Limitations to Fluid Replacement During Exercise

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Abstract/Résumé
Fluid replacement during exercise is essential for endurance exercise performance and reducing the risk of heat illness. Fluids supply water, which ameliorates dehydration, and also substrate for the working muscles. Absorption of water and nutrients occurs in the upper part of the small intestine, and replacement may be limited by the rate at which fluid is emptied from the stomach or absorbed in the intestine. Gastric emptying of liquids is influenced primarily by the volume of fluid in the stomach and by its energy density. Increasing the volume will speed emptying, but increasing the nutrient content will slow emptying. Osmolality, temperature, and pH of drinks, as well as exercise intensity, are of minor importance. Intestinal water absorption is a passive process: water follows osmotic gradients but will also follow the active absorption of nutrients, especially glucose, which is actively co-transported with sodium. Water transport is maximised by the presence in the intestine of hypotonic solutions of glucose and sodium. Hypertonic solutions promote net water secretion into the intestinal lumen, resulting in a temporary net loss of water from the body. The amount of fluid ingested by athletes is normally much less than can be tolerated, therefore issues such as palatability and practising drinking during training are important.

En plus d’être essentiel à l’épreuve d’endurance, le remplacement des liquides au cours d’un effort minimise le risque de troubles dus à la chaleur. Les boissons consommées durant l’exercice peuvent constituer aussi une source d’énergie additionnelle pour les muscles actifs. L’absorption de l’eau et des nutriments se fait dans la portion supérieure du petit intestin; le remplacement peut donc être limité par le taux de vidange gastrique et celui de l’absorption intestinale. La vidange gastrique est principalement dépendante du volume de

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liquide dans l’estomac et de sa densité énergétique. Une augmentation du volume fait accroître la vidange mais une augmentation de son contenu en nutriments la fait ralentir. D’autres facteurs, d’importance mineure, sont l’osmolalité, la température, et le pH des boissons ainsi que l’intensité de l’effort. L’absorption d’eau intestinale est un processus passif: l’eau suit le gradient osmotique mais elle participe aussi au processus actif d’absorption des nutriments, particulièrement le glucose dont le transport est accompagné du sodium. Le transport de l’eau dans l’intestin est maximisé en présence d’une solution hypotonique de glucose et de sodium. Une solution hypertonique favorise la sécrétion d’eau, d’où une augmentation de la quantité d’eau la lumière de l’intestin et une perte temporaire d’eau corporelle. La quantité d’eau consommée par les athlètes est généralement inférieure à leur capacité. In n’en demeure pas moins que le goût de la boisson et l’habitude de boire durant l’entraînement constitue d’autres facteurs importants.

Introduction

The preceding papers by Lindinger and Barr have reviewed the factors relating to prolonged exercise in the heat, and to the need for fluid replacement to minimise the disturbances of homeostasis that occur in this situation. It is clear that the capacity to undertake prolonged exercise is impaired at high ambient temperatures, and indeed performance is reduced at even relatively modest temperatures (20 °C) relative to that achieved in cooler (~10 °C) conditions (Galloway and Maughan, 1997). The recognition that exercise in the heat is impaired and that it is associated with an increased risk of heat illness is not new. It has also long been known that the performance of prolonged exercise in hot conditions is improved if water is ingested (Pitts et al., 1944). It has also long been recognised that carbohydrate is an important fuel in prolonged exercise and that carbohydrate ingestion is beneficial for the endurance athlete (Gordon et al., 1925). These ideas evolved further and led to the development of sports drinks: dilute carbohydrate solutions with electrolytes added. The rationale for the addition of electrolytes seems largely based on the loss of electrolytes in sweat.

In spite of the early demonstration that ad libitum intake of fluids does not occur fast enough to balance the rate of sweat loss, and that higher rates of fluid are beneficial, athletes normally ingest only small amounts of fluid during prolonged exercise (Noakes, 1993). This prompts two questions: Why are larger volumes not ingested in most sports situations? What determines the upper limit to the ingestion of fluids during exercise? The answers to these questions will have major implications for the formulation of drinks intended for athletes.

Most athletes assume that ingested fluids are immediately available to the body, yet fluid inside the gastrointestinal tract is effectively outside the body. There is little net exchange of water or other nutrients—the important exception being alcohol—in the stomach. Absorption occurs primarily and more or less completely in the upper part of the small intestine. The function of the stomach is therefore to contain the ingestate and prepare it for delivery to the duodenum. The availability of ingested water or nutrients may therefore be limited by the delay imposed by gastric emptying, or by the absorptive capacity of the intestine. It is easy to demonstrate that either process can, in some situations, limit the rate of exogenous fuel and fluid delivery, but the concern has to be with the factors having the greatest impact on the limitations to exercise performance. Usually replacement is limited
by the volume of fluid ingested. In endurance running events, voluntary intake seldom exceeds about 0.5 litres per hour (Noakes, 1993). A sensation of fullness or of abdominal discomfort is the reason most often cited for not drinking more fluid (Brouns et al., 1987).

**Gastric Emptying**

The process of gastric emptying and its physiological regulation has been extensively studied. The first systematic studies were those of Hunt and colleagues in the 1950s and 1960s. They established the basic principles that regulate gastric emptying rates, as listed below:

- **Volume**—Increasing volume promotes emptying.
- **Energy density**—Increasing energy density slows emptying in proportion to the energy content: carbohydrate, fat, protein, and alcohol seem to exert similar effects.
- **Osmolality**—Markedly increasing osmolality slows emptying, but this effect is small relative to the energy density.
- **pH**—Marked deviations from neutrality slow emptying.
- **Exercise**—Hard (>70–75% VO₂ max) exercise slows emptying.
- **Stress**—Severe mental or emotional stress slows emptying.

The early findings have largely been confirmed by subsequent studies, and later refinements are largely a result of improvements in the methods used to study gastric emptying in healthy volunteers at rest or during exercise. It is also true, however, that there is no universal agreement on some details. This conflict is due at least partly to a failure to recognize the limitations of some methods used to study gastric emptying, and to the frequent use of complex solutions in which many variables were changed simultaneously.

Most of the early studies used either a single time-point gastric aspiration method or followed the emptying of a gamma-emitting tracer using a scintigraphic detector. The latter method has been most widely used in clinical settings and can be applied to the study of the gastric emptying of solids, liquids, or mixtures. The major difficulties encountered arise only when solid meals are studied, and the tracers used may not faithfully follow the test meal. The same is not true for liquid meals when a suitable tracer is used and when appropriate corrections are applied to account for the extrapolation from a 2-D image to a process occurring in three dimensions. A good agreement between the scintigraphic method and direct measurements by gastric aspiration has been confirmed when dilute or concentrated glucose solutions are studied (Beckers et al., 1992). There remains the problem of accounting for changes in gastric volume due to the addition of gastric secretions, nor is it possible to determine how these secretions change the composition of the gastric contents.

The single time-point gastric aspiration technique has been widely used in exercise studies as well as in resting subjects, and much of the available information has been obtained with this method. However, the limitations of assessment at a single time point become apparent when it is realised that emptying of liquids, except perhaps those with an unusually high energy content, is an exponential rather than a linear process. An example of the limitations is shown in Figure 1.
Figure 1. Gastric emptying rate of glucose-containing drinks vs. plain water. The concentrated drinks clearly empty more slowly and are not effective in delivering fluid to the small intestine.

which compares the emptying rates of flavoured water and glucose solutions of increasing concentration. The interaction between the two most significant controllers of emptying (volume and energy density) is clearly seen. Water empties faster than the glucose-containing solutions, so the gastric volume falls more rapidly and the rate of emptying falls over time. At the 30-min sample point it could legitimately be concluded that emptying of all the glucose-containing solutions is delayed relative to water. At the 40-min time point, however, the conclusion would be that only at glucose concentrations in excess of 10% is emptying slowed. The single time-point aspiration method effectively allows only one of these answers to be obtained, but when the whole curve is available, the true result is apparent.

The double sampling method, introduced by George (1968) and modified by Beckers et al. (1988), allows measurements to be made at relatively frequent intervals and also allows us to estimate the volume and composition of gastric secretions added between successive measurements. This should be the method of choice in measurements of the gastric emptying of liquids. This method is now gradually displacing the others that have been used and should resolve some of the conflict in the literature.
Whatever the composition of the ingested fluid, the volume of the stomach contents has a major influence on the emptying rate. By refilling the stomach at intervals, the volume in the stomach can be kept high. When this has been investigated using dilute carbohydrate-electrolyte solutions, a high rate of gastric emptying was maintained, greatly enhancing both the volume of solution and the amount of carbohydrate delivered to the small intestine for absorption (Mitchell and Voss, 1991; Rehrer et al., 1990b). With concentrated carbohydrate solutions, however, the rate of emptying is slow, and care must be taken to ensure that repeated drinking does not lead to accumulation of fluid in the stomach and a sensation of discomfort.

The composition of ingested fluids also has a major effect on the rate of emptying, and emptying is slowed if solutions are markedly hypertonic with respect to the osmolality of body fluids, by increasing acidity, and by increasing energy density; all of these factors are relevant to the formulation of drinks to be used during exercise. It seems well established that the emptying rate of CHO solutions is slowed relative to water or to isotonic saline solutions. The difficulties come in trying to establish at what point the effect of increasing CHO content becomes significant, for it is clear that a drastic slowing of gastric emptying will limit rehydration during exercise.

The effect of increasing glucose concentrations on the time course of emptying has been extensively investigated. In several studies, dilute glucose solutions (<2.5%) have been reported to empty from the stomach at the same rate as water, and there are also reports that solutions of 5% carbohydrate will delay the rate of gastric emptying compared with water, suggesting that the critical CHO concentration for an effect is somewhere between these values. But others, including a number of recent studies, have found that solutions containing carbohydrates of concentrations up to 7.5% empty from the stomach at rates similar to water (Houmard et al., 1991; Mitchell et al., 1988; 1989; Rehrer et al, 1989). There are also published results showing no difference in the rate of gastric emptying between water and a 10% glucose solution (Owen et al., 1986; Zachwieja et al., 1992).

At least part of this apparent discrepancy is probably due to the design of these studies. Many of them used a single time-point aspiration method, and most used solutions containing a number of ingredients in addition to carbohydrate, as well as a variety of different CHO sources. If a fixed volume of two different glucose solutions is given, one dilute and one concentrated, the initial emptying rate for the dilute solution will be more rapid; as the volume falls, the emptying rate is reduced, but this effect will be less marked for the more concentrated solution.

Recent results obtained using the double-sampling gastric aspiration method indicate that glucose concentrations in excess of about 4% will delay gastric emptying (Figure 2) (Vist and Maughan, 1994). It is also apparent that, although increasing the glucose content of the ingested fluid does slow the rate at which fluid leaves the stomach, it results in a faster delivery of glucose (Hunt et al., 1985; Vist and Maughan, 1995).

Substitution of maltose, sucrose, or glucose polymers for free glucose may help promote the emptying of glucose-electrolyte solutions from the stomach by reducing the osmolality of the solution while maintaining the total carbohydrate content, although the published studies are not in agreement. Sole and Noakes (1989) found that a 15% glucose polymer solution emptied faster than a 15%
solution of free glucose, although 5 and 10% solutions of free glucose and polymer appeared to be emptied at the same rate. In another recent study, Naveri et al. (1989) found that the emptying rates of electrolyte solutions with 3% CHO added in the form of glucose or a polymer were the same. Owen et al. (1986) also found no difference in the rate of emptying of 10% solutions of glucose or glucose polymer, in spite of the higher osmolality of the free glucose solution. Rehrer et al. (1992) also observed similar emptying rates with 18% solutions of glucose polymer (313 mosmol/kg) and free glucose (1,223 mosmol/kg); however, a 4.5% glucose solution emptied faster than an 18% polymer solution with the same osmolality. From this, it might be concluded that osmolality becomes important at high solute concentrations, but the effect is small compared to that of energy density, especially in dilute solutions. Many of the solutions tested in these studies contained a variety of electrolytes and flavourings, which were not always kept the same when different drinks were being compared.

In a systematic study, Vist and Maughan (1994) evaluated the effects of osmolality and energy density by comparing solutions of free glucose or glucose polymers. A 4% polymer solution emptied only slightly faster than a 4% glucose solution (osmolality 42 vs. 230 mosmol/kg). An 18.8% polymer solution with the same osmolality as the 4% glucose solution emptied much more slowly, but emptied
faster than an 18.8% free glucose solution (osmolality 1,300 mosmol/kg). Even though there were differences in the results, in none of the above studies was the emptying rate of polymer solutions slower than that of free glucose solutions with the same energy density, and the polymer solutions were generally emptied faster even when the differences were not statistically significant.

In summary, gastric emptying of liquids is regulated by a number of factors, of which the most important are the volume of stomach contents and the energy density and osmolality of drinks consumed. Increasing the CHO content of drinks will delay emptying. Substitution of glucose polymers for free glucose appears to slightly increase the rate of delivery of fluid and substrate to the small intestine. It now seems likely that several other factors such as carbonation and the temperature of ingested drinks, which were formerly thought to be important, do not have a major influence on the rate of emptying. The factors regulating gastric emptying have been the subject of extensive reviews (see Maughan, 1991, for review).

**Intestinal Absorption**

Water absorption occurs largely in the proximal segment of the small intestine and, although water movement is itself a passive process driven by local osmotic gradients, is closely linked to the active transport of solute. The method of choice for measuring intestinal absorption of water involves placing a triple lumen tube in the region of interest. The test solution contains a nonabsorbable marker and is perfused at a fixed rate within the physiological range for gastric emptying (usually 5–15 ml/min). A sample of the intestinal contents is aspirated via the second tube from a point 10–20 cm distal to the perfusion port, and the change in composition gives a measure of the effects of mixing of the test solution with the endogenous secretions. Aspiration via the third tube from a site 20–60 cm farther along the intestine allows net exchange of solute and water in the test segment to be calculated (Leiper and Maughan, 1988).

This technique allows reliable measures to be made of the net flux of water and solutes in a well-defined region of the gut. Although the technique is reliable and reproducible in itself, it has important limitations. Because the test solutions are added directly to the jejunum, the role of the stomach in moderating the delivery rate and modifying the composition of ingested fluids is ignored. A constant perfusion rate is normally used in perfusion studies, and this may represent an unphysiological situation. A recent modification to the technique involves repeated ingestion of the test drinks orally in order to maintain a constant rate of gastric emptying, with simultaneous aspiration from three or four sampling sites located in the small intestine.

The effects of solute secretion may be important, and there is evidence that when electrolyte-free solutions are ingested orally, there is a rapid secretion of sodium such that equilibrium is rapidly reached (Gisolfi et al., 1995; Schedl et al., 1994). If this is indeed the case, it confounds the evidence available from the perfusion method which indicates an increased water uptake when sodium-containing fluids are perfused (Leiper and Maughan, 1988). The technique also looks only at a small part of the whole intestinal surface that is available for absorption in the intact individual; thus, concentrated solutions stimulate water secretion in the upper part of the intestine, but absorption will still occur in the distal regions.
The absorption of glucose occurs in the small intestine and is an active, energy-consuming process linked to the transport of sodium. There is no active transport mechanism for water, which will cross the intestinal mucosa in either direction depending on the local osmotic gradients. The rate of glucose uptake depends on the luminal concentrations of glucose and sodium, and dilute glucose-electrolyte solutions with an osmolality that is slightly hypotonic with respect to plasma will maximise the rate of water uptake (Wap nir and Lifshitz, 1985).

![Net water flux diagram](image)

**Figure 3.** Net water flux in the upper small intestine perfused with water or different drinks. The dilute CHO-electrolyte drinks promote water uptake, with the hypotonic oral rehydration solution (ORS) being most effective. Apple juice, with a very high osmolality, promotes a net secretion of water into the intestinal lumen.

Figure 3 compares net water flux from different solutions. Solutions with a very high glucose concentration will not necessarily promote an increased glucose uptake relative to more dilute solutions, but, because of their high osmolality, will cause a net movement of fluid into the intestinal lumen (Gisolfi et al., 1990). This results in an effective loss of body water and will exacerbate any preexisting dehydration. Other sugars such as sucrose or glucose polymers can be substituted for glucose without impairing glucose or water uptake. In contrast, the absorption of fructose is not an active process in humans: it is absorbed less rapidly than glucose and promotes less water uptake (Fordtran, 1975). The use of different sugars which are absorbed by different mechanisms, and which might thus promote increased water uptake, is supported by recent evidence from an intestinal perfusion study (Shi et al., 1995).
Much of the information in this area is derived from intestinal perfusion studies aimed at identifying solutions that can effectively replace fluid in individuals, especially children, who suffer from infectious diarrhea (Walker-Smith, 1992). Large water losses in childhood diarrhea cause severe dehydration, and death is not an uncommon outcome in some third world countries. Isotonic glucose-electrolyte oral rehydration solutions (ORS) have been widely promoted for the treatment of dehydration resulting from infectious diarrhea (Elliott et al., 1986). The mechanisms underlying this effect have not been established, but it is known that hypotonic solutions (200–250 mosmol/kg) promote a greater rate of water absorption in the small intestine than isotonic solutions (Elliott et al., 1986; Hunt et al., 1989). Clearly there are implications of these results for other situations, such as exercise in the heat, when rapid replacement of fluid losses is essential for maintaining homeostasis.

**Tracer Methods**

The rate of gastric emptying and the rate of absorption in segments of the small intestine can be measured separately. By introducing an isotopic tracer for water to ingested solutions and measuring the appearance of this tracer in the circulation, we can obtain an indication of the combined effect of gastric emptying and intestinal absorption. The accumulation in the circulation of a tracer added to the test drink has been used as an index of water absorption from ingested solutions (Davis et al., 1987; Leiper and Maughan, 1988). The rate of accumulation in the circulation of deuterium after adding deuterium oxide to the ingested solutions has been shown to follow known gastric emptying and intestinal absorption patterns of the ingested solution (Davis et al., 1987).

Using simultaneous measurements of intestinal absorption with the triple lumen perfusion method and appearance in the circulation of a tracer added to the perfusate, Gisolfi et al. (1990) suggested that results obtained with this method gave little useful information and might actually be misleading. This suggestion was based on the fact that while the deuterium tracer method followed only the unidirectional movement of water from the intestinal lumen into the circulation, accumulation of tracer is observed even when a net efflux of water into the intestinal lumen is indicated by the perfusion method. However, this ignores the fact that the relative rates of water absorption indicated by the tracer method agree rather well with the results obtained by the more invasive perfusion method.

As used by other investigators, the technique has involved addition of the tracer to a bolus of fluid ingested orally. This is quite a different situation from that in which a test solution containing a constant tracer concentration is perfused at a constant rate directly into the jejunum, and the available evidence suggests that useful results as to the relative rates of water availability from ingested fluids may be obtained with this method.

**Effects of Exercise on Gastrointestinal Function**

Several studies have shown that exercise at intensities less than about 70% of \( \dot{V}O_2 \) max has little or no effect on intestinal function, although both gastric emptying and intestinal absorption may be reduced when the intensity exceeds this level. At high exercise intensities, however, when there is likely to be a serious barrier to
the availability of ingested food or fluids, the exercise time will probably be too short to reap any benefit from nutrients ingested during the exercise period. When subjects have been able to sustain high intensity exercise for prolonged periods, attempts to ingest large volumes of fluid have led to gastrointestinal discomfort and impaired exercise tolerance. In the study of Robinson et al. (1995), subjects attempted to ride as far as possible on a cycle simulator for one hour; the exercise intensity corresponded to about 85% \( \dot{V}O_{2} \max \). When no fluid was consumed, subjects pedaled 43.1 km, but when 1.5 L of flavoured water was consumed during the trial, the distance covered was reduced (\( p < 0.05 \)) to 42.3 km. The reduction in performance was ascribed to the discomfort of stomach fullness. It seems unlikely that drinking such a volume at rest would produce this effect, suggesting a reduced capacity of the gastrointestinal tract to function at a high exercise intensity.

Compared with the extensive literature on the regulation of gastric emptying at rest, relatively few measurements have been made during exercise. Costill and Saltin (1974) showed that 15 min of cycling exercise had no effect on gastric emptying of a dilute glucose-electrolyte solution until a work intensity of about 70% \( \dot{V}O_{2} \max \) was reached; at 80–90% \( \dot{V}O_{2} \max \) the emptying rate was only about 50% of the resting rate. In a rather poorly controlled study, Ramsbottom and Hunt (1974) found that 20 min of “severe exercise” (100 W!) reduced the emptying rate of a 278-mmol/L (5%) glucose solution in 4 of 6 subjects. During intermittent cycling exercise at 74% of \( \dot{V}O_{2} \max \), gastrointestinal transit time, estimated by breath hydrogen analysis, was not different from rest and was not different when concentrated glucose (1,000 mmol/L) or flavoured dilute (150 mmol/L) solutions were given (Segal et al., 1985). Mitchell et al. (1989) found that prolonged (105 min) cycling at 70% \( \dot{V}O_{2} \max \) did not affect the rate of emptying of a 6% CHO (4% glucose polymer, 2% sucrose) solution compared with rest; their subjects drank approximately 620 ml/hr and the calculated emptying rate was close to 600 ml/hr; similar results were obtained during intermittent exercise (Mitchell et al., 1988).

Emptying rates in excess of 1 L/hr, corresponding to over 90% of the ingested volume, can be achieved during prolonged (3 hrs) exercise at 60% \( \dot{V}O_{2} \max \) in the heat (Ryan et al., 1989). Using a double-sampling gastric aspiration technique that allowed the time course of emptying to be measured, Rehner et al. (1989) reported that exercise at 50 or 70% \( \dot{V}O_{2} \max \) had no significant effect on the emptying rate of sweetened water or CHO-electrolyte solutions, although there was a trend toward a decreased emptying rate of the CHO-electrolyte solutions, but not of water, with increasing exercise intensity. Rehner et al. also showed that gastric emptying and gastric secretion did not differ between trained and untrained individuals.

The above studies all involved cycling exercise, but earlier albeit rather poorly controlled investigations had established that gastric emptying is delayed during running (Campbell et al., 1928). In 1967 Fordtran and Saltin reported that the rate of emptying of a concentrated glucose-electrolyte solution (740 mmol/L [13.3%] glucose; 52 mmol/L NaCl) was not changed during 1 hour of treadmill running at 70% \( \dot{V}O_{2} \max \) compared with rest; emptying of plain water was much faster and was slightly delayed by exercise. Costill et al. (1970) found no differences in the gastric emptying rates of water and a dilute glucose-electrolyte solution during 2 hrs of treadmill running at 70% \( \dot{V}O_{2} \)
max in highly trained runners. Owen et al. (1986) found no difference in emptying rates of solutions containing 10% glucose (586 mosmol/kg) or 10% glucose polymer (194 mosmol/kg) compared with sweetened water during 2 hrs of treadmill running in the heat (35 °C) at 65% VO\textsubscript{2} max; emptying of the glucose solution, but not of the others, was retarded relative to sweetened water ingested at a lower (25 °C) ambient temperature.

In contrast to these results, Neufer et al. (1986) found that 15 min of running at 50 or 70% VO\textsubscript{2} max increased the rates of emptying of water and CHO-containing solutions relative to rest, and later (Neufer et al., 1989a) confirmed these results for walking and running at 28–65% VO\textsubscript{2} max, but found a decreased emptying rate at 75% VO\textsubscript{2} max compared with rest. The same authors also reported that exercise in the heat (49 °C) or after dehydration reduced gastric emptying compared with exercise at a neutral temperature (Neufer et al., 1989b). These results were confirmed by Rehrer et al. (1990a). Sole and Noakes (1989) have reported that gastric emptying of water, but not of a 10% glucose polymer solution, is delayed during 30 min of treadmill running at 75% VO\textsubscript{2} max; this result is the opposite of that obtained by Rehrer et al. (1989) during cycling.

Houmand et al. (1991) have shown that the gastric emptying rate of water was slowed during either cycling or running at 75% VO\textsubscript{2} max, but that exercise had no effect on the emptying rate of a 7% CHO-electrolyte solution, which was emptied more slowly than water at rest but not during exercise. There was no difference between the two exercise modes. Although the study was generally well controlled in that the same subjects were studied at rest and during both exercise modes, it again suffers from the limitation that only a single measurement was taken of the volume of the gastric residue at the end of the 1-hr study. However, Rehrer et al. (1990b) also found no difference in gastric emptying between cycling and running at the same relative intensities with repeated drinking when serial measurements were made throughout exercise.

As with the resting studies described above, some of the variability between these exercise studies is probably an effect of differences in sampling times. In some studies, the experimental protocol required the subjects to ingest several test beverages sequentially during a single session. The effects of the presence of previous drinks in the small intestine cannot be excluded as a source of error (Rehrer et al., 1989).

There have been few studies on the effects of exercise on intestinal absorption, largely due to the practical problems associated with perfusing the small intestine in exercising individuals. Using this technique, Fordtran and Saltin (1967) found no effect of treadmill exercise at 70% VO\textsubscript{2} max on intestinal absorption of glucose, water, or electrolytes from a glucose-electrolyte solution. More recently, Barclay and Turnberg (1988) reported large reductions in water and electrolyte absorption when an electrolyte solution containing no carbohydrate was perfused during low intensity cycling exercise. The workload was poorly controlled in their study and was varied to achieve a heart rate 40–50% above the resting rate. Gisolfi et al. (1991) showed that 60 min of cycle exercise each at 30, 50, and 70% VO\textsubscript{2} max had no effect on water absorption from water or a CHO-electrolyte solution. In addition, they demonstrated that water absorption was greater from the CHO-electrolyte solution than from distilled water during exercise as well as at rest.

Results obtained using an isotopic tracer technique to follow ingested fluids have suggested there may be less availability of ingested fluids even during low
intensity exercise: a decreased rate of appearance in the blood of a tracer for water added to the ingested drinks indicated a decreased rate of appearance of the tracer at an exercise intensity of 40% \( \dot{V}O_2 \text{ max} \) (Maughan et al., 1990). Unpublished data from our laboratory show this is not due to a quicker disappearance of the tracer as it equilibrates with the extravascular water; an increased rate of equilibration of the tracer with the total body water pool has been demonstrated by injecting tritiated water directly into the circulation. However, it is apparent from the results shown in Figure 4 that the peak plasma deuterium tracer after ingestion of deuterium-labeled drinks occurs progressively later with increasing exercise intensity. If the reduced accumulation rate were due to a faster disappearance from the circulation, the peak concentration would occur earlier, not later.

![Figure 4](image-url). Rate of accumulation in body fluids (here plasma) of a deuterium tracer added to drinks allows the net effect of gastric emptying and intestinal absorption to be assessed. Results suggest the availability of ingested fluids is decreased even at moderate exercise intensities (40–60% \( \dot{V}O_2 \text{ max} \)) as well as during more intense exercise (80% \( \dot{V}O_2 \text{ max} \)). (From Maughan et al., 1990, “Effects of exercise intensity on absorption of ingested fluids in man,” *Experim. Physiol.* 75: 419-421. Reproduced with permission).

There are clearly some individuals who experience gastrointestinal problems during exercise, and the possible reasons for their susceptibility to this potentially debilitating condition has received much attention in recent years. O'Connor et al. (1995) measured the circulating concentrations of a number of gastrointestinal peptide hormones in 26 runners before and after a marathon race. The plasma levels of all the peptides, except insulin, increased during the race, but there was no relationship between these changes and the incidence of gastrointestinal distress, which affected 8 runners. The factors associated with gastrointestinal problems during exercise have recently been reviewed (Peters et al., 1995), but there is no clear indication as to the cause of the problem or how to avoid it. The mechanisms by which exercise might influence the function of the gastrointestinal tract are thought to be related to the increased circulating catechola-
mine level and to reduced perfusion of the splanchnic vascular bed during strenuous exercise; these effects have been reviewed by Murray (1987). The studies investigating gastrointestinal function during exercise have been reviewed and summarised by Brouns et al. (1987) and by Maughan (1991).

References


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