THE EFFECTS OF REHYDRATION ON CYCLING PERFORMANCE AFTER EXERCISE-INDUCED DEHYDRATION

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Abstract. The effects of 7.6% carbohydrate-electrolyte solution (CES) and placebos (P) on rehydration (R) after exercise-induced dehydration and on a subsequent time-trial (TT) of cycling performance were studied. Thirteen male subjects exercised in a thermally-controlled environment (28ºC, 63% RH) until 3% of their body weight was lost. After exercise, the subjects moved to a neutral environment (22ºC) and rested for 30 minutes prior to a 2-hour R period. During R, subjects were fed CES or P to a maximum volume of 120% of previous body mass loss at 0, 30, and 60 minutes, in bolus-doses of 50%, 40% and 30% respectively. After R, subjects performed a 1-hour TT with no further fluid intake. % R with CES was significantly higher than with P (70±3% *vs* 60±5%; $p<0.01$). During the TT, blood glucose dropped in the CES group but not in the P group. It was found that, despite a more effective R with CES, the performance results did not differ between groups (65.1±2.2 minutes and 65.2±2.3 minutes for CES and P respectively). It is suggested that an insulin-mediated rebound effect on CHO metabolism during TT, in which no further CHO was supplied, nullified the benefits of rehydration.

INTRODUCTION

It is generally accepted that a prolonged bout of exercise in a hot environment can have an adverse effect on the body's cellular environment due to dehydration; such exercise may cause the loss of more than 1 liter of body fluid per hour (Costill, 1977). The rapid replacement of fluid following a bout of exercise is of paramount concern to athletes, who may have to exercise more than once a day. Fluid replacement solutions containing a variety of electrolytes, carbohydrate and of varying degrees of carbonation have been examined following exercise-induced dehydration (Costill and Sparks, 1973; Nielsen *et al*, 1986; Carter and Gisolfi, 1989; González-Alonzo *et al*, 1992; Greenleaf, 1992; Lambert *et al*, 1992; Maughan *et al*, 1994; Wong *et al*, 1998). In these experiments it was found that incomplete rehydration or 'involuntary dehydration' often occurs. One reason for this phenomenon is that the normal dipsogenic drive is not strong enough to replace all the fluid that is lost during exercise (Gisolfi and Duchman, 1992; Greenleaf, 1992). It has been noted that, regardless of the composition of rehydration solution, forced fluid administration during the 2 to 4 hours after exercise is insufficient to bring about rehydration even though 100% of the weight lost via sweating is ingested (Costill and Sparks, 1973; Nielsen *et al*, 1986; González-Alonso *et al*, 1992; Maughan *et al*, 1994;). It has been suggested that a large volume of fluid is necessary for successful rehydration during a recovery of several hours (Shirreffs *et al*, 1996). However, even the forced intake, of as much as 150% of fluid lost, of a relatively dilute solution was found not to be an effective method of rapid rehydration (Mitchell *et al*, 1994).

As the ingestion of carbohydrate-electrolyte solutions did not restore fluid balance, the effectiveness of the addition of sodium or potassium salts to the post-exercise rehydrating solution were examined by Mack *et al*, (1993),

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Maughan *et al* (1994), Nielsen *et al* (1986) and Shirreffs *et al* (1996). Improved whole body water and electrolyte balance resulted from the ingestion of electrolyte-containing drinks; however, there appeared to be no additive effect of including both sodium and potassium in the rehydrating beverage.

Studies examining the effect of rehydration regimens on the restoration of normal physiological status and physical function have found generally, that many physiological variables shift toward, but do not return to, normal in the limited time available after a bout of exercise or after weigh-in and before competition (Costill and Sparks 1973; Houston *et al*, 1981; Nielsen *et al*, 1986; Burge *et al*, 1993). Many of these rehydration protocols used water as the rehydration beverage. To our knowledge, no studies have examined the effect of exercise-induced dehydration and rehydration on immediate cycling performance. The purpose of the study was, therefore, to examine the effect of rehydration on fluid balance, metabolic function, and cycling performance following exercise-induced dehydration; either a high sodium carbohydrate-electrolyte beverage or a placebo was used.

MATERIALS AND METHODS

Subjects

Thirteen healthy male competitive cyclists, triathletes or recreational athletes participated in this study; all completed the study. Their mean (± SEM) age, body weight, height, and maximal physical working capacity (Wmax) were 23.5 (±1.2) yrs, 71.9 (±0.9) kg, 183.2 (±1.6) cm, and 391.6 (±10.4) W respectively. Before starting the experimental trials, the nature and the risks of the experimental procedures were explained and written informed consent was obtained. The study was approved by the ethics committees of Universiti Sains Malaysia and the University of Maastricht.

Preliminary testing

Maximal physical working capacity was determined while cycling on an electromagnetically-braked cycle ergometer (Lode, Groningen) during a graded exercise test to the point of exhaustion, according to the method of Kuipers *et al* (1985).

Experimental design

All experimental trials began in the morning and subjects were required to abstain from strenuous exercise for at least 48 hours prior to each test. Each subject consumed the breakfast of his choice before the first experiment and was required to eat an identical meal before the second experiment.

On reporting to the laboratory, subjects voided their bladder as completely as possible and the entire volume was collected. Nude body weight was then measured (Chyo-MW-150K, Japan; weighing accuracy of ± 20 g). Subjects were then seated in a room maintained at a temperature of approximately 22ºC and remained in a comfortable sitting position for 15 minutes before a teflon venous catheter fitted with a 3-way tap was inserted into a forearm vein for blood sampling; this catheter remained in place for the remainder of the study. An initial blood sample was obtained: this sample represented the euhydrated state; all blood samples were obtained without venous stasis.

The subjects then exercised in an environmental chamber (28ºC; 63% RH) at an intensity of 50% Wmax for 90 minutes to dehydrate approximately 3% of body weight. The second and third blood samples were drawn at 1 minute into the 50% Wmax dehydration exercise and during the last minute of dehydration exercise. After the dehydration exercise, the subjects were allowed 10 minutes to cool off and change their clothes and resume a seated position in a thermo-neutral environment (20ºC). Thirty minutes after exercise and after twenty minutes of sitting, a fourth blood sample was obtained (dehydrated state); this was followed by the determination of nude body weight, which represented dehydration level. The second urine sample was then collected. Immediately afterwards, the subjects

were seated and drank one of the test drinks in a volume (in milliliters) equal to the mass (in grams) of 50% of the fluid lost. This signaled the beginning of the 2-hour rehydration period. After 30 minutes the subjects drank 40% of the fluid lost; the remaining 30% of the rehydration drink, necessary to replace 120% of the fluid lost, was ingested at 60 minutes. The beverages were either a 7.6% carbohydrate-electrolyte solution (CES; Isostar®, Sandoz, Bern) or a sweetened placebo (P). The composition of the beverages is listed in Table 1.

Further blood and urine samples were collected every 30 minutes during the rehydration period. At the end of the 2-hour rehydration period, the third nude body weight was determined. This was followed by a time-trial in which the subjects were asked to perform a certain amount of work as fast as possible, according to the method of Jeukendrup *et al* (1995). The measure of performance was the time taken to complete the target amount of work. This target amount of work was based on the Wmax and was calculated according to the formula:

Target amount of work (J) = 0.75 x Wmax x 3,600

After the time trial, the subjects dried themselves with towels and their final body weights were determined; thus was followed by the collection of a final urine sample.

Analytical procedures

Part (3 ml) of each blood sample (7 ml) was mixed with lithium heparin (50 U/ml) and used for the measurement, in duplicate, of hemoglobin by conversion to cyanmethemoglobin and comparison of the resultant optical density with that of a known standard (OSM2 Hemoximeter, Radiometer, Copenhagen); hematocrit was determined in duplicate after microcentrifugation (Haemofuge, Heraeus Sepatech, Germany). Relative changes in plasma volume (PV) from pre-dehydration levels were calculated according to Dill and Costill (1974). The remaining blood was centrifuged at 4,300 rpm for 5 minutes at 4ºC. The supernatant was removed and analyzed for plasma sodium, potassium and chloride concentrations by an electrolyte analyzer (AVL 988-3, Switzerland). Plasma osmolality was measured by freezing point depression (Osmomat 030-D, Gonotec, Germany). The remainder of each blood sample (4 ml) was mixed with anticoagulant (2 mg/ml EDTA) and centrifuged at 4,300 rpm for 5 minutes at 4ºC. The plasma was removed and frozen at -80ºC and later analyzed for glucose (COBAS) and free fatty acids (COBAS). Plasma insulin was determined by the radioimmuno assay method.

The total volume of each urine sample was measured and a portion was used for the measurement of sodium, potassium, and chloride concentrations (by flame photometry) and for the measurement of magnesium and calcium (by photometric method-COBAS). Urine osmolality was determined by the method used for plasmaosmolatity. Cumulative urine output was calculated and net fluid balance was calculated based on body mass loss, volume of fluid ingested, and urinary volume.

The percent of body weight loss that was regained was used as an index of whole body rehydration (percent rehydration). The percent rehydration represented the amount of ingested fluid that was retained in the body at the end of the 2-hour rehydration period. It was calculated according to the formula of Gonzalez-Alonso *et al* (1992). The rehydration index was calculated according to the formula of Mitchell *et al* (1994).

Statistical analysis

Results in the text, tables and figures are expressed as mean (± SEM) values. Comparison between the two beverages was made using the overall mean over time and analyzing these means by the Wilcoxon signed rank test. Significant differences between treatment were determined using the Wilcoxon signed rank test. Differences between treatments were accepted as being significant when a p-value of less than 0.05 was obtained.

RESULTS

There were no significant differences in the times taken to achieve the targeted work. The average calculated power outputs during time trial were similar for both CES and P trials; these were obtained at 70% of the maximum work load (Table 2).

After the 90-minute dehydration period, the body weight of the subjects decreased from 71.85 (±0.99) kg to 69.58 (±0.98) kg or by 3.2 (±0.1) %. During the rehydration period, the subjects drank an average of 2.72 (±0.11) kg (Fig 1). At the end of the 2-hour rehydration period, all the subjects except for three (CES trial) and one (P trial) were still somewhat hypohydrated (range: 0.02-1.78 kg below the euhydrated body weight; $p<0.01$; Fig 1). Incomplete rehydration resulted from fluid loss during the rehydration period in urine, sweat, and respiration and the body weight loss to metabolism.

The percent of body weight loss that was regained at the end of the 2-hour rehydration period, *ie* the percent rehydration, during CES (70±3%) was significantly ($p<0.01$) higher than that of P (60±5%) (Fig 1). At the end of the rehydration period, the difference in body weight between CES and P was 270 (±90) g ($p<0.01$).

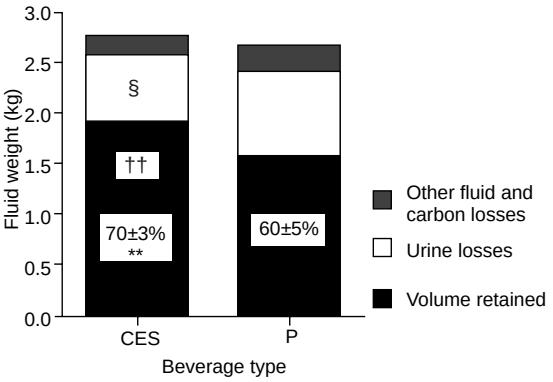

Fig 1–Fate of the ingested volume when comparing CES and P. The height of the graph represents the total amount of fluid consumed (in kg). The stacked bars represent the fate of the ingested volume: the ingested fluid was either retained in the body or lost in the form of urine, sweating, and respiration. The percentage of the body weight loss that was regained, (percent rehydration) was used as an indicater of the volume retained. The percent rehydration following the ingestion of CES was significantly higher than that of P (**$p<0.01$; $n=13$). †† the volume of fluid retained following ingestion of CES was significantly higher than that of P ($p<0.01$; $n=13$). § the urine output following the ingestion of CES was significantly lower than that of P ($p<0.05$; $n=13$).

Table 1
Chemical composition and osmolality of the drinks tested.

Variables	CES	P
Sucrose (g/l)	59	-
Maltodextrin (g/l)	17	-
Fructose (g/l)	-	5
Aspartamate (g/l)	-	0.08
Acesulfame K (g/l)	-	0.08
Na^+ (mg/l)	690	-
K^+ (mg/l)	180	-
Cl^- (mg/l)	300	-
Mg (mg/l)	10	-
Osmolality (mOsm/kg)	303	41

CES: carbohydrate-electrolyte solution; P: placebo

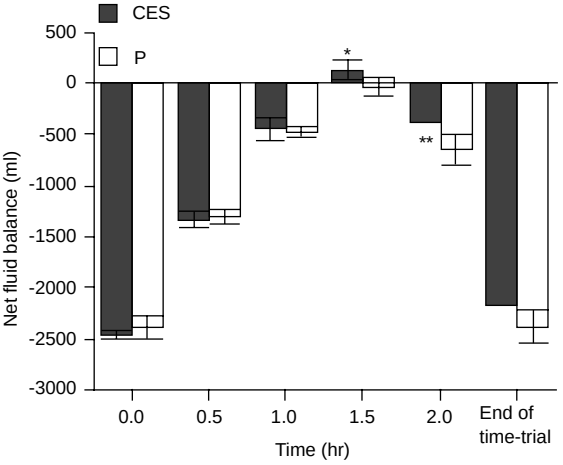

Fig 2–Net fluid balance during the rehydration period and at the end of the time-trial. Significantly different from P, *=$p<0.05$; **=$p<0.01$.

Table 2
Effect of dehydration and subsequent rehydration on mean (±SEM) physiological and performance variables during the time-trial.

	CES	P
Time trial (minute)	65.1 ± 2.2	65.2 ± 2.3
Average HR (b/minute)	167 ± 4.0	171 ± 3.0
Average power output (W)	275.9 ± 13.9	275.8 ± 14.1
Average %Wmax (%)	70.1 ± 2.3	70.1 ± 2.4

Table 3
Plasma sodium, chloride, and potassium levels (mean±SEM) after exercise-induced dehydration, during the rehydration period and at the end of the time-trial.

Time (minute)	CES	P
a) Plasma sodium (mmol/l)		
Pre-exercise	145.6 ± 0.4	145.9 ± 0.6
End of dehydration	150.4 ± 0.5[b]	150.6 ± 0.4[d]
0	149.0 ± 0.4[b]	149.1 ± 0.4[d]
30	147.6 ± 0.4[b]	147.6 ± 0.5
60	147.8 ± 0.4[b]	145.9 ± 0.4[f]
90	148.0 ± 0.5[b]	144.1 ± 0.4[c,f]
120	146.7 ± 0.5[a]	143.1 ± 0.5[d,f]
End of time-trial	151.2 ± 0.5[b]	149.4 ± 0.6[d,e]
b) Plasma chloride (mmol/l)		
Pre-exercise	108.1 ± 0.4	108.2 ± 0.5
End of dehydration	112.5 ± 0.4[b]	113.2 ± 0.5[d]
0	111.0 ± 0.5[b]	111.6 ± 0.5[d]
30	109.2 ± 0.4[a]	109.1 ± 0.5[c]
60	108.4 ± 0.4	107.7 ± 0.6
90	108.2 ± 0.3	106.2 ± 0.5[d,f]
120	107.8 ± 0.4	105.5 ± 0.4[d,f]
End of time-trial	109.9 ± 0.4[b]	109.2 ± 0.6
c) Plasma potassium (mmol/l)		
Pre-exercise	4.19 ± 0.08	4.22 ± 0.09
End of dehydration	5.25 ± 0.07[b]	5.27 ± 0.08[d]
0	4.63 ± 0.09[b]	4.52 ± 0.07[e]
30	4.72 ± 0.09[b]	4.97 ± 0.09[d]
60	4.57 ± 0.09[b]	5.01 ± 0.14[d,e]
90	4.24 ± 0.08	4.97 ± 0.12[d,f]
120	3.97 ± 0.04[b]	4.55 ± 0.14[c,f]
End of time-trial	5.35 ± 0.16[b]	5.67 ± 0.14[d]

Significantly different from the euhydrated state: [a]and [c]($p<0.05$); [b]and [d]($p<0.01$). Significantly different from CES [e]($p<0.05$) and [f]($p<0.01$).

The rehydration index, which indicated how much of what was ingested was actually used for body weight restoration, was calculated as 1.85 (±0.17) for CES and it was significantly ($p<0.01$) lower than the 3.30 (±0.78) index calculated for the P trial.

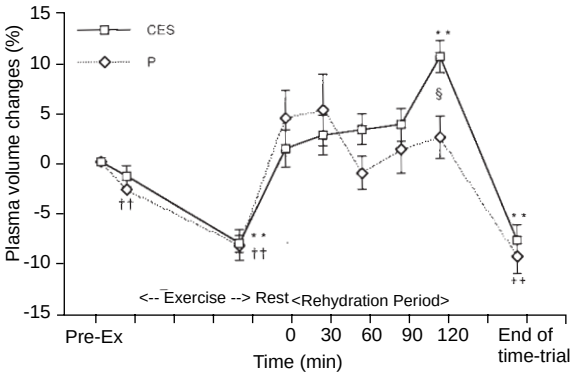

Fig 3–Plasma volume changes after exercise-induced dehydration, during the 2-hour rehydration period and at the end of the time-trial. All values are expressed as a percent change from the resting (euhydrated levels). ** and †† Significantly different from plasma volume in the euhydrated state ($p<0.01$). § significantly different from P ($p<0.05$).

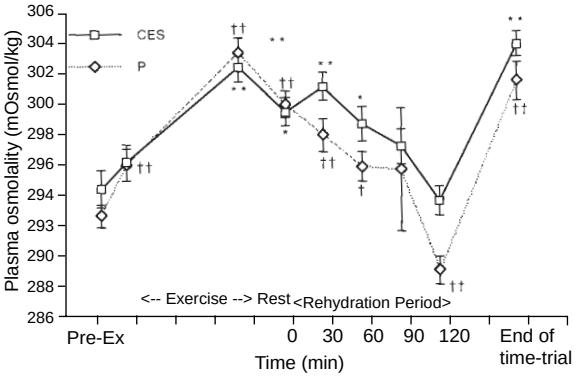

Fig 4–Plasma osmolality after exercise-induced dehydration, during the 2-hour rehydration period and at the end of the time-trial. Significantly different from the euhydrated state denoted by * and † ($p<0.05$) and by ** and †† ($p<0.01$).

Cumulative urine output during the rehydration period and the time trial was higher after ingestion of P but was not significantly different from CES (1,046.8±144.7 ml *vs* 850.3±107.1 ml). There were no differences at any time between the two solutions in urine output. However, the net fluid balance was positive with CES with 1.5 hours of the rehydration period (128.1±49.5 ml *vs* -36.5±83.8 ml; $p<0.05$), which then become negative at the end of the 2-hour rehydration period but still significantly ($p<0.01$) less negative than the net fluid balance with P (Fig 2).

Body weight loss during the 2-hour rehydration period, not accounted for by urine formation, was significantly ($p<0.01$) higher for P (645.4±142.8 g) than for CES (375.4±93.7 g).

Changes in plasma volume as the result of exercise-induced dehydration, during the 2-hour rehydration period, and at the end of the time trial are shown in Fig 3. All values are expressed as a percent change from the resting euhydrated levels. Similar responses were observed before the rehydration period. At the end of the rehydration period (*ie* 120 minutes), plasma volume during P was similar to euhydrated plasma volume, but plasma volume during CES was 10.4 (±1.6)% higher ($p<0.01$). Plasma volume at 120 minutes after CES ingestion was significantly greater than that of P ($p<0.05$) (Fig 3). The plasma volume decreased during the time trial and there were no significant differences between the drinks at the end of the time trial, but both were significantly lower than the euhydrated level ($p<0.01$).

Plasma osmolality was significantly ($p<0.05$) higher with CES than with P throughout the experimental period (Fig 4). No significant differences in the pre-exercise euhydrated plasma osmolality were observed between the two fluid trials. After exercise, plasma osmolality was elevated by an average of 9.4 (±0.9) mOsm/kg above the euhydrated level. When CES was consumed, plasma osmolality at the end of the 120 minutes rehydration period returned to a level that was not significantly different from the euhydrated values, whereas ingestion of P resulted in a significantly lower osmolality when compared with the euhydrated value ($p<0.01$) (Fig 4). In addition, plasma osmolality at the end of the 2-hour rehydration period and time trial with CES remained higher than that with P (NS).

Plasma sodium and chloride concentra-

Table 4
Plasma free fatty acid (mmol/l) (mean±SEM) after exercise-induced dehydration, during the rehydration period and at the end of the time-trial.

Time (minute)	CES	P
Pre-exercise	0.21 ± 0.03	0.23 ± 0.05
End of dehydration	0.64 ± 0.07[a]	0.72 ± 0.07[b]
0	0.68 ± 0.11[a]	0.74 ± 0.10[b]
120	0.28 ± 0.04	1.09 ± 0.09[b,c]
End of time-trial	0.42 ± 0.06[a]	0.76 ± 0.11[b,c]

[a]and [b]significantly different from the euhydrated state ($p<0.01$).
[c]significantly different from CES ($p<0.05$).

tions remained significantly higher with CES than with P throughout the experimental period ($p<0.01$ and $p<0.05$ respectively) (Table 3). In addition, plasma sodium concentrations remained elevated above the euhydrated level when CES was consumed. At the end of the 2-hour rehydration period, plasma sodium and chloride concentrations remained significantly higher with CES than with P ($p<0.01$). Plasma potassium concentrations were significantly lower with CES than with P throughout the experimental period ($p<0.01$). However, at the end of the 120-minute rehydration period plasma potassium concentrations with CES and P were significantly different from the euhydrated values; the potassium concentration was significantly ($p<0.01$) higher with P compared with CES. At the end of the time trial, potassium levels rose and significant differences between CES and P remained ($p<0.05$).

Plasma glucose concentrations were similar for both conditions before the rehydration period (Fig 5). At the end of the 2-hour rehydration period, plasma glucose was higher with CES, but was not significantly different from the plasma glucose levels with P. During the time trial, the glucose level of CES fell steeply and at the end of the time trial glucose level was significantly ($p<0.01$) lower than that of the euhydrated level, but not significantly different from glucose concentrations with P trial. The insulin levels were not significantly different at the end of the exercise-induced dehydration period, however, insulin levels rose significantly ($p<0.01$) at the end of the rehydration period with CES. At the end of the time trial, insulin levels with CES declined steeply, but were still significantly ($p<0.01$) higher than P; both levels were not statistically different from the dehydration levels (Fig 5). Interestingly, the fall in plasma glucose level during the time trial was directly proportional to the time taken to complete the targeted work in the time trial, indicating that the larger the fall in glucose the slower the time taken to complete the targeted work ($r= 0.69$; $p<0.01$) (Fig 6).

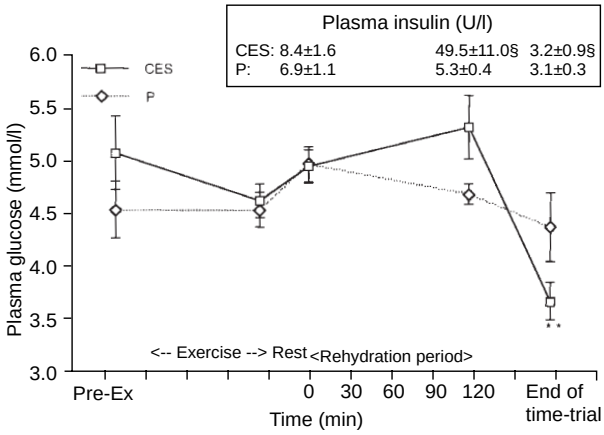

Fig 5–Plasma glucose after exercise-induced dehydration, during the 2-hour rehydration period and at the end of the time-trial. ** Significantly different from the euhydrated level ($p<0.01$). Insert table shows the plasma insulin level the points indicated. § significantly higher than P ($p<0.01$).

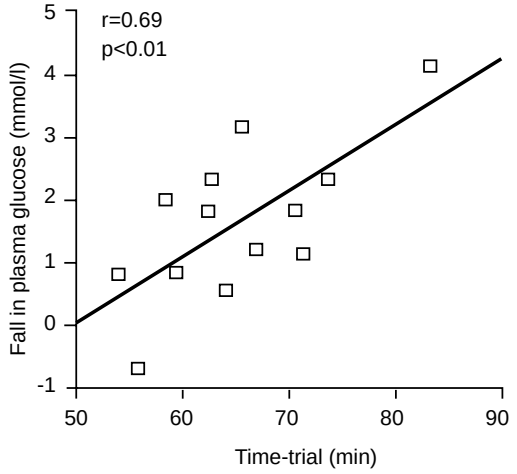

Fig 6–Correlation between time taken to achieve targeted work and fall in glucose during time-trial after CES ingestion.

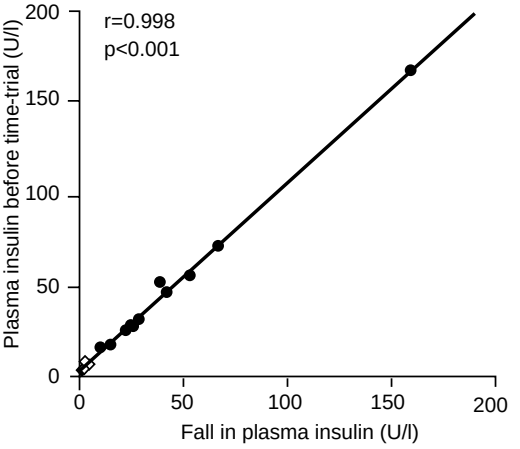

Fig 8–Correlation between plasma insulin before exercise and fall in plasma insulin during time-trial after ingestion of CES (●) or placebo (◇) solution.

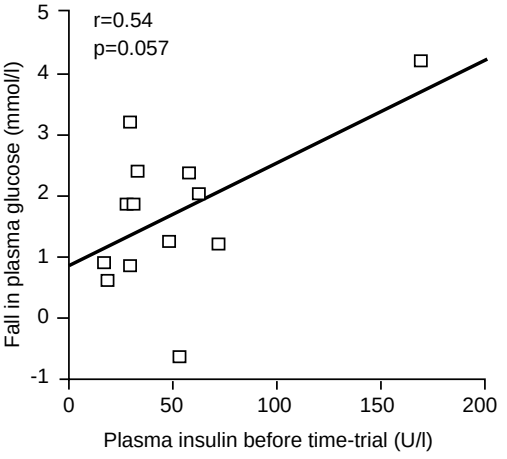

Fig 7–Correlation between plasma insulin before exercise and fall in glucose during time-trial after CES ingestion.

Since the plasma insulin level in the beginning of the time-trial was 5.9-fold higher, and the time-trial-induced fall in plasma glucose was 1.4-fold, we determined whether any relationship existed between insulin prior to exercise and the fall in blood glucose during the time-trial. Indeed, as shown in Fig 7, the fall in plasma glucose was closely, although not significantly, related to the plasma insulin levels before exercise (r=0.54).

During exercise, plasma insulin levels rapidly fell back to basal in the CES group. In addition, in the placebo group plasma insulin fell to 42% below the rehydration level during the time-trial. As shown in Fig 8, in both studies the fall in plasma insulin concentration during the 70 minutes of time-trial was closely related to the circulating insulin levels at the beginning of time-trial ($r = 0.998$; $p<0.001$).

No significant differences in the pre-exercise euhydrated plasma free fatty acid levels were observed between the two different fluid trials (Table 4). However, the plasma free fatty acid levels were raised significantly ($p<0.01$) from the euhydrated values in both trials at the end of the exercise-induced dehydration period; during the rehydration period the free fatty acids with CES declined and at the end of the 2-hour rehydration period the level was below that of the euhydrated state, whereas the fatty acid levels with P were significantly ($p<0.01$) higher than that of the euhydrated state. At the end of the time trial the free fatty acids in P were still significantly ($p<0.01$) higher than those in the CES trial; both were still significantly ($p<0.01$) different from the euhydrated levels.

DISCUSSION

The main purpose of this investigation was to compare the effect of a high CES beverage with that of a placebo on whole body rehydration and plasma volume restoration during a 2-hour period after exercise-induced dehydration followed by cycling. To our knowledge no studies have examined the effect of exercise-induced dehydration and a 2-hour rehydration period on cycling performance, although Burge *et al* (1993) have reported on rowing performance following 24-hour dehydration and partial rehydration and Fallowfield *et al* (1995) have reported on subsequent endurance capacity and rehydration after 4-hour of recovery with a CES beverage. In this study, after drinking a volume equal to 120% of the body fluid loss during exercise, although we observed a higher percent rehydration with CES there was no difference in cycling performance between the two drinks (Fig 1 and Table 2).

The ingestion of 120 % of the body fluid loss was able to restore plasma volume balance to the euhydrated level with both CES and P, but plasma volume at the end of the 2-hour rehydration period was significantly ($p<0.01$) higher with CES.

The degree of rehydration found in this study is in the range of those reported by others using forced (Costill and Sparks, 1973; Nielsen *et al*, 1986; González-Alonso *et al*, 1992) and *ad libitum* rehydration protocols (Nose *et al*, 1988). Both Costil and Sparks (1973) and Nielsen *et al* (1986) did not find any significant differences in the percent rehydration among the rehydration solutions used, but González-Alonso *et al* (1992) found rehydration to be lower with diet coke but no difference between water and carbohydrate-electrolyte solution. The 73% and 74% rehydration after full fluid replacement with CE solution during the 2-hour and 3-hour rehydration period respectively after dehydration of the studies of González-Alonso *et al* (1992) and Costill and Sparks (1973) were similar to our study for CES with 120% fluid replacement. However, this is lower than the 81% rehydration with high-sugar high-sodium solution obtained after ingesting 110% fluid loss in the study of Nielsen *et al* (1986). The 60% rehydration with P in our study is also similar to that obtained by González-Alonso *et al* (1992) for water after full fluid replacement.

The lower degree of dehydration with P in our study did not affect the performance of the time-trial in which a similar time was taken to achieve the targeted work with similar power output and percentage of the maximum work load with CES (Table 2). In spite of the subjects exercising with a lower percent rehydration, no significant differences were observed between average heartrate during P and CES trials (Table 2).

Although there was a significant increase in the rehydration level (70%) with CES after exercise-induced dehydration, the present findings confirm previous observations that carbohydrate administration prior to exercise results in lowering of glucose during vigorous exercise (Costill *et al*, 1977; Foster *et al*, 1979; Koivisto *et al*, 1981). It is possible that a failure in the rise of counter-regulatory hormones could contribute to a rapid fall in blood glucose, which could give rise to the mechanism of the exercise-induced lowering of glucose after carbohydrate ingestion. However, cortisol, catecholamines, and glucagon were not measured in the present study; it is suspected that these factors may also be responsible for the lowering of glucose during time-trial after CES ingestion.

Insulin is the main regulator of glucose homeostasis during exercise (Vranic *et al*, 1976; Zinman *et al*, 1979). A rise in plasma insulin following glucose administration enhances exercise-stimulated glucose uptake and, in concert with a fall in plasma glucagon, prevents a rise in splanchnic glucose production that is necessary to meet the needs of the exercising muscle (Vranic *et al*, 1976; Zinman *et al*, 1979). In the present study, the close correlation between the plasma insulin concentration prior to the time-trial and the fall in plasma glucose levels during the time-trial (Fig 7) emphasizes the important role of insulin in

plasma glucose reduction.

In addition to the direct effect of hyperinsulinemia on glucose metabolism, insulin may also have indirectly augmented glucose utilization during the time-trial by diminishing lipolysis (Carlström, 1969). In the present study, plasma FFA levels were lower after CES than placebo ingestion (Table 4). Since FFA uptake by the exercising muscle is dependent on substrate availability (Ahlborg *et al*, 1974; Ahlborg and Felig, 1977), decreased FFA concentrations after glucose ingestion may result in decreased FFA utilization (Porte and Williams, 1966) and enhance glucose uptake during exercise.

The rapid fall in insulin levels following CES ingestion during the time-trial may be mediated by a variety of factors. A rise in adrenergic activity occurring during exercise (Galbo *et al*, 1975) is known to decrease insulin secretion (Porte and Williams, 1966) and the fall in plasma glucose and a subsequent decline in the hyperglycemic stimulus may further decrease insulin secretion.

Despite more effective rehydration, higher blood-borne glucose, greater FFA availability, and better electrolyte retention in plasma, no difference in cycling performance, measured as the time taken to complete the targeted work, was found between the rehydration fluids. It is suggested that an insulin-mediated rebound effect on carbohydrate metabolism during the performance trial, in which no further carbohydrate was supplied, nullified any rehydration benefit. Carbohydrate feeding, just before and during the time-trial, could therefore be recommended to prevent this insulin-mediated rebound effect on carbohydrate metabolism.

In conclusion, the current findings indicate that despit the more effective rehydration given by high-sodium carbohydrate-electrolyte solutions after exercise-induced dehydration, carbohydrate-electrolyte solution ingestion during the 2-hour rehydration period prior to the time-trial cycling performance results in a lowering of plasma glucose and a decrease in FFA availability during vigorous exercise. This decline in blood-borne fuel availability is mediated, at least in part, by hyperinsulinemia, which in turn adverely affects the benefit of rehydration.

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