optimal Composition of an Electrolyte Replacement Drink for Endurance Exercise**

It is common for ironman triathletes to be competing in excess of 12 hours in challenging environments. Sweat losses can be as high as 12 litres throughout the race. These losses represent a substantial percentage of body weight and will rapidly lead to dehydration unless replacement fluid is consumed. Dehydration will impair exercise capacity and may pose a serious risk to health; the replacement of lost fluid volume during the ironman event is therefore imperative.

Fluid replacement should approximate sweat losses and maintain body weight to within a 2% reduction. Ideally athletes should use their individual sweat losses as an indication of their fluid needs, and assist in the development of a fluid plan.

Athletes benefit from the use of a sports drink during endurance exercise in excess of 60 minutes, particularly if sweat rates are high. The most appropriate fluid to use throughout both training and competition is one that contains carbohydrate and electrolytes, mainly sodium and to a lesser extent potassium. Including these substances in the rehydration drink can maintain blood glucose, carbohydrate oxidation, and electrolyte balance and can prevent premature fatigue.

### **1.11.1 Addition of Sodium**

Sweat is hypotonic to plasma and contains approximately 45 mEq/L of sodium. The addition of sodium to a beverage enhances carbohydrate absorption, improves palatability as well as promoting fluid homeostasis. It has been shown that the addition of sodium to a replacement beverage maintains plasma volume more effectively than plain water [58, 59]. Modigliani and Bernier (1971) performed an experiment to determine the optimal concentration of glucose and sodium in order to maximise absorption. They determined that the maximal absorption rate occurred when a 17mEq/L NaCl solution was added to a 133mM glucose solution. At a glucose concentration of 200mM, water absorption fell significantly, at a glucose concentration of 260mM net water secretion occurred. Therefore the optimal glucose/Na ratio in this study was 2:1. To replace sodium lost in sweat and improve palatability a sodium concentration of between 20 and 30 mEq/L should be added to an electrolyte replacement beverage.

### **1.11.2 Addition of Glucose**

There are mixed results in the literature regarding the best concentration of carbohydrate to maximise water absorption while still providing an energy source. For endurance events, a study by Tsintzas et al [60] examined the effect of carbohydrate and electrolyte drinks on marathon performance. They found that a 5.5% solution improved treadmill-running performance when compared with water. They also reported that numerous runners experienced gastrointestinal discomfort with the use of the more concentrated 6.9 % solution [60]. These results are consistent with other studies comparing the effects of carbohydrate solutions and water on performance [61-63]. Other studies in the literature do not agree. A study by Morris et al [64] looked at the influence of a 6.5% carbohydrate solution on prolonged intermittent high intensity running performance. Nine male student games players consumed flavoured water, a taste placebo (2mmol Na) or a 6.5% CHO electrolyte solution during intermittent high intensity running. The running session consisted of 3 sessions of 5 bouts of 15 minutes at variable speeds, separated by 4 minutes rest. There was found to be no performance difference between the trials. However there was a trial order effect with each subject running further in the final trial compared with the initial. The trials however were performed in a random counterbalanced order showing that there was no difference in drinks in terms of exercise performance. This may have been attributed to the small sample of subjects selected, or due to the variability in fitness levels between subjects. Further studies reported in the literature have also found no performance advantages of consuming a carbohydrate electrolyte solution over water (Chryssanthopoulos 1998). The inconsistency in results that is seen when reviewing the literature in this area can be attributed to a number of factors.

- 1) Differences in the mode of exercise along with the duration and intensity of the prescribed session.
- 2) Differences in the age, gender and fitness of the subjects.
- 3) Often the studies are either quite intrusive or complex in nature, for example the use of the aspiration technique as a measurement of gastric emptying rate. Due to the high burden on the subjects and intrusive nature, low subject number can become a factor influencing the reliability of the results.
- 4) The formulation of the test solutions is often very varied between studies; therefore comparison between trials can be difficult.

Most commercial sports drinks range in carbohydrate concentration between 3% and 10%. Further investigation is required to determine whether these concentrations of carbohydrate are optimal to maximise absorption along with minimising gastric discomfort.

### **1.11.3 Addition of Potassium**

The concentration of potassium in sweat generally ranges from 1-15mEq/L, however can become more significant during prolonged exercise in the heat (Gisolfi 1990). Potassium depletion (hypokalemia) can cause serious symptoms such as disorientation and muscle weakness.

Research suggests that Potassium should be added to an electrolyte replacement beverage at a concentration of between 5 to 10mEq/L to offset sweat losses. Potassium may also help in replacing lost intracellular fluid volume [35, 36].

#### **1.11.4 Addition of Magnesium**

There is no evidence to suggest that magnesium should be added to an electrolyte replacement beverage. The extracellular fluid contains approximately 1% of total body magnesium with the plasma concentration being approximately 1mmol/l. Therefore, only traces of magnesium are lost in sweat. Further to this the kidneys are extremely efficient at conserving magnesium, therefore when intake decreases the urine becomes almost magnesium free. The inclusion of magnesium in a sports drink is therefore not warranted, only serving to increase the tonicity of the drink, which in turn may cause a decrease in absorption from the small intestine.

#### **1.11.5 Addition of Calcium**

There have been few published studies reporting positive effects of the addition of calcium to an electrolyte replacement beverage. A study by Milosevic (1997) was designed to study the dental hazards from the consumption of various compositions of sports drinks. Chemo physical analysis indicated that all sports drinks in the study had erosive potential, however, the addition of Calcium to a drink significantly reduced this erosive potential. This study, however, did not study the effects of the drinks in humans; therefore there is no conclusive evidence of its benefits to athletes. Far more research is needed before there is sufficient evidence for the inclusion of calcium in a sports drink.

#### **1.11.6 Effect of Exercise on the Gastrointestinal Tract**

During exercise there is an increase in sympathetic and decrease in parasympathetic activity which has a large influence on digestion. Blood is moved away from the gastrointestinal tract in order to increase blood flow to the working muscles and skin [51]. These changes have an effect on gut motility, absorption and secretion. These changes can be related to the range of gastrointestinal symptoms that are experienced by many endurance athletes.

#### **1.11.7 Incidence of Gastrointestinal Discomfort in Endurance Athletes**

There is a very high prevalence of gastrointestinal complaints in long distance runners, endurance triathletes and other athletes competing in ultra endurance events [3]. Reported symptoms include nausea, vomiting, bloating or a feeling of fullness, abdominal cramps,

diarrhoea and dizziness. Riddock et al [65] investigated the prevalence of running induced gastrointestinal disturbances during the 1986 Belfast marathon. From the 471 runners surveyed 83% indicated that they had suffered one or more gastrointestinal complaints either during or after running [65].

The French Medical Society [66] carried out a study looking at gastric discomfort during triathlons. Of the 25640 competitors participating, 8.9% of the triathletes reported gastric distress during the race. [66]. Jeukendrup et al [67] found an even higher prevalence of gastrointestinal distress during an endurance triathlon. Of the thirty-three triathletes that were surveyed 92% reported at least one complaint during the event. Although these two studies are both reporting similar findings, a much lower sample of athletes is studied in the second example, because of this a much higher incidence of gastrointestinal complaints are reported.

### **1.11.8 Factors Affecting Gastrointestinal Discomfort**

- a) **Training Status:** Untrained athletes are more likely to suffer from discomfort [51].
- b) **Pre-competition food intake:** Meals that are high in dietary fibre, fat or protein are more likely to cause discomfort, especially if consumed shortly prior to exercise [9].
- c) **Exercise Intensity:** Elite athletes who are competing at maximal exertion more commonly report distress [51].
- d) **Level of dehydration:** Gastric emptying rate has been shown to be slowed if an athlete is dehydrated, these athletes report significantly more gastrointestinal symptoms than well hydrated athletes [68].
- e) **Sports drink consumption:** Some studies suggest that ingestion of sports drinks that are highly concentrated hypertonic solutions may induce gastrointestinal distress [54, 60, 69]. (Refer Section 2.12.4)

### **1.11.9 Gastrointestinal Discomfort and Sports Drink Consumption**

Athletes have been reported to limit their sports drink consumption in order to avoid gastrointestinal distress [70]. Between 30 to 50% of athletes have been reported to suffer from gastrointestinal discomfort; these athletes may risk dehydration in order to avoid such discomfort. A summary of research indicates that subtle differences in carbohydrate concentration of a beverage may influence gastric tolerance. There have been few studies in the literature looking particularly at the effects of sports drink tonicity and carbohydrate content on gastric discomfort.

**Table 2** shows a summary of five studies that have looked at the effect of a variety of different sports drink compositions on gastrointestinal distress. Close examination of these studies reveals that there are significant gaps in the literature. All five of the studies

concluded that the high carbohydrate sports drinks increased the symptoms of discomfort in the athletes [50, 60, 69, 71]. What is not clear from this literature is the most appropriate level of carbohydrate for use by endurance athletes. An ideal sports drink is one that rapidly replaces lost fluid volume while providing a sufficient energy source. Provision of water is the first priority in the case of endurance sport, therefore a drink with a carbohydrate concentration of between 3% and 4% may restrict the rate at which carbohydrate is provided, but maintain hypotonicity and therefore maximise fluid absorption [72]. The majority of studies have compared the effect of a water placebo and either one or two hypertonic solutions varying in concentration between 5% and 12%. The comparison between a hypotonic (less than 280mOsm/L) and a hypertonic solution may provide further information as to the most appropriate level of carbohydrate and electrolytes to minimise gastric disturbances.

A study by Davis et al [69] used 15 male trained cyclists to determine whether there was a difference between a 12% and 6% carbohydrate solution on markers of absorption, gastric discomfort ratings and palatability ratings during 2 consecutive 60 minute cycling bouts at 65% of VO<sub>2</sub> max. Throughout the cycling session subjects were provided with 275ml of either one of the drinks. Results showed that significantly more nausea and symptoms of abdominal fullness were reported with the higher carbohydrate solution. They also reported that more subjects stated that they would not use the 12% solution again during either training or competition [69]. Similar results were reported by Shi et al [73] who assessed gastrointestinal discomfort during intermittent, high intensity exercise in 36 adult and adolescent athletes. The athletes were tested on separate days in a double blind randomised trial of 6% and 8% carbohydrate electrolyte beverages during four, 12 min quarters of circuit training. The circuit included intermittent sprints, lateral hops, shuttle runs and vertical jumps. Gastrointestinal discomfort surveys were completed before the first quarter and immediately after each quarter. The overall gastrointestinal discomfort rating was higher for the 8% carbohydrate solution than for the 6% [73]. In this study there was no reported monitoring of intensity throughout the circuit session, therefore it can be assumed that there was significant variation both between subjects as well as within subjects. It is possible that this variation may have influenced the results.

Tsintza et al [60] examined gastric distress associated with varying carbohydrate content of sports drinks in marathon runners. Seven endurance-trained runners completed three 42.2km treadmill time trials that were randomly assigned 4 weeks apart. They observed that when the athletes used a 6.9% CHO solution compared with either a 5.5% CHO or water the incidence of gastrointestinal distress was doubled [60]. The confounding effect of both mental and physical fatigue in these athletes could have influenced the reported results. The completion of three marathon runs within a 12 weeks period is substantial and would have inevitably resulted in significant fatigue in the athletes.

A field study performed by Rehrer et al [54] investigated the relationship between gastrointestinal complaints and dietary intake in triathletes. They surveyed 55 male triathletes after they had completed a half-ironman triathlon. They observed that gastrointestinal complaints were more likely to occur with the ingestion of fat, fibre and protein and concentrated carbohydrate solutions during the triathlon. Athletes consuming beverages with high osmolarity were shown to have a significantly greater chance of gastric distress [54].

There are obvious limitations with the design of the former study. It is likely that the athletes surveyed would have experienced difficulties in correctly resighting their intakes for the duration of the competition; therefore the athletes reported intakes may not have been entirely reliable.

A further field study performed by Van Nieuwenhoven et al [74] investigated the effect of 3 different sports drinks on gastrointestinal complaints and performance during running in a controlled field study. Ninety-eight well-trained subjects performed an 18km run three times within 8 days. The drinks compared were an 8% carbohydrate sports drink, an 8% carbohydrate sports drink with caffeine and water. The subjects were to report their gastrointestinal distress using a 10 point scale at the end of the run. Results showed no differences in performance between the drinks, however significant increase in gastrointestinal distress was noted with the use of sports drinks during the run [74]. Due to the design of this study involving three 18km runs within 8 days, both mental and physical fatigue in the final trial may have had an effect on the results.

Far more research assessing the effect of sports drinks on gastrointestinal complaints in endurance athletes during competition is required. However, in order to produce accurate and reliable results it may be necessary to provide the athletes with particular fluid type and volume during an event such as this. This would enable accurate data to be collected on the athlete's intakes and would not rely on data recall.

Comparison of results between the 5 studies in

**Table 2** is difficult due to the large variation in the athletes used, the type, intensity and duration of the exercise sessions prescribed, along with large differences in the composition of the sports drinks chosen. When assessing the effect of sports drink consumption of gastrointestinal distress in athletes, possibly the most important factor to control for is the subject's pre-testing meal. It is well established that significant variation exists in the rate of digestion and absorption of different macronutrients. Therefore, in order to eliminate the effects of this meal, standardisation is required. Another major factor would impact on gastrointestinal discomfort is the volume of fluid consumed by the subjects and the length of time between feedings. The 5 studies reported have all used varying fluid volumes; this factor makes it difficult to draw firm conclusions from the data.

**Table 2: Studies assessing the relationship between sports drink composition and gastric discomfort in endurance exercise**

Reference	Sport/Activity	Sample	Beverage Used	Gastric Distress reported
Davis et al [69]	Cycling: 2 x 60 minute bouts at 65% VO2 max	15 trained male cyclists	Water Placebo  6% CHO solution  12% CHO solution	12% CHO caused significantly more nausea and fullness than 6% CHO and water. More subjects said they would not consume 12% during training
Shi et al [73]	Intermittent High intensity circuit exercise	36 adult/adolescent adults	6% CHO solution  8% CHO solution	Cumulative gastrointestinal index significantly greater for 8% CHO solution
Rehrer et al [54]	Half Ironman Triathlon Competition	55 male triathletes	Variation between athletes	Surveys after the half ironman suggested that 93% of the athletes who had consumed a hypertonic beverage had nausea symptoms.
Tsintzas et al [60]	Marathon running	7 endurance trained runners	Water placebo  5.5% CHO solution  6.9% CHO solution	The incidence of gastrointestinal distress was similar for 5.5% CHO and water but significantly higher in the 6.9% group.
Van Nieuwenhoven et al [74]	18km running	98 well trained runners	8% CHO, 8% CHO + caffeine and water	The use of the sports drink lead to a higher incidence of both upper and lower gastrointestinal complaints

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