Benefits of fluid replacement with carbohydrate during exercise

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ABSTRACT

COYLE, E. F. and S. J. MONTAIN. Benefits of fluid replacement with carbohydrate during exercise. *Med. Sci. Sports Exerc.* Vol. 24, No. 9 Supplement, pp. S324–S330, 1992. Ingestion of approximately 30–60 g of carbohydrate during each hour of exercise will generally be sufficient to maintain blood glucose oxidation late in exercise and delay fatigue. Since the average rates of gastric emptying and intestinal absorption exceed 1,250 $ml \cdot h^{-1}$ for water and solutions containing up to 8% carbohydrate, exercising people can be supplemented with both carbohydrate and fluids at relatively high rates. When cyclists exercise at competitive intensities for 2 h in the heat with a sweat rate of 1,400 $ml \cdot h^{-1}$, it is clear that the closer that fluid consumption matches sweating rate (at least up to 80% of sweating rate), the better. Increasing dehydration, due to inadequate fluid consumption, directly impairs stroke volume, cardiac output, and skin blood flow, which results in larger increases in body core temperature, heart rate, and ratings of the difficulty of exercise. This same phenomenon probably also applies to running, which argues against the notion that a certain amount of dehydration (i.e., up to 3%) is permissible and without major cardiovascular consequences. However, runners generally drink only 500 $ml \cdot h^{-1}$ of fluid and thus allow themselves to dehydrate at rates of 500–1,000 $ml \cdot h^{-1}$. The performance question boils down to "Will the time lost as a result of drinking larger volumes be compensated by the physiological benefits drinking produces and the faster running pace that might be achieved during the last half of the race?" However, if the goal is safety, which means minimizing hyperthermia, there is no question that the closer that the rate of drinking can match the rate of dehydration, the better.

By ingesting fluids during prolonged exercise, it is possible to attenuate the detrimental effects of dehydration on body temperature and exercise performance (17). The addition of carbohydrate to fluid replacement beverages is also important because it provides carbohydrate late in prolonged exercise when there is often an inadequate supply of bodily carbohydrate to meet the energy requirements of the exercise task (6). Therefore, it is beneficial to ingest both fluid and carbohydrate. The question is "What is the optimal amount of fluid and carbohydrate that should be consumed?" Knowledge of both the individual fluid and carbohydrate requirements for the exercise task will determine the volume of fluid ingestion per hour of exercise and the carbohydrate concentration of the fluid replacement beverage. However, attention must also be given to the possibility that large fluid volumes may impair carbohydrate assimilation and that solutions of high carbohydrate concentration may impair fluid absorption.

CARBOHYDRATE INGESTION DURING PROLONGED INTENSE EXERCISE

The primary purpose of carbohydrate ingestion during continuous strenuous exercise is to maintain blood glucose concentration and maintain carbohydrate oxidation during the latter stages of prolonged exercise (6,8). As a result, subjects can exercise longer and sprint faster at the end of exercise (6). Most studies demonstrating improved performance have given subjects 25–60 g of carbohydrate per hour of exercise (6,19), although some have given more (8). We therefore recommend that individuals consume solutions which provide 30–60 g of carbohydrate per hour in the form of glucose, sucrose, or starch (6). It should be realized that solid carbohydrate feedings in the form of food containing sucrose or starch can probably also supply the carbohydrate needs of exercise (11). However, most athletes prefer to "drink" rather than "eat" carbohydrate during exercise for the obvious practical reasons.

Table 1 lists the concentration and volumes of various solutions which the athlete can drink to obtain 30–60 $g \cdot h^{-1}$ of carbohydrate. To obtain just 30 g of carbohydrate per hour when ingesting a 2% carbohydrate solution (i.e., 2 g of carbohydrate per 100 ml of solution), a person's stomach must be able to empty 1,500 $ml \cdot h^{-1}$. If 60 $g \cdot h^{-1}$ carbohydrate is needed, the gastric emptying rate for a 2% carbohydrate solution must increase to 3,000 $ml \cdot h^{-1}$. However, gastric emptying rates of 1,500 to 3,000 $ml \cdot h^{-1}$ are unreasonably high (15). Therefore, when dilute carbohydrate solutions (i.e., 2%) are consumed, there is a trade-off in that carbohydrate supplementation is compromised because the dilute solution cannot be emptied from the stomach at the rates required. On the other hand, 60 $g \cdot h^{-1}$ of carbohydrate supplementation can be achieved by emptying and absorbing 1,000 $ml \cdot h^{-1}$ of a 6%, or 750 $ml \cdot h^{-1}$ of an 8% carbohydrate solution. As discussed below, these rates of gastric emptying (625–1,250 $ml \cdot h^{-1}$) are possible for most people. By ingesting relatively large

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volumes of solutions containing 4–8% carbohydrate, most people can meet their carbohydrate needs while also obtaining 625–1,000 ml·h^{-1} of fluid. The question becomes, "At what rate can and should fluid be replaced while also ingesting 30–60 g of carbohydrate per hour of exercise?" Are there situations where more than 1,000 ml·h^{-1} is beneficial?

FLUID INGESTION DURING PROLONGED EXERCISE

General recommendations. The American College of Sports Medicine currently recommends that runners drink 100–200 ml of fluid after every 2–3 km (2). This very general recommendation provides little useful information for runners to decide how much to drink during exercise. At the extremes, it could be interpreted as recommending that slow runners (i.e., keeping a pace of 10 km·h^{-1} and drinking 100 ml every 3 km) should drink only 330 ml·h^{-1}, whereas the faster runners (i.e., keeping a pace of 20 km·h^{-1} and drinking 200 ml every 2 km) should drink 2,000 ml·h^{-1}. When sweating heavily, the low rate of fluid consumption (i.e., 330 ml·h^{-1}) will be suboptimal for preventing hyperthermia, and the large rate of fluid consumption (i.e., 2,000 ml·h^{-1}) would probably cause intolerable gastrointestinal discomfort for most runners (15).

Obviously, the recommended rate of fluid consumption during exercise will vary in relation to the rates of dehydration due to sweating. Depending upon the environmental conditions, sweating rate in most people usually ranges from 500 to 2,000 ml·h^{-1} when running, although there have been some reports of top marathon runners sweating at 3,000 ml·h^{-1}. Because of their increased rates of heat production, faster runners have higher core temperatures and sweat at higher rates. The decision as to how much fluid to ingest during exercise should be based upon a risk-benefit analysis. The benefits of fluid ingestion are reduced cardiovascular stress and reduced hyperthermia which, by themselves, can improve exercise performance. The risks are gastrointestinal discomfort and reduced pace during competition due to the time spent drinking large volumes of fluid.

Is a certain amount of dehydration acceptable or without physiological consequence?. During the past 20–25 yr, the notion has developed that a certain amount of dehydration is acceptable during exercise, particularly running. This notion implies that thermoregulation, cardiovascular function, and performance are not significantly impaired until a critical amount of dehydration has been incurred. The most referenced data in support of this notion were reported by Wyndham and Strydom in 1969 (31) and are displayed in Figure 1. They simply measured post-marathon race rectal temperature vs the percentage of body weight loss due to sweating in numerous runners. They interpreted Figure 1 to suggest that only when the body water deficit exceeded 3% of body weight loss (i.e., 2,100 ml for a 70-kg person or a body weight loss of 4.6 lb) did runners exhibit hyperthermia (i.e., rectal temperature above 102°F or 39°C). They focused their attention on the scatter in rectal temperature between 2–3% water deficit and on the observation that one subject experienced no dehydration because he drank large fluid volumes, yet he had a somewhat elevated rectal tem-

TABLE 1. Listing of the volume of solution to be ingested each hour to provide 30, 40, 50, and 60 g·h^{-1} of carbohydrate. The top section lists volumes of solution that are too large (i.e., >1,250 ml·h^{-1}). The middle sections list volumes which provide 625–1,250 ml·h^{-1} of fluid. The bottom sections lists volumes of 600 ml·h^{-1} or less.

Volume of Fluid to Ingest Each Hour to Obtain the Noted Amount of Carbohydrate

Concentration in Drink (gram/100 ml)	30 gm/hr	40 gm/hr	50 gm/hr	60 gm/hr
2%	1500 ml	2000 ml	2500 ml	3000 ml
4%	750	1000	1250	1500
6%	500	667	833	1000
8%	375	500	625	750
10%	300	400	300	600
15%	200	267	333	400
20%	150	200	250	300
25%	120	160	200	240
50%	60	80	100	120

Volume Too Large > 1,250 ml/hr

Adequate Fluid Replacement 600-1250 ml/hr

Low Fluid Replacement < 600 ml/hr

•Gastric emptying does not usually exceed 1,000-1,200 ml per hour unless large volume consumed.

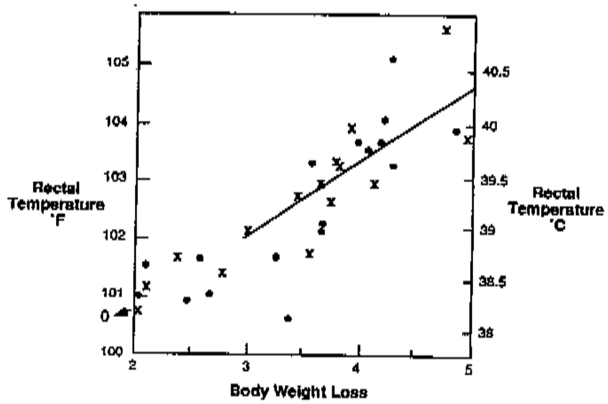

Figure 1—The relationship between rectal temperature after a 20-mile race and the percentage of body weight loss of 31 runners competing in two different races (*filled circle* and *x*). Note the *small arrow* reports the rectal temperature of one subject who drank sufficient fluid to prevent dehydration; from Wyndham and Strydom (31).

perature. From this relationship they proposed, in our opinion arbitrarily, that fluid should be ingested at a rate that prevents the development of a 3% water deficit. We disagree with their interpretation of Figure 1 because we do not see any reason for concluding that rectal temperature was not influenced by dehydration in the range of 0–3% body weight loss. As presented below, we now realize that any amount of dehydration impairs cardiovascular function and elevates core temperature.

We suspect that marathon runners allow themselves to dehydrate to some extent because they feel they cannot drink and "stomach" the high rates of fluid ingestion necessary to totally offset sweating (3). In general, most runners drink only about 500 ml of fluid per hour (20,21). Since sweat rates often average 1,000–1,500 $ml \cdot h^{-1}$, marathon runners commonly dehydrate at a rate of 500–1,000 $ml \cdot h^{-1}$, although dehydration rates can be much higher when the fastest runners compete in hot environments. Table 2 lists the changes in body weight with time in people (i.e., 70 kg) who allow themselves to dehydrate. A rate of dehydration of 500 $ml \cdot h^{-1}$, which is not uncommon for a 4-h marathoner who sweats at 1,000 $ml \cdot h^{-1}$ and drinks 500 $ml \cdot h^{-1}$, results in a 3% body weight loss after approximately 4 h, the end of the marathon. A rate of dehydration of 1,000 $ml \cdot h^{-1}$, which is likely for a top marathoner who sweats 1,500 $ml \cdot h^{-1}$ while drinking only 500 $ml \cdot h^{-1}$, will result in a 3% body weight loss in a little over 2 h, which also is the end of the marathon for this runner. Therefore, it generally appears that the drinking schedule adopted by marathoners, slow and fast, is one that allows them to become dehydrated by about 3% of their body weight at the end of the race.

Are there any benefits of allowing this amount of dehydration that might counteract the increased cardiovascular and heat stress it imposes? For one thing, the loss of body weight may reduce the energy expenditure needed to run at a given speed. If the reduction in energy expenditure is directly related to the weight loss, theoretically this might allow a runner to maintain a 5–10 $s \cdot mile^{-1}$ faster pace at the end of the marathon, provided all other factors are equal, which obviously will not be the case since the cardiovascular stress will be greater when dehydrated. Drinking larger volumes of fluid may also cost the runner additional seconds per mile in making his/her way to the aid station table. Also, the difficulty in drinking and breathing when running and added gastrointestinal discomfort may cause an additional slowing of the pace for a period. The performance question boils down to "Will the time lost in drinking larger volumes be compensated by the physiological benefits and the faster pace that might be achieved during the last half of the race?" However, if the goal is safety, which means minimizing hyperthermia, there is no question that the closer that the rate of drinking can match the rate of dehydration, the better.

TABLE 2. Changes in % body weight with time when people allow themselves to become dehydrated at a rate of either 500 $ml \cdot h^{-1}$ or 1,000 $ml \cdot h^{-1}$. The values were calculated for a person weighing 70 kg (154 lb).

	Dehydration Rate of 550 $ml \cdot h^{-1}$		Dehydration Rate of 1,000 $ml \cdot h^{-1}$	
Exercise Time (h)	Absolute Dehydration (ml)	Body Weight Loss (% and lb)	Absolute Dehydration (ml)	Body Weight Loss (% and lb)
1	500	0.7% = 1 lb	1,000	1.4% = 2 lbs
2	1,000	1.4% = 2 lb	2,000	2.9% = 4.5 lb
3	1,500	2.1% = 3 lb	3,000	4.3% = 6.5 lb
4	2,000	2.9% = 4.5 lb	4,000	5.7% = 8.8 lb

To our knowledge, no studies to date have directly compared the running or cycling performance effects of fluid replacement at rates that prevent dehydration compared with the rates chosen by many endurance athletes (i.e., 500 $ml \cdot h^{-1}$) who replace only 30–50% of fluid losses. The cardiovascular benefits of full compared with partial partial fluid replacement when cycling are discussed below, and it is likely that the same cardiovascular benefits are derived when running. However, as discussed above, it is not clear how dehydration influences running performance. These questions have been confused even more by recent reports from Noakes et al. (21) entitled "Metabolic rate, not percent dehydration, predicts rectal temperature in marathon runners." Noakes et al. (20,21) argue that the degree of hyperthermia at the end of the marathon is not related to the level of dehydration during prolonged exercise in mild environments (19–22°C) with sweat rates of about 1 $l \cdot h^{-1}$ and when runners uniformly drink 400–600 $ml \cdot h^{-1}$. On average, after finishing a 3.5-h marathon, their subjects experienced a homogeneous dehydration of about 2 l, which corresponds to a body weight loss of approximately 2.5%. Under these conditions of homogeneous dehydration among subjects, the rectal temperatures at the end of the marathon were related to the subjects running pace during the last 6 km, and thus their rates of heat production. These results are not surprising because body temperature will be determined by the balance between heat production and heat dissipation. The observation that heat production can influences core temperature should not be interpreted to indicate that heat dissipation is less important than production or that the effectiveness of fluid replacement for maintaining heat dissipation is minor. It is likely that the runners in the study of Noakes et al. (21) would have experienced less hyperthermia if they increased their rate of fluid consumption.

Low intensity exercise and fluid replacement. In early experiments, it was repeatedly found that fluid ingestion during prolonged low-intensity exercise such as walking and stair stepping attenuated deep body (core) temperature and improved exercise performance (1,4,10,24). According to Eichna et al. (10), when fluids were restricted from 600 $ml \cdot h^{-1}$ to only 150 $ml \cdot h^{-1}$ during 5 h of intermittent work, dehydration produced "total incapacitation in some, and the ineffective working of the others who remain on their feet." Furthermore, "subjects who had performed a given task easily, energetically, and cheerfully are reduced to apathetic, listless, plodding men straining to finish the same task."

In 1947, Rothstein and Towbin (28) found that there was a direct linear relationship between the magnitude of dehydration accrued during prolonged marching, and the magnitude of increase in rectal temperature. These findings are supported by the observations of other investigators who found that fluid ingestion equal to the rate of sweating was more effective than *ad libitum* or partial fluid replacement (4,10,24). Furthermore, *ad libitum* fluid ingestion during low intensity exercise is more effective in attenuating hyperthermia than when fluid intake is restricted to either small volumes or no fluid ingestion (10,24). Thus, during prolonged, low-intensity, intermittent exercise, the optimal rate of fluid replacement for attenuating hyperthermia appears to be the rate that most closely matches the rate of sweating. What about exercise performed at the higher intensities experienced during athletic competition?

Cardiovascular benefits of high rates of fluid replacement during intense cycling in the heat. We have recently completed studies that determined the effect of different rates of fluid replacement during prolonged cycling on hyperthermia, heart rate (HR), and stroke volume (SV) (16,17). On four different occasions endurance-trained cyclists exercised in a warm environment (33°C db, 50% rh) at the highest intensity that could be maintained for 2 h when no fluid was ingested (i.e., 62–67% $\dot{V}O_{2max}$). During exercise, they randomly received either no fluid (NF), or drank small (SF, 300 $ml \cdot h^{-1}$ for 2 h), moderate (MF, 700 $ml \cdot h^{-1}$ for 2 h), or large (LF, 1,200 $ml \cdot h^{-1}$ for 2 h) volumes of a "sport drink" containing 6% carbohydrate and electrolytes. These fluid volumes replaced approximately 20%, 50%, and 80%, respectively, of the fluid lost in sweat during exercise. The protocol resulted in graded magnitudes of dehydration as body weight declined 4%, 3%, 2%, and 1%, respectively, during NF, SF, MF, and LF. The increases in core temperature (i.e., both esophageal and rectal temperature) during the 2 h of exercise were progressively diminished as more and more fluid was consumed (Fig. 2). The magnitude of dehydration accrued after 2 h of exercise in the 4 trials was the major factor causing hyperthermia and cardiovascular stress. Figure 3 demonstrates that the core temperature, cardiac output, and heart rate values observed after 2 h of exercise were directly related to the rate of fluid ingestion and thus the amount of dehydration experienced. Every 1,000 ml loss of water and body weight (i.e., 2.2 lb, which corresponds to a 1.4% loss of body weight) caused heart rate to be

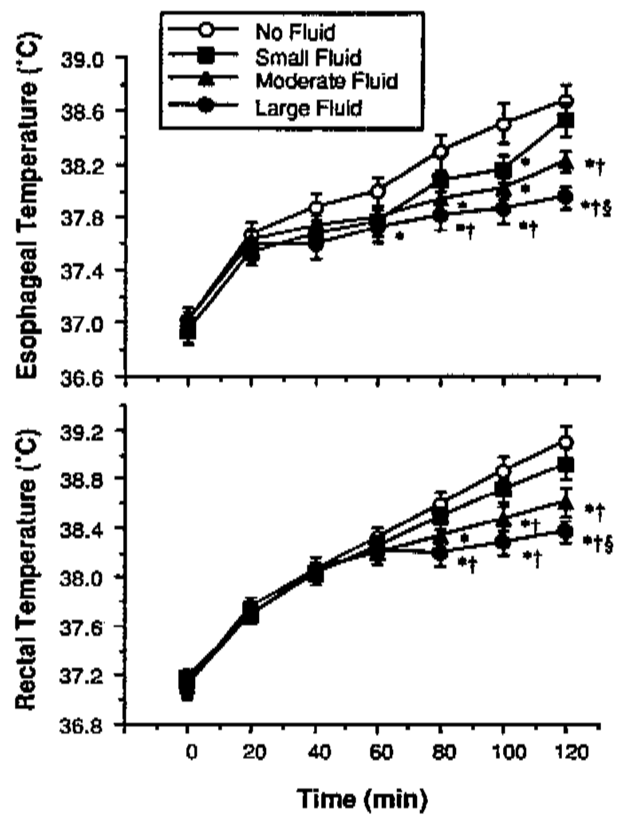

Figure 2—Esophageal ($N = 7$) and rectal ($N = 8$) temperature (i.e., core temperatures) during 120 min of exercise when ingesting no fluid, or small (i.e., 300 $ml \cdot h^{-1}$), moderate (i.e., 700 $ml \cdot h^{-1}$), and large volumes of fluid (i.e., 1,200 $ml \cdot h^{-1}$). Values are means ± SE. *Significantly lower than no fluid, $P < 0.05$. † Significantly lower than small fluid, $P < 0.05$. § Significantly lower than moderate fluid, $P < 0.05$.

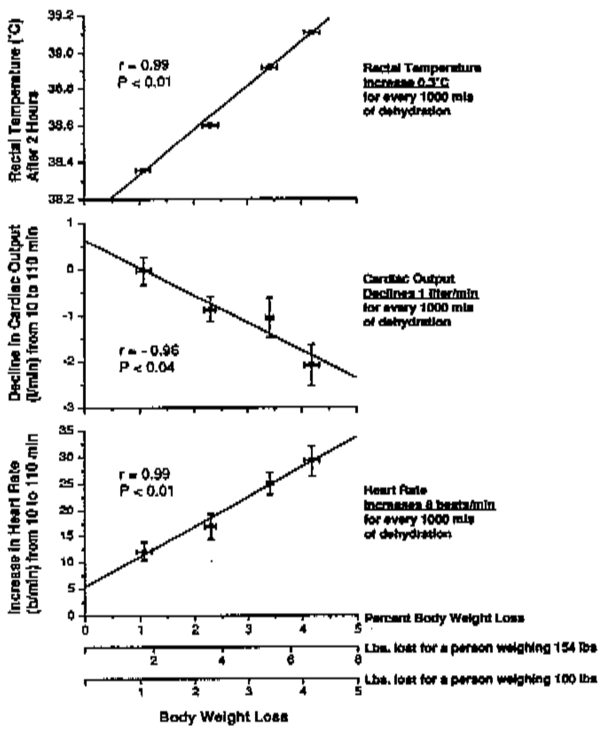

Figure 3—The influence of dehydration, as assessed by the percent reduction in body weight after 2 h of exercise, on the change in rectal temperature, cardiac output, and heart rate.

elevated by 8 beats·min^{-1}, cardiac output to decline by 1 l·min^{-1}, and core temperature to increase by 0.3°C. Fluid consumption attenuated hyperthermia by promoting a higher skin blood flow and thus a higher rate of heat dissipation.

Therefore, we maintain that there is not a critical amount of dehydration (i.e., 3%) that can be tolerated before cardiovascular function and thermoregulation are impaired. Drinking 1,200 ml·h^{-1} was better than drinking 700 ml, which was better than drinking 300 ml·h^{-1}. Although performance was not actually measured in this study, several subjects were barely able to complete 2 h of exercise without fluid ingestion. Drinking progressively larger volumes of fluid reduced the difficulty and level of perceived exertion, as shown in Figure 4. After 2 h of exercise, these cyclists rated the exercise as being "very hard" when no fluid was ingested and "hard" when only 300 ml·h^{-1} of fluid was ingested (SF). However, when fluid was consumed at 700 ml·h^{-1} and 1,200 ml·h^{-1}, the exercise never became hard. It is likely that these sensations of effort provide indirect information about performance ability after 2 h of cycling with different amounts of fluid replacement. Additionally, none of the cyclists complained of gastrointestinal discomfort or difficulty drinking 1,200 ml·h^{-1}. We therefore concluded that this rate of fluid replacement is comfortable during cycling, although we do not know about these responses when running.

Reasonable rates of gastric emptying for fluid replacement solutions. Figure 5 presents a compilation of 11 studies (5,7,12–15,25–27,29,30) that measured the rate of gastric emptying of various fluid replacement solutions. The two primary factors regulating gastric emptying appear to be the volume of fluid ingested and the carbohydrate concentration of the solution (14,22). From Figure 5, it is clear that when the volume of a given solution is increased, as noted by the listed rates of fluid ingestion (i.e., 600–1700 ml·h^{-1}), the rate of gastric emptying also increases. Furthermore, solutions containing up to 8% carbohydrate appear to have little deleterious influence on the rate of gastric emptying, especially when the drinking schedule adopted maintains a high gastric volume (22). Thus, it appears quite possible to ingest 30–60 g of carbohydrate per hour and still replace 600–1,100 ml·h^{-1} of fluid.

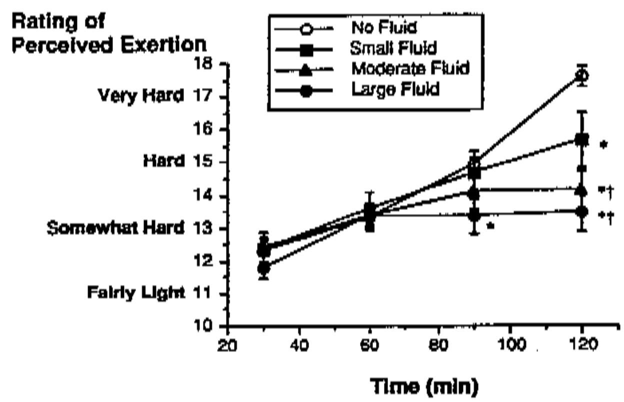

Figure 4—The rating of perceived exertion during 120 min of exercise when ingesting no fluid, or small (i.e., 300 ml·h^{-1}), moderate (i.e., 700 ml·h^{-1}) and large volumes (i.e., 1,200 ml·h^{-1}) of fluid. *Significantly lower than no fluid, $P < 0.05$. † Significantly lower than small fluid, $P < 0.05$.

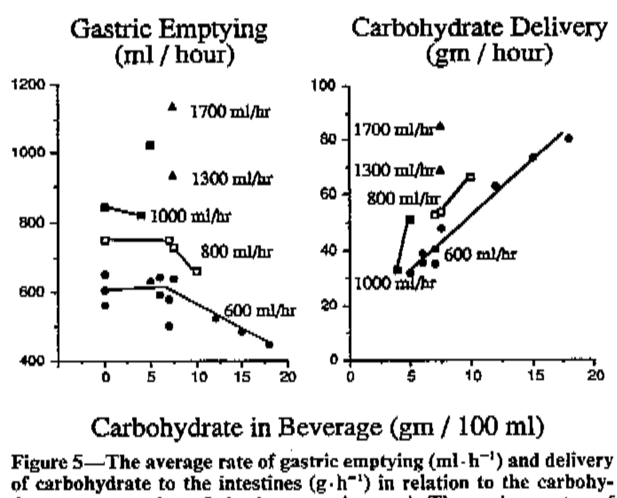

Figure 5—The average rate of gastric emptying (ml·h^{-1}) and delivery of carbohydrate to the intestines (g·h^{-1}) in relation to the carbohydrate concentration of the beverage ingested. The various rates of fluid ingestion are denoted by the different symbols (i.e., 600 ml·h^{-1} is *filled circle;* 800 ml·h^{-1} is *open square;* 1,000 ml·h^{-1} is *filled square;* 1,300 ml·h^{-1} and 1,700 ml·h^{-1} are *filled triangles.*

However, the maximal rates of gastric emptying for solutions containing 8% or more carbohydrate have not been directly determined, but the data in Figure 5 suggest that they might not be high (i.e., >800–1,000 $ml \cdot h^{-1}$).

Figure 5 also demonstrates that few studies have been conducted to determine the gastric volume and drinking schedule that result in maximal rates of gastric emptying. Of their own accord, endurance athletes usually do not drink more than 400–600 $ml \cdot h^{-1}$ (20). However, it seems that most people can empty 1,000 $ml \cdot h^{-1}$ during exercise (Fig. 5). Our experience is that cyclists have no difficulty drinking 1,200 $ml \cdot h^{-1}$ of a 6% carbohydrate solution. Such high rates of fluid ingestion will obviously require large gastric volumes, and likely cause gastrointestinal discomfort in some runners. Therefore, in runners, it remains to be determined whether the benefits of high rates of fluid replacement outweigh the discomfort they may cause.

The composition of the fluid replacement solution. Several investigations have compared the influence of drinking tap water or carbohydrate-electrolyte solutions on core temperature and heart rate during prolonged exercise (5,7,9,18,23). These experiments have demonstrated that carbohydrate-electrolyte solutions of up to 8–10% carbohydrate are equally as effective as water in attenuating hyperthermia and heart rate during prolonged exercise. Such findings agree with the gastric emptying data presented in Figure 5, demonstrating that water and solutions containing up to 8% carbohydrate have similar rates of gastric emptying, and thus fluid replacement. Therefore, it appears that the fluid replacement beverage can contain up to 8% carbohydrate without compromising fluid replacement.

SUMMARY

Ingestion of approximately 30–60 g of carbohydrate during each hour of exercise will generally be sufficient to maintain blood glucose oxidation late in exercise and delay fatigue. Since the average rate of gastric emptying and intestinal absorption exceeds 1,250 $ml \cdot h^{-1}$ for water and solutions containing up to 8% carbohydrate, exercising people can be supplemented with both carbohydrate and fluids at relatively high rates.

When cyclists exercise at competitive intensities for 2 h in the heat with a sweat rate of 1,400 $ml \cdot h^{-1}$, it is clear that the closer that fluid consumption matches sweating rate (at least up to 80% of sweating rate), the better. Increasing dehydration, due to inadequate fluid consumption, directly impairs stroke volume, cardiac output, and skin blood flow, resulting in larger increases in body core temperature, heart rate, and ratings of the difficulty of exercise. This same phenomenon probably also applies to running, which argues against the notion that a certain amount of dehydration (i.e., up to 3%) is permissible and without major cardiovascular consequences. However, runners generally drink only 500 $ml \cdot h^{-1}$ of fluid and thus allow themselves to dehydrate at rates of 500–1,000 $ml \cdot h^{-1}$. The performance question that runners should address is: "Will the time lost as a result of drinking larger volumes of fluids be compensated by the physiological benefits and the faster running pace that might be achieved during the last half of the race?" However, if the goal is safety, which means minimizing hyperthermia, there is no question that the closer that the rate of drinking can match the rate of dehydration, the better.

PRACTICAL RECOMMENDATIONS

1) Monitor the rate of dehydration by changes in nude body weight. Each one pound of weight loss corresponds to 450 ml (15 fluid ounces) of dehydration.

2) When it is important to minimize cardiovascular stress, hyperthermia, and the difficulty of exercise, people should attempt to drink fluids at the same rate that they are dehydrating due to sweating (or at least drink at a rate that is close to 80% of sweating rate).

3) Runners should determine themselves if the time lost as a result of drinking larger volumes of fluid is compensated by the physiological benefits it produces during the last half of the race.

4) Generally, the exercising endurance athlete can meet both his/her carbohydrate (i.e., 30–60 $g \cdot h^{-1}$) and fluid needs by drinking 625–1,250 $ml \cdot h^{-1}$ of beverages containing 4–8% carbohydrate.

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