

Carbohydrate and fluid ingestion during exercise: are there trade-offs?

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ABSTRACT

COYLE, E. F. and S. J. MONTAIN. Carbohydrate and fluid ingestion during exercise: are there trade-offs? *Med. Sci. Sports Exerc.*, Vol. 24, No. 6, pp. 671-678, 1992. Intense exercise (i.e.; above 60% $\dot{V}O_{2max}$) can be maintained for prolonged periods provided sufficient carbohydrate is available for energy and the heat generated from muscle metabolism does not cause excessive hyperthermia and/or dehydration due to sweating. It is clear that people should ingest carbohydrate during prolonged exercise (i.e.; longer than 1-2 h), which causes fatigue because of an inadequate supply of blood glucose and that fluids should also be ingested in an attempt to offset dehydration and reduce hyperthermia. Ingestion of approximately 30-60 g of carbohydrate (i.e.; glucose, sucrose, or starch) 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 can reach $1 \text{ l} \cdot \text{h}^{-1}$ for water and solutions containing up to 8% carbohydrate, exercising people can be supplemented with both carbohydrate and fluids at relatively high rates (over $60 \text{ g} \cdot \text{h}^{-1}$ of carbohydrate and $1 \text{ l} \cdot \text{h}^{-1}$ of fluid). Therefore, when sweat rate is not high (i.e.; less than $1 \text{ l} \cdot \text{h}^{-1}$), the addition of carbohydrate to fluids, and *vice versa*, does not prevent adequate supplementation of each, especially if large volumes are consumed to keep the stomach somewhat full and thus increase gastric emptying. Therefore, in most situations there are no trade-offs between fluid and carbohydrate. However, the scientific literature contains surprisingly little direct data regarding the extent to which fluid replacement during exercise should match sweat rate to offset cardiovascular drift and hyperthermia when sweat rate approaches or exceeds $1 \text{ l} \cdot \text{h}^{-1}$ and hyperthermia is common. Therefore, it is not possible at this time to develop scientifically sound recommendations regarding the optimal fluid replacement regimen, which may vary from person to person because of the tremendous interindividual variability in gastric emptying rate. It remains to be determined whether the benefits of high rates of fluid ingestion during continuous exercise (i.e.; $600\text{-}1,200 \text{ ml} \cdot \text{h}^{-1}$) outweigh the interruption of exercise and the discomfort it may cause.

Intense exercise can be maintained for prolonged periods provided that the heat generated from muscle metabolism does not increase body temperature to levels which cause fatigue and that sufficient carbohydrate is available for energy. The heat produced during exercise is primarily dissipated by the evaporation of sweat and by convection. Dehydration, a consequence of the body water loss due to sweating, impairs the process of heat dissipation, resulting in elevated deep body (core) temperatures and reduced endurance per-

formance (45). However, by ingesting fluids during exercise, it is possible to attenuate the detrimental effects of dehydration on body temperature and exercise performance. The addition of carbohydrate to fluid replacement beverages is also important because it provides carbohydrate late in exercise when there is often an inadequate supply of endogenous carbohydrate to meet the energy requirements of the exercise task (12). Therefore, in an effort to reduce fatigability, and improve performance during prolonged exercise, it may be beneficial to ingest both fluid and carbohydrate. The difficult task is in deciding on the optimal amount of fluid and carbohydrate intake for a given activity. In theory, knowledge of both the 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.

In our opinion, sufficient information is presently available from which we can reasonably estimate the rate at which carbohydrate should be ingested so as to delay fatigue during prolonged intense exercise (12). However, the present literature contains less information regarding the extent to which fluid ingestion should offset dehydration during prolonged exercise. This latter situation prevents us, at this time, from developing specific practical recommendations which have scientific validity. 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 to the exercise participant because at the extremes, it could be interpreted to suggest that it is permissible for slow runners (i.e.; $10 \text{ km} \cdot \text{h}^{-1}$) to drink only $330 \text{ ml} \cdot \text{h}^{-1}$ whereas the fastest runners could interpret this to indicate they should drink $2,000 \text{ ml} \cdot \text{h}^{-1}$.

The purpose of this article is to review the literature regarding the need for fluid replacement and carbohy-

hydrate supplementation during prolonged exercise and discuss whether there may be trade-offs in obtaining both optimal fluid replacement and optimal carbohydrate supplementation. Our approach will be to first present information pertaining to carbohydrate supplementation during prolonged exercise. Next, we will review what is known about fluid replacement during exercise-induced dehydration. Finally, we will address whether there are trade-offs between obtaining optimal fluid replacement and carbohydrate supplementation during prolonged exercise. It should be noted that all recommendations are made for a person weighing 70 kg and generalization to a person of a different body weight will require recalculation according to their weight difference from 70 kg.

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 (12,15) (Fig. 1). When carbohydrate supplementation is provided during prolonged moderately intense exercise, subjects can exercise longer and produce greater power during short-term performance tasks at the end of exercise (12). Thus, carbohydrate supplementation is recommended whenever the exercise task may deplete endogenous carbohydrate stores, thus reducing exercise performance.

Carbohydrate type. Studies that have directly determined the effects of ingesting glucose compared with maltodextrins or sucrose during exercise, either alone or in combination, have found little difference among these carbohydrates in terms of their ability to maintain blood glucose concentration and carbohydrate oxidation, or their ability to improve performance

(6,31,38,44). Maltodextrins have become a popular form of carbohydrate in sport drinks. Probably the major reason for including maltodextrins compared with glucose or sucrose is that they are not sweet tasting, making solutions containing more than 10% carbohydrate more palatable. It appears that carbohydrate in solid form, when supplemented with water ingestion, produce a similar response to liquid carbohydrate (20,25). However, most exercising athletes prefer liquid carbohydrate because it is more easily ingested and because it also offsets dehydration.

Rate of carbohydrate ingestion. Most studies which have reported that carbohydrate ingestion throughout exercise can improve performance have given subjects 25–60 g of carbohydrate per hour of exercise (12,39), although some have given more (15). These rates of supplementation have provided the additional 45–60 g of carbohydrate required to maintain blood glucose oxidation late in exercise (12). These observations are in general agreement with the finding that the rate of intravenous glucose infusion required to restore and maintain blood glucose availability and carbohydrate oxidation late in exercise is over $1 \text{ g} \cdot \text{min}^{-1}$ (10). Because fatigue was delayed by about 45 min, 45–60 g of glucose were needed to maintain blood glucose concentration late in exercise.

Timing of carbohydrate ingestion. The goal of supplementing blood glucose at a rate of over $1 \text{ g} \cdot \text{min}^{-1}$ during the latter stages of prolonged exercise can be achieved by either ingesting carbohydrate throughout exercise or by delaying carbohydrate ingestion until late in exercise (11). However, if subjects delay carbohydrate ingestion until too late in exercise (i.e., less than 30 min before fatigue), the rate at which the ingested carbohydrate enters the blood as glucose may not be fast enough to maintain euglycemia and performance may suffer (10–12). In general, it appears that a person should begin carbohydrate ingestion at least 30 min prior to the time when fatigue would normally occur if no carbohydrate were ingested during exercise (11), although there is a large amount of variability from subject to subject in this regard (12). Furthermore, adopting a strategy of not ingesting carbohydrate until late in exercise will require that a concentrated carbohydrate solution be ingested, for adequate carbohydrate delivery into the blood. Such a strategy may be a poor choice for individuals with relatively slow rates of gastric emptying. An alternative and less risky approach for carbohydrate supplementation is to drink carbohydrate-containing solutions throughout exercise so that blood glucose concentration and carbohydrate oxidation can be maintained late in exercise (12).

It is important to realize that these results apply to continuous exercise performed at 70–75% $\dot{V}O_{2\text{max}}$, conditions under which carbohydrate ingestion does not alter the decline in muscle glycogen (12,15). It is pos-

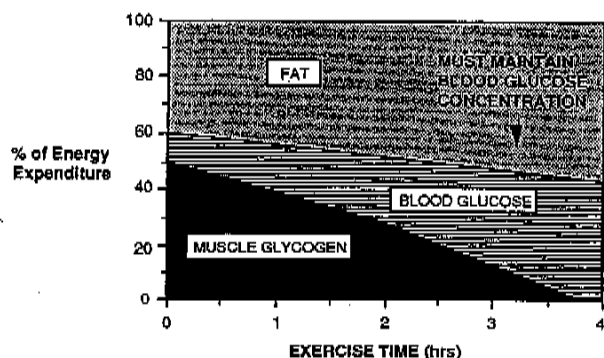


Figure 1—Sources of energy when cycling at 70% $\dot{V}O_{2\text{max}}$. Late in exercise, when muscle glycogen is low, ingested carbohydrate maintains blood glucose concentration and becomes the major source of carbohydrate energy.

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sible that carbohydrate supplementation throughout intermittent or low intensity exercise may promote glycogen resynthesis in resting fibers (13,27). Under these conditions, carbohydrate ingestion throughout exercise may prove more beneficial to performance than ingesting carbohydrate only late in exercise.

General recommendation for carbohydrate. It is recommended that during exercise which is sufficiently long and intense enough to promote premature fatigue due to an inadequate blood glucose concentration that individuals consume solutions which provide 30-60 g of carbohydrate per hour. Table 1 lists the volume and concentration of various solutions which meet this recommendation. To obtain just 30 g of carbohydrate per hour when ingesting a 2% carbohydrate solution, a person's stomach must be able to empty 1,500 ml·h⁻¹. If 60 g·h⁻¹ carbohydrate is needed, the gastric emptying must increase to 3,000 ml·h⁻¹, which is an unreasonably high rate of gastric emptying (35). Therefore, when dilute carbohydrate solutions (i.e., 2% or g·100 ml⁻¹) are consumed, there is a trade-off in that carbohydrate supplementation is compromised because dilute solutions can not be emptied from the stomach at the rates required. On the other hand, 60 g·h⁻¹ of carbohydrate supplementation can be achieved by absorbing 1,000 ml·h⁻¹ of a 6%, or 750 ml·h⁻¹ of an 8% or 600 ml·h⁻¹ of a 10% carbohydrate solution. As shown in Figure 2 and discussed below, these rates of gastric emptying are possible for most people. By ingesting relatively large volumes of solutions containing 6-10% carbohydrate, most people can meet their carbohydrate needs while also obtaining 600-1,000 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?

Additionally, it has yet to be determined whether there are situations during which it is beneficial to have the ingested carbohydrate being delivered to the intestines and entering into the blood at very high rates, for example 100 g·h⁻¹. Figure 2 indicates that the rate of carbohydrate delivery into the intestines increases as the carbohydrate concentration of the drink increases in the range of 5-20%. Extrapolation of Figure 2 suggests that carbohydrate supplementation at a rate of 100 g·h⁻¹ might require ingestion of large volumes (>800 ml·h⁻¹) of 20% carbohydrate solutions (Table 1). If fluid replacement is not important, 100 g·h⁻¹ may be obtained by ingesting very concentrated carbohydrate solutions (i.e.; >50% carbohydrate).

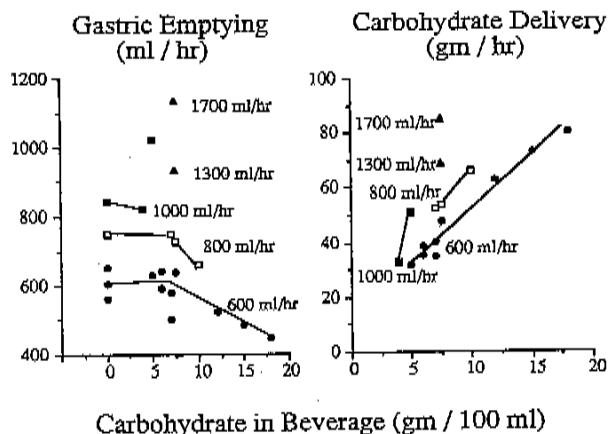


Figure 2—The average rate of gastric emptying (ml·h⁻¹) and delivery of carbohydrate to the intestines (g·h⁻¹) in relation to the carbohydrate concentration of the beverage ingested. The various rates of fluid ingestion are denoted by the different symbols (i.e.; 600 ml·h⁻¹ is filled circle; 800 ml·h⁻¹ is open square; 1,000 ml·h⁻¹ is closed square; 1,300 ml·h⁻¹ is open triangle; and 1,700 ml·h⁻¹ is filled triangle).

Volume Ingested Each Hour to Provide the Noted Amount of Carbohydrate

Concentration in Drink	30 gm/hr 40 gm/hr 50 gm/hr 60 gm/hr 100 gm/hr				
	1500 ml	2000 ml	2500 ml	3000 ml	5000 ml
2%	1500	2000	2500	3000	5000
4%	750	1000	1250	1500	2500
6%	500	667	833	1000	1667
8%	375	500	625	750	1250
10%	300	400	500	600	1000
15%	200	267	333	400	667
20%	150	200	250	300	500
25%	120	160	200	240	400
50%	60	80	100	120	200

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

TABLE 1. Listing of the volume of solution to be ingested each hour to provide 30, 40, 50, 60, or 100 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 that provide 625-1,000 ml·h⁻¹ of fluid. The bottom sections lists volumes of 600 ml or less.

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Reasonable rates of gastric emptying for fluid replacement solutions. Figure 2 presents a compilation of 11 studies (8,14,26,33-35,46-48,50,56) that have 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 (34,43). From Figure 2 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 influence on the rate of gastric emptying, especially when a drinking schedule is adopted which maintains a high gastric volume (43). Thus, it appears quite possible to ingest 30-60 g of carbohydrate per hour and still replace 600-1,000 ml·h⁻¹ of fluid.

Figure 2 also demonstrates that few studies have been conducted to determine the gastric volume and drinking schedule which results in maximal rates of gastric emptying. Of their own accord, endurance athletes usually do not drink more than 400-600 ml·h⁻¹ (41). However, it seems that most people can empty 1,000 ml·h⁻¹ during exercise (Fig. 2). It remains unclear whether it is possible to completely offset dehydration when the sweat rate is high (1,000-1,500 ml·h⁻¹). Such high rates of fluid ingestion will obviously require large gastric volumes, and it is likely that some individuals will develop gastrointestinal discomfort. Another "trade-off" to be considered is the benefit of high rates of fluid replacement relative to the discomfort it may cause.

The need for fluid replacement during prolonged exercise. It has long been recognized that exercise-induced dehydration will augment hyperthermia, thus increasing the risk of developing heat stroke during prolonged exercise. The benefits of offsetting dehydration by ingestion of fluids during exercise were reported in experiments conducted in the mid-1940s. In these experiments, it was repeatedly found that fluid ingestion during prolonged low-intensity exercise attenuated deep body (core) temperature and improved exercise performance (1,5,18,45). Figure 3 illustrates data from Pitts et al. (45) in which one subject ingested either no water, sufficient water to completely offset sweat loss, or *ad libitum* consumption of water after 1 h of exercise during 5 h of treadmill walking in a hot environment. On the two days in which no water was ingested, rectal temperature rose progressively throughout exercise, reaching 39°C by 4 h of exercise. During one of the no fluid trials, the subject had to discontinue exercise after 4 h. When fluid intake matched the rate of sweat loss, rectal temperature was maintained at approximately

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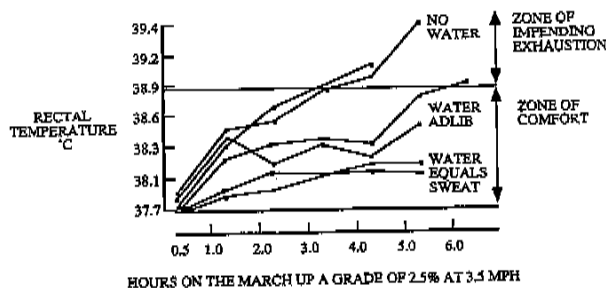


Figure 3—Effect of water consumption on marching in the heat. (Six experiments in subject J.S. at temperature 37.7°C, relative humidity 35-45%; from Pitts et al. (45).)

38.1°C throughout exercise and the subject completed 5 h of treadmill walking. Finally, when *ad libitum* (approximately equal to 70% of sweat loss) fluid intake was provided after 1 h of exercise, rectal temperature was maintained at 38.3°C from 1 to 4 h of exercise, after which rectal temperature began to increase, reaching approximately 38.6°C after 5 h of exercise. The effects of dehydration are also illustrated by the subjective symptoms displayed by subjects when fluids are withheld during the exercise task. According to Eichna et al. (18), when fluids were restricted from 600 ml·h⁻¹ to only 150 ml·h⁻¹ during 5 h of intermittent work, dehydration produced "total incapacitation in some, the ineffective working of the others who remain on their feet." Furthermore, "acclimatized subjects who had performed a given task easily, energetically, and cheerfully are reduced to apathetic, listless, plodding men straining to finish the same task."

More recently, several experiments have demonstrated that fluid ingestion during 2 h of moderately intense exercise (60-75% $\dot{V}O_{2max}$) can also attenuate hyperthermia (14,23,24). In 1970, Costill et al. (14) reported that ingestion of 100 ml after every 10 min of exercise significantly attenuated the increase in rectal temperature during 2 h of exercise in five trained marathon runners, as the rectal temperature was approximately 38.5 and 39.2°C after 2 h of running when given fluid or no fluid, respectively. In addition, we (14) recently observed that fluid ingestion sufficient to match the rate of sweating attenuated increases in rectal temperature and heart rate, and prevented a decline in stroke volume during exercise.

However, it has been suggested that fluid replacement will not attenuate hyperthermia or enhance exercise performance during relatively high intensity exercise that results in fatigue in approximately 1 h or less. Deschamps et al. (17) reported that intravenous infusion of saline, compared with no fluid infusion, did not improve time to fatigue (21.96 ± 3.56 vs 20.82 ± 2.63 min) when nine males cycled at 84% of $\dot{V}O_{2max}$ until exhaustion. Furthermore, Maughan et al. (32) found that water ingestion, compared with no fluid intake,

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did not significantly attenuate hyperthermia, heart rate, or endurance time (76.2 ± 9.1 vs 70.2 ± 8.3 min).

Despite these findings, it is clear that fluid replacement during prolonged low intensity exercise in the heat will attenuate hyperthermia and often enhance performance when a significant reduction in body weight occurs due to sweating. As previously stated, the problem for the endurance exercise participant is to determine the optimal volume of fluid intake to attenuate hyperthermia and enhance exercise tolerance without sacrificing performance time due to slowing race pace to drink or from possible side effects (stomach distress, urination) from attempting to drink too much during the exercise period. Is there a point where the benefits of increasing the rate of fluid replacement for preventing hyperthermia and cardiovascular drift are small compared with the possible discomfort? This requires elucidation of the relationship between dehydration and hyperthermia and performance. Unfortunately, it is not possible at the present time to identify the optimal rate of fluid ingestion during prolonged exercise, as it remains unresolved how fluid replacement attenuates hyperthermia and what influence the rate of fluid ingestion has on hyperthermia during prolonged moderately intense exercise.

The mechanisms by which fluid replacement attenuates hyperthermia. As already discussed in Sawka's chapter (55), much of our understanding of how body water loss alters the regulation of body temperature during exercise has been derived from hypohydration experiments, in which a body water deficit is induced prior to exercise. Typically, hypohydration is produced during the 24-h period preceding the experimental exercise period by exercising in a warm environment, sauna exposure, diuretics, food and fluid restriction, or some combination of these methods. These experiments have demonstrated that a 3–7% of reduction in body weight will elevate core temperature and heart rate during the subsequent exercise period (53,54), and that the elevation in core temperature appears to be due to a delayed onset of sweating and a reduced skin blood flow (21). Additionally, experiments which have increased serum osmolality (see Greenleaf's chapter and Sawka's chapter) or have reduced blood volume (21,40) prior to exercise have concluded that hyperosmolality and hypovolemia can independently alter sweating and skin blood flow during exercise, thus augmenting hyperthermia (52).

However, it is questionable whether hypohydration experiments are applicable, in all cases, to understanding the mechanisms by which exercise-induced dehydration augments hyperthermia. As illustrated in Table 2, hypohydration by 3–5% of body weight through diuretics, sauna exposure, and water and food denial results in plasma volume reductions ranging from 8 to 18% (7,9,51,53). In contrast, during exercise-induced

TABLE 2. Comparison of percentage decline in body weight and plasma volume through various methods of dehydration.

Study	Dehydration Method	% Reduction in Body Weight	% Reduction in Plasma Volume*
Sawka et al., 1985 (53)	Water and food denial	3	8
	Water and food denial	5	15
Caldwell et al., 1984 (7)	Diuretics	4	14
	Sauna	4	10
	Prolonged exercise	4	1
Saltin, 1964 (51)	Sauna	4	18
	Prolonged exercise	4	3
Claremont et al., 1976 (8)	Diuretics	3	16

*% Reduction in plasma volume, measured during submaximal exercise when hypohydrated, below the plasma volume during submaximal exercise when euhydrated.

Water and food denial for 15 h after exercising in mild heat.

dehydration of 4% of body weight, the reduction in blood volume, below levels observed after the first few minutes of exercise is only 1–4% (24,51). Therefore, hypohydration experiments induce a much larger reduction in blood volume than is typically observed during exercise-induced dehydration. Furthermore, a recent experiment in our laboratory (36) has demonstrated that the intravenous infusion of 397 ml of a blood volume expander, to maintain blood volume similar to when fluid ingestion replaced 80% of sweat loss during 2 h of moderate-intensity cycling, was unable to attenuate the hyperthermia that occurred when no fluid was ingested during exercise. These data demonstrate that the approximately 300-ml reduction in blood volume accompanying 2 h of exercise-induced dehydration are not responsible for augmenting hyperthermia in well-trained cyclists. These findings also demonstrate that the results of experiments that hypohydrate people before exercise do not necessarily explain the mechanisms by which fluid ingestion attenuates hyperthermia during prolonged exercise.

To date, the physiological responses accompanying fluid replacement during exercise-induced dehydration have not been well characterized. While it is clear that high rates of fluid replacement can attenuate hyperthermia and reduce heart rate during prolonged exercise, no study has determined what influence the rate of fluid replacement has on hyperthermia, heart rate, and stroke volume during prolonged moderately intense exercise. Furthermore, no study has reported the relationship between elevations in either serum osmolality or sodium concentration and elevations in core temperature during prolonged exercise when the rate of dehydration is altered by fluid ingestion.

The mechanisms by which fluid replacement attenuates hyperthermia during prolonged exercise also remain unresolved. While some investigators have reported that fluid ingestion maintains a higher sweat rate compared with when no fluid is ingested during prolonged exercise (19,29), others have found no difference in sweat rate (1,3,8,14,18,23,28,30,45). No in-

vestigation has yet reported whether fluid replacement, compared with no fluid ingestion, maintains a higher skin blood flow during exercise.

The optimal rate of fluid replacement during prolonged exercise. Unfortunately, while it is clear that fluid replacement can attenuate hyperthermia and improve work tolerance, the optimal rate of fluid intake for attenuating hyperthermia and preserving exercise tolerance remains unclear. In 1947, Rothstein and Towbin (49) found that there was a linear relationship between the magnitude of dehydration accrued during prolonged marching and the magnitude of increase in rectal temperature (Fig. 4). In addition, they reported that the ingestion of fluids during exercise did not alter the relationship between dehydration and hyperthermia. 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 (5,18,45). Furthermore, it has been reported that *ad libitum* fluid ingestion during exercise is more effective in attenuating hyperthermia than when fluid intake is restricted to either small volumes or no fluid ingestion (18,45). Thus, during prolonged low-intensity intermittent exercise, the optimal rate of fluid replacement for attenuating hyperthermia appears to be the rate which most closely matches the rate of sweating.

However, Wyndham and Strydom (57) have suggested that full fluid replacement of body water loss during moderately intense exercise may not be necessary to fully attenuate the increase in core temperature associated with dehydration. In our opinion, to date, no published study has systematically determined the thermoregulatory and cardiovascular effects of different rates of fluid replacement during prolonged exercise at 50–80% $\dot{V}O_{2max}$. The studies which have been conducted have not performed repeat tests on the same subjects while varying the amount of fluid replacement and thus the amount of dehydration. Instead, the stud-

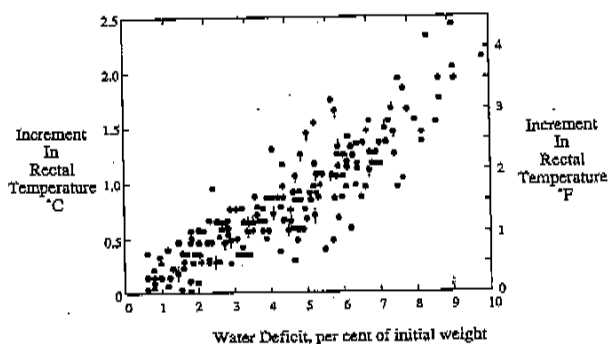


Figure 4—The relationship between the increase in rectal temperature and the amount of dehydration, expressed as a percent of body weight loss in individual subjects after walking in the heat, with and without fluid replacement, which offset dehydration to varying degrees; from Rothstein and Tobin (49), Figures 11 and 12.

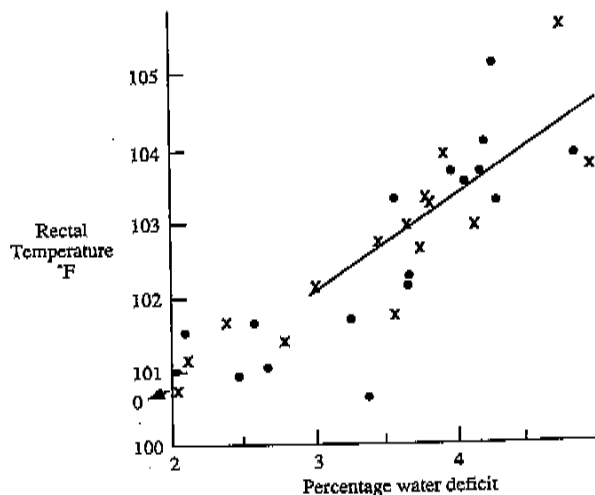


Figure 5—The relationship between rectal temperature after a 20-mile race and the percentage of body weight loss of 31 runners competing in two different races (filled circle and x) in a cool environment (i.e.; dry bulb temperature of 9–17°C). Note the small arrow reporting the rectal temperature of one subject who drank sufficient fluid to prevent dehydration; from Wyndham and Strydom (57).

ies discussed below have simply measured rectal temperature after competition, in rather large and heterogeneous populations of runners, to determine the relationship between the amount of dehydration incurred and rectal temperature (41,42,57).

Wyndham and Strydom (57) interpreted their data, displayed in Figure 5, as indicating a significant relationship between post-marathon race rectal temperature and the water deficit in participants, but only when the water deficit exceeded 3% of body weight loss. They focused attention on the scatter in rectal temperature between 2–3% water deficit, and the observation that one subject experienced no dehydration because he drank large fluid volumes, yet he had a somewhat elevated rectal temperature. From this relationship they proposed that the optimal rate of fluid replacement is a rate that prevents the development of a 3% water deficit. To date, Wyndham and Strydom's hypothesis has never been directly tested. However, Bar-Or et al. (4) reported no difference in rectal temperature, heart rate, plasma volume, or osmolality when 10- to 12-yr-old boys replaced either 70% or 100% of their water loss during 3–4 h of intermittent exercise. Furthermore, Noakes et al. (41,42) argue that during prolonged exercise in mild environments (19–22°C) with sweat rates of $1 \text{ l} \cdot \text{h}^{-1}$ and a fluid intake of $0.4\text{--}0.6 \text{ l} \cdot \text{h}^{-1}$, that the degree of hyperthermia at the end of the marathon is not related to the level of dehydration. After 3.5 h of exercise their subjects were hypohydrated by about 2 l, which corresponds to a body weight loss of approximately 2.5%.

Again, we are not aware of any investigations that

directly addressed the questions, "Should fluid intake equal the rate of weight loss so as to prevent dehydration?" or as suggested by Wyndham and Strydom (57) and Noakes et al. (41,42), "Should endurance athletes keep their *ad libitum* fluid intake at a rate well below sweating that allows them to become dehydrated at a rate of $0.5 \text{ l}\cdot\text{h}^{-1}$?"

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 (8,14,16,37,44). 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 2, demonstrating that solutions containing up to 8% carbohydrate have similar rates of gastric emptying, and thus fluid replacement, as water. Therefore, it appears that the fluid replacement beverage can contain up to 8% carbohydrate without compromising fluid replacement.

Summary of The Optimal Rate of Fluid and Carbohydrate Ingestion During Prolonged Exercise

Ingestion of approximately 30–60 g of carbohydrate (i.e., glucose, sucrose, or starch) 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 exceeds $1 \text{ l}\cdot\text{h}^{-1}$ for water and solutions containing up to 8% carbohydrate, exercising people can be supplemented with both carbohydrate and fluids at relatively high rates (over $60 \text{ g}\cdot\text{h}^{-1}$ of carbohydrate and $1 \text{ l}\cdot\text{h}^{-1}$ of fluid). Therefore, when sweat rate is not very high (i.e., less than $1 \text{ l}\cdot\text{h}^{-1}$), the addition of carbohydrate to fluids, and *vice versa*, does not prevent adequate supplementation of each, especially if large volumes are consumed to keep the stomach somewhat full and thus increase gastric emptying. Therefore, when sweat rate is $1 \text{ l}\cdot\text{h}^{-1}$ or less, there are no trade-offs between fluid and carbohydrate supplementation.

Several investigators have demonstrated that full fluid replacement is better than *ad libitum* fluid replacement during low intensity intermittent exercise in the heat when sweating at up to $1 \text{ l}\cdot\text{h}^{-1}$ because it attenuates the increases in core temperature and heart rate and it improves performance (18,28,45). During prolonged continuous exercise at 50–80% $\dot{V}O_{2\text{max}}$, sweat rate usually exceeds $1 \text{ l}\cdot\text{h}^{-1}$, whereas people prefer to drink at rates of only about $500 \text{ ml}\cdot\text{h}^{-1}$. The unanswered question is "Are the benefits of higher rates of fluid ingestion during continuous exercise at 50–80% $\dot{V}O_{2\text{max}}$ (i.e., $>1 \text{ l}\cdot\text{h}^{-1}$ and up to the rate of sweating) worth the discomfort and the time that might be lost attempting to drink large volumes during competition?"

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