

Effects of Recovery Beverages on Glycogen Restoration and Endurance Exercise Performance

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ABSTRACT

The restorative capacities of a high carbohydrate-protein (CHO-PRO) beverage containing electrolytes and a traditional 6% carbohydrate-electrolyte sports beverage (SB) were assessed after glycogen-depleting exercise. Postexercise ingestion of the CHO-PRO beverage, in comparison with the SB, resulted in a 55% greater time to exhaustion during a subsequent exercise bout at 85% maximum oxygen consumption ($\dot{V}O_{2max}$). The greater recovery after the intake of the CHO-PRO beverage could be because of a greater rate of muscle glycogen storage. Therefore, a second study was designed to investigate the effects of after exercise CHO-PRO and SB supplements on muscle glycogen restoration. Eight endurance-trained cyclists ($\dot{V}O_{2max} = 62.1 \pm 2.2$ ml·kg⁻¹ body wt·min⁻¹) performed 2 trials consisting of a 2-hour glycogen-depletion ride at 65–75% $\dot{V}O_{2max}$. Carbohydrate-protein (355 ml; ~0.8 g carbohydrate (CHO)·kg⁻¹ body wt and ~0.2 g protein·kg⁻¹ body wt) or SB (355 ml; ~0.3 g CHO·kg⁻¹ body wt) was provided immediately and 2 hours after exercise. Trials were randomized and separated by 7–15 days. Ingestion of the CHO-PRO beverage resulted in a 17% greater plasma glucose response, a 92% greater insulin response, and a 128% greater storage of muscle glycogen (159 ± 18 and 69 ± 32 $\mu\text{mol}\cdot\text{g}^{-1}$ dry weight for CHO-PRO and SB, respectively) compared with the SB ($p < 0.05$). These findings indicate that the rate of recovery is coupled with the rate of muscle glycogen replenishment and suggest that recovery supplements should be consumed to optimize muscle glycogen synthesis as well as fluid replacement.

Key Words: carbohydrate, protein, ergogenic supplement, glucose, insulin

Reference Data: Williams, M.B., P.B. Raven, D.L. Focht, and J.L. Ivy. Effects of recovery beverages on glycogen restoration and endurance exercise performance. *J. Strength Cond. Res.* 17(1):12–19. 2003.

Introduction

Sport beverages for recovery from prolonged aerobic exercise are generally designed to replace water

and electrolyte losses due to sweat secretion (28). These beverages generally contain relatively small amounts of carbohydrate for replenishment of muscle and liver glycogen stores, which can also be reduced substantially during prolonged aerobic exercise. A relationship between muscle glycogen concentration and aerobic endurance is well established. The relationship is based on the observation that during prolonged strenuous exercise the decline in muscle glycogen closely parallels perception of fatigue and once substantially depleted, necessitates termination of exercise or a significant reduction in exercise intensity (1, 3, 14). Furthermore, the increase in aerobic endurance after exercise training is related to an increased muscle glycogen storage capacity, as well as its more efficient use (15, 17).

Because aerobic endurance is tightly coupled to the concentration of muscle glycogen, nutritional strategies have been developed to enhance glycogen synthesis during short-term recovery in preparation for additional exercise (18, 19, 27, 32, 35). However, the effectiveness of restoring muscle glycogen during short-term recovery on subsequent exercise performance has not been studied. Comparisons of carbohydrate supplementation with flavored water, however, have suggested that recovery can be enhanced if carbohydrate stores are replenished. For example, Wong et al. (34) reported that providing a 6.9% carbohydrate-electrolyte supplement during a 4-hour exercise recovery period increased subsequent run time to exhaustion by 24 minutes. This was similar to the 22-minute improvement in subsequent run time reported by Fallowfield et al. (12) when subjects were provided 1.0 g carbohydrate (CHO)·kg⁻¹ body wt of a 6.9% carbohydrate-electrolyte solution immediately and 2 hours after exercise. The effect of providing different amounts of carbohydrate during recovery on subsequent performance is equivocal, however. Fallowfield and Williams (11) reported that aerobic performance was sim-

ilar after a 4-hour recovery period during which either 1.0 g CHO·kg⁻¹ body wt or 3.0 g CHO·kg⁻¹ body wt was provided. Likewise, Wong and Williams (33) could find no difference in aerobic performance after providing 50 or 167 g of carbohydrate during a 4-hour recovery period. Therefore, the purpose of the first study was to compare the effectiveness of a supplement designed to rapidly replenish muscle glycogen, a carbohydrate-protein (CHO-PRO) beverage (32, 35), with that of a traditional sports beverage (SB) designed primarily for rehydration. Time to exhaustion during a second aerobic exercise session was used to assess the degree of recovery. Time for recovery was 4 hours.

The results indicated that the CHO-PRO supplement, when compared with the traditional SB, enhanced the rate of recovery as evidenced by an extended exercise time to exhaustion. Because there were no differences found in plasma volume or electrolytes between treatments, the difference in performance could be because of a difference in muscle glycogen storage. Therefore, a second study was conducted to determine whether differences in muscle glycogen storage during the 4-hour recovery period could have contributed to the difference in aerobic endurance performance observed.

Methods

Experimental Approach to the Problem

Two studies were conducted to compare the efficacy of 2 different supplements, a supplement designed for rapid restoration of muscle glycogen and a traditional SB, on recovery after exhaustive aerobic exercise. Study 1 was conducted at the University of North Texas Health Science Center, Forth Worth, TX, and study 2 was conducted at the University of Texas, Austin, TX. For both studies, a randomized crossover experimental design was used with each subject serving as his/her own control. Because studies 1 and 2 were conducted in separate locations, it was necessary to use different subjects for each study. Detailed time lines for both studies 1 and 2 are illustrated in Figure 1.

Subjects

Eight trained male cyclists were recruited for study 1. The mean (\pm SEM) age, weight, and maximum oxygen consumption ($\dot{V}O_{2\max}$) were 28.4 \pm 1.7 years, 73.7 \pm 1.3 kg, and 62.4 \pm 1.1 ml·kg⁻¹ body wt·min⁻¹, respectively. For study 2, 8 different cyclists from those used in study 1 were recruited. The mean (\pm SEM) age, weight, and $\dot{V}O_{2\max}$ of the subjects in study 2 were 24.3 \pm 1.0 years, 67.3 \pm 1.3 kg, and 62.1 \pm 2.2 ml·kg⁻¹ body wt·min⁻¹, respectively. The protocol and the potential benefits and risks associated with participation were fully explained to each subject before they signed an informed consent document. Study 1 was approved by the Institutional Review Board for the Use of Human Subjects at the University of North Texas Health

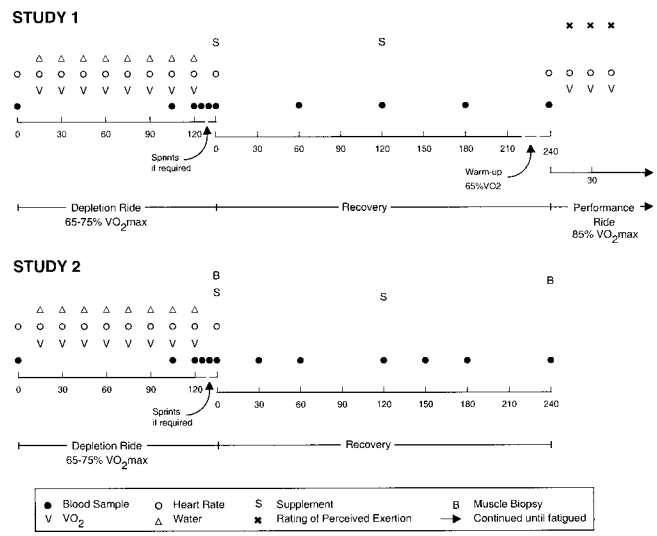


Figure 1. Time line for study 1 and study 2. Note that the effects of the supplements on performance were determined in study 1 and their effects on muscle glycogen store after exercise were determined in study 2.

Science Center, whereas study 2 was approved by the Institutional Review Board of The University of Texas at Austin. All subjects were asked to keep a training log and diet recall for the week before each experimental trial to standardize their physical activity and diet on the days leading up to testing. Subjects were also asked to fast for 12 hours and to abstain from strenuous activity and alcohol-containing beverages for at least 24 hours before any scheduled test. All experimental trials were conducted at a room temperature of 20 \pm 1° C.

Preliminary Testing

$\dot{V}O_{2\max}$ was determined by use of a continuous exercise test performed on an electrically braked cycle ergometer (Ergometrics 800-S, Sensormedics, Ergo-line GmbH, Bitz, Germany). The protocol consisted of a 4-minute warm-up and then 2-minute stages beginning at 200 W with an increasing workload of 50 W at each stage until 350 W. After 350 W, the workload was increased 25 W every minute. A respiratory exchange ratio of greater than 1.1 and an increase in $\dot{V}O_2$ of less than 0.2 L·min⁻¹ over the previous workload were the criteria to ascertain that $\dot{V}O_{2\max}$ was achieved.

Experimental Protocol

After the preliminary testing, each subject underwent 2 randomized experimental treatments separated by 7–15 days. In study 2, a 2-hour practice ride was conducted to adjust or verify appropriate exercise intensity for the experimental trials. Otherwise, testing for studies 1 and 2 were essentially the same except where noted (Figure 1). On the day of an experiment, the subjects reported to the laboratory 30 minutes before the start of exercise. They were weighed and fitted with a heart rate monitor (Polar Beat, Polar Electro Oy,

Finland). Next, a 20-gauge catheter was inserted into a large forearm vein and kept patent with sterile saline. Once the catheter was in place the subjects mounted the bicycle ergometer. After remaining seated on the ergometer for several minutes, a resting blood sample (5 ml) was drawn, heart rate recorded, and then the cycling exercise commenced. The subjects rode on a cycle ergometer for 2 hours at 65–75% $\dot{V}O_{2\max}$ to deplete muscle glycogen and to lower blood glucose. To verify that the subjects were working at the proper intensity, $\dot{V}O_2$ was determined during the last 4 minutes of each 15-minute interval during the ride. A blood sample was taken after 105 minutes of exercise to determine whether blood glucose had declined below a predetermined level of 4 mmol·L⁻¹. If the blood glucose had not declined below 4 mmol·L⁻¹ by the end of 2 hours, subjects performed 5-minute sprints at 85% of $\dot{V}O_{2\max}$ interspersed with 5 minutes of cycling at 75% $\dot{V}O_{2\max}$ until the appropriate blood glucose concentration was achieved. The maximum number of sprints required to lower the blood glucose concentration below 4 mmol·L⁻¹ was 4. All subjects performed the same number of sprints for each of their treatments. To minimize thermal stress, air was circulated over the subjects with a standing floor fan, and water (2 ml·kg⁻¹ body wt) was provided every 15 minutes of exercise. Immediately after exercise and again 2 hours after exercise, the subjects received 355 ml of a CHO-PRO beverage (Endurox R4, PacificHealth Laboratories, Woodbridge, NJ) or 355 ml of a traditional 6% CHO SB (Gatorade, The Gatorade Company, Chicago, IL). Endurox R4 was selected because the addition of protein to a carbohydrate supplement will increase the efficiency of carbohydrate to increase the plasma insulin concentration and promote rapid restoration of muscle glycogen after exercise (32, 35). Gatorade was selected because it is considered the quintessential SB.

Supplement Ingredients

The manufacturer-suggested serving (355 ml) of the CHO-PRO beverage contained 53 g carbohydrate and 14 g protein (including 0.42 g of L-glutamine and 1.42 g of L-arginine), providing ~0.8 g CHO·kg⁻¹ body wt and ~0.2 g protein·kg⁻¹ body wt. The equivalent serving (355 ml) of the SB provided 21 g carbohydrate (~0.3 g·kg⁻¹ body wt) and contained no protein. Thus, during the 4-hour recovery period, subjects received 106 g carbohydrate (~0.40 g CHO·kg⁻¹ body wt·h⁻¹) and 28 g protein (~0.10 g protein·kg⁻¹ body wt·h⁻¹) with the CHO-PRO beverage while receiving only 42 g carbohydrate (~0.15 g CHO·kg⁻¹ body wt·h⁻¹) with the SB. Macro- and micronutrient details for each supplement are presented in Table 1.

Performance Ride (Study 1)

Subjects were prepared for the performance ride during the last minutes of the recovery period. The sub-

Table 1. Comparison of supplement ingredients.

Ingredients (per 355 ml)	Supplements	
	Endurox R4	Gatorade
Carbohydrate (g)*	53.0	21.0
Protein (g)	14.0	0
Fat (g)	1.5	0
Sodium (mg)	230	165
Potassium (mg)	140	45
Calcium (mg)	100	0
Magnesium (mg)	250	0
Iron (mg)	2	0
Chloride (mg)	270	145
Vitamin C (mg)	470	0
Vitamin E (IU)	400	0
Glutamine (mg)	420	0
Arginine (g)	1.4	0

* The carbohydrate for Endurox R4 consisted of sucrose, maltodextrin, and fructose. For Gatorade, the carbohydrate consisted of sucrose, glucose, and fructose. Total calories in 355 ml of Endurox R4 and Gatorade were 280 and 75, respectively.

jects performed a warm-up of 10 minutes at an exercise intensity of 65% $\dot{V}O_{2\max}$ followed by a ride to fatigue at an exercise intensity of 85% $\dot{V}O_{2\max}$. All timing devices were hidden from the subjects' view so as not to bias riding performance. In addition, the subjects were not allowed to stand while cycling. During the first 5–10 minutes, $\dot{V}O_2$ was assessed to determine whether adjustments were needed to maintain an exercise intensity of 85% $\dot{V}O_{2\max}$. If needed, the change in watts was noted enabling a duplicate adjustment during the next experimental trial. The subjects were strongly encouraged to continue as long as possible. Ratings of perceived exertion were measured using the Borg Scale (4), which has been validated against heart rate and is a cognitive assessment of the perception of exercise stress. Performance was quantified as time to fatigue with fatigue being defined as the point at which pedal cadence fell below 60 rpm for 5 seconds.

Physiological Measurements and Tissue Analyses

In study 1, $\dot{V}O_2$ was continually monitored with a mass spectrophotometer (Perkin-Elmer MGA-1100A, Norwalk, CT), as was heart rate. During testing the mass spectrophotometer was calibrated periodically. Blood samples (5 ml) were collected in heparinized tubes before and immediately after the glycogen-depletion ride and during 60, 120, 180, and 240 minutes of recovery. Blood concentrations of sodium (mmol·L⁻¹), potassium (mmol·L⁻¹), calcium (mmol·L⁻¹), hematocrit (%), and hemoglobin (g·L⁻¹) were measured with the IL System 35 (Instrumentation Laboratory Co., Lexington, MA).

Percent change in plasma volume was determined using the method of Dill and Costill (9).

In study 2, $\dot{V}O_2$ was monitored with a computer-based open-circuit gas analysis system (Max-1 Physio-Dyne Instruments Corporation, Quogue, NY). As with the mass spectrophotometer, the gas analysis system was calibrated periodically during testing. Blood samples (5 ml) were drawn before and immediately after exercise and 30, 60, 120, 150, 180, and 240 minutes after ingestion of the first supplement after exercise. Four milliliters of blood were transferred to a chilled test tube containing ethylenediaminetetraacetic acid ($24 \text{ mg}\cdot\text{ml}^{-1}$, pH 7.4). From this tube 0.5 ml of blood was transferred to a tube containing 1 ml of 8% perchloric acid. Plasma and acid-extract samples were recovered by centrifugation (15 minutes at $1,000g$) and stored at -80°C . Two muscle samples were obtained through biopsy from the vastus lateralis according to the technique of Bergström (2). The first biopsy occurred within the first 3 minutes of completing the glycogen-depletion exercise and the second after 4 hours of recovery. After local anesthesia (1% Lidocaine-HCl, Elkins-Sinn, Inc., Cherry Hill, NJ), an 8-mm incision was made through the skin and fascia, 2 in. from the midline of the thigh and 4 in. above the patella. The initial incision was used for both biopsy procedures with the first biopsy sample always taken distal to the second. Biopsy samples were trimmed of adipose and connective tissue, frozen in liquid N_2 , and stored at -80°C for subsequent determination of glycogen.

Plasma glucose was assayed using the Trinder reaction (kit model 315, Sigma Chemical, St. Louis, MO). Plasma insulin concentration was determined by radioimmunoassay with the use of a double antibody procedure (kit model HI-14K, Linco Inc., St. Charles, MO). The sensitivity of this assay is $2 \mu\text{U}\cdot\text{ml}^{-1}$, its selectivity for human insulin 100%, and its recovery ability 95–100%. Insulin samples were counted on a Gamma 5500 counter (Beckman Instruments, Inc., Fullerton, CA). Blood lactate concentration was determined spectrophotometrically (Beckman DU 640, Beckman) on the acid extracts according to the enzymatic procedure of Hohorst (16). For glycogen determination the biopsy samples were weighed, lyophilized overnight, reweighed, and digested in 0.5 ml of 1 N KOH for 20 minutes at 70°C . The digest was then neutralized with 0.5 ml of 1 N HCl. To hydrolyze the muscle glycogen to glucose units, a well-mixed aliquot of the muscle digest was then transferred and incubated overnight in 0.3 M sodium acetate buffer, pH 4.8 that contained $5 \text{ mg}\cdot\text{ml}^{-1}$ amyloglucosidase (Mannheim Boehringer, Germany). The muscle glycogen concentration was determined fluorometrically (Fluorometer-A4, Farrand Optical Co., Inc., Valhalla, NY) using an enzymatic assay (25) and made relative to muscle dry weight. All assays were conducted in duplicate.

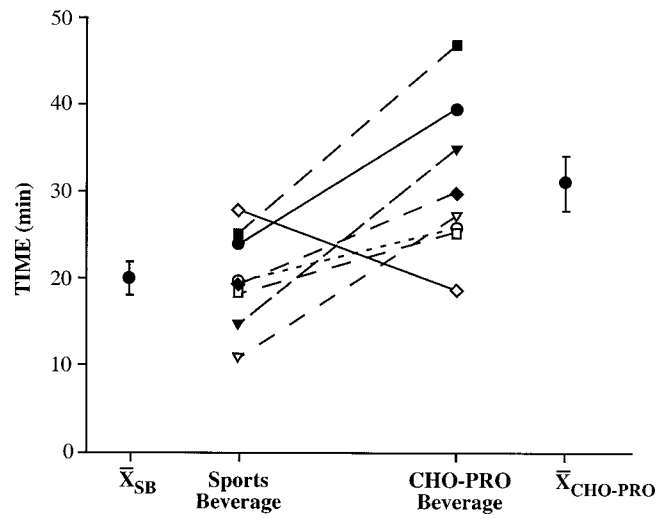


Figure 2. Data from individual subjects and the mean increase in time to exhaustion in the subsequent exercise bout. Note that one subject's performance time decreased during the carbohydrate-protein (CHO-PRO) treatment. However, the mean increase represented a 55% gain in performance time for the CHO-PRO beverage ($\bar{X}_{CHO-PRO}$) vs. the sports beverage (\bar{X}_{SB}) ($p < 0.05$).

Statistical Analyses

The data from studies 1 and 2 were analyzed using either a one-way or two-way repeated measures analysis of variance depending on the variable being tested. Post hoc analyses were performed using Fischer's protected least significant differences test. Statistical significance was set at the 0.05 probability level for all tests.

Results

Study 1

Performance Ride Time. The average performance times after ingesting the CHO-PRO and SB were 31.1 ± 3.2 and 20.0 ± 2.0 minutes, respectively (Figure 2). One subject demonstrated a decreased time to exhaustion during the CHO-PRO treatment as compared with the SB treatment. Regardless, postexercise consumption of the CHO-PRO beverage resulted in a 55% increase in performance time compared with the same volume of SB ($p < 0.05$). There was no difference in $\dot{V}E$, $\dot{V}O_2$, heart rate, or respiratory exchange ratio during the CHO-PRO and SB performance rides. In addition, ratings of perceived exertion and heart rate were not statistically different when comparing the first and last 5 minutes of either supplement performance trial. This indicated that the subjects were equally exhausted after the use of both supplements. However, at 20 minutes into the performance trial, subjects having ingested the SB were at the upper limit of their rating of perceived exertion (19.3 ± 0.4), whereas subjects having consumed the CHO-PRO beverage were at a

Table 2. Blood variables before exercise and during recovery.*

Variable	Treatment	Time					
		Exercise		Recovery (min)			
		Before	After	60	120	180	240
Na ⁺	CHO-PRO	137.0 ± 0.6	141.8 ± 1.3	137.9 ± 1.4	138.4 ± 1.0	137.5 ± 0.9	137.0 ± 0.8
mmol·L ⁻¹	SB	137.5 ± 0.7	141.6 ± 1.3	138.6 ± 1.2	137.6 ± 1.0	136.6 ± 1.1	136.8 ± 0.7
K ⁺	CHO-PRO	3.84 ± 0.10	4.27 ± 0.08	4.09 ± 0.08	3.91 ± 0.09	3.74 ± 0.08	3.85 ± 0.11
mmol·L ⁻¹	SB	3.81 ± 0.06	4.18 ± 0.08	4.18 ± 0.07	4.08 ± 0.08	3.96 ± 0.09	3.86 ± 0.04
Hct	CHO-PRO	41.5 ± 0.7	46.4 ± 1.2	39.5 ± 1.2	39.8 ± 1.2	38.5 ± 0.9	41.8 ± 1.0
%	SB	42.1 ± 1.3	45.9 ± 1.2	40.6 ± 1.4	38.8 ± 1.1	38.7 ± 1.0	42.4 ± 0.9
Hb	CHO-PRO	141 ± 2	155 ± 4	139 ± 4	136 ± 2	133 ± 3	138 ± 3
g·L ⁻¹	SB	143 ± 4	154 ± 3	138 ± 3	136 ± 2	134 ± 2	138 ± 3
PV	CHO-PRO		-16.5 ± 2.4	5.5 ± 3.1	7.0 ± 3.2	11.4 ± 2.3	1.8 ± 2.7
% Change	SB		-13.8 ± 2.6	7.4 ± 5.4	12.5 ± 5.3	14.1 ± 4.4	4.2 ± 4.3

* Values are means ± SEM. Hct = hematocrit; Hb = hemoglobin; PV = plasma volume; CHO-PRO = carbohydrate-protein; SB = sports beverage.

lower rating of perceived exertion (18.4 ± 0.4) and were able to continue exercising ($p < 0.05$).

Body Weights and Blood Variables. Body weight was not significantly different between treatments before exercise (74.3 ± 1.5 kg CHO-PRO vs. 74.1 kg SB), immediately after exercise (72.9 ± 1.4 kg CHO-PRO vs. 72.5 ± 1.4 kg SB), or after the recovery period (73.4 ± 1.3 kg CHO-PRO vs. 73.0 ± 1.2 kg SB). Changes in plasma volumes (Table 2) during the CHO-PRO and SB treatments were also similar. Furthermore, the effects of these treatments on blood sodium, potassium, hematocrit, and hemoglobin did not differ during recovery.

Study 2

Plasma Glucose, Insulin, and Blood Lactate. There was no difference in plasma glucose concentrations during the 2 treatments before (4.2 ± 0.1 mmol·L⁻¹) and after the glycogen-depletion exercise (3.4 ± 0.2 mmol·L⁻¹) (Figure 3). However, 30 minutes after ingestion of the first supplement, glucose levels increased by 43.2% above pre-exercise concentrations in the CHO-PRO treatment and 18.5% above pre-exercise concentrations in the SB treatment. Thirty minutes after ingestion of the second supplement, glucose levels were 43.2 and 12.7% above pre-exercise levels in the CHO-PRO and SB treatments, respectively. Plasma glucose concentrations during the CHO-PRO treatment were significantly elevated ($p < 0.05$) above those of the SB treatment at 60 minutes after the initial supplement and 30 and 60 minutes after the second supplement feeding, i.e., 150 and 180 minutes after exercise. Thus, ingestion of the CHO-PRO beverage resulted in a 17% greater plasma glucose response (incremental area under the curve) compared with the SB. Plasma glucose concentrations returned to below pre-exercise values in both the CHO-PRO (3.6 ± 0.3 mmol·L⁻¹) and SB (3.4 ± 0.2 mmol·L⁻¹) treatments at the end of the 4-hour recovery period.

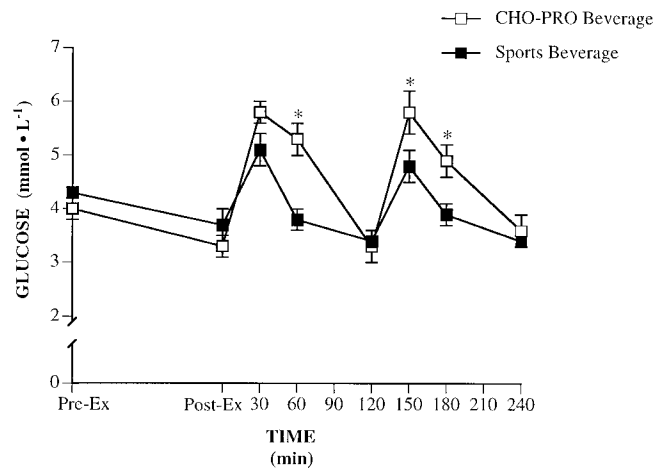


Figure 3. Plasma glucose concentrations before and at the end of 2 hours of exercise and during the 4-hour recovery period for subjects receiving the carbohydrate-protein beverage or the sports beverage (SB). Supplements were provided immediately and 2 hours after exercise. Values are means ± SEM. *Significantly different from SB.

Plasma insulin levels were similar between treatments before exercise and immediately after exercise (Figure 4). However, the insulin concentrations of the CHO-PRO treatment were significantly elevated above the insulin concentrations of the SB treatment at 30 and 60 minutes after supplement ingestion. Ingestion of the CHO-PRO beverage resulted in a 92% greater insulin response (incremental area under the curve) compared with the SB. Insulin concentrations returned to near pre-exercise values in both the CHO-PRO and SB treatments by the end of the 4-hour recovery period.

Blood lactate concentrations for the 2 treatments were similar before exercise. During exercise, blood lactate rose from an average of 1.70 ± 0.14 to $8.93 \pm$

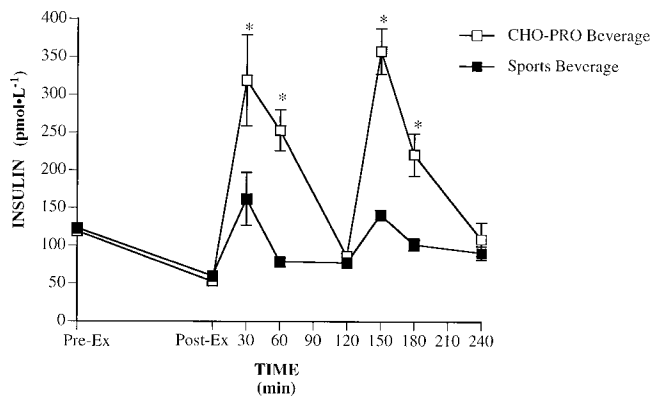


Figure 4. Plasma insulin concentrations before and at the end of 2 hours of exercise and during the 4-hour recovery period for subjects receiving the carbohydrate-protein beverage or the sports beverage (SB). Supplements were provided immediately and 2 hours after exercise. Values are means \pm SEM. *Significantly different from SB.

Table 3. Muscle glycogen ($\mu\text{mol}\cdot\text{g}^{-1}$ dry weight) concentrations for muscle biopsy samples taken from the vastus lateralis immediately after exercise and after the 4-hour recovery period.†

	After exercise	After recovery	Δ
CHO-PRO	227 \pm 32	386 \pm 35*	159 \pm 18*
Sports beverage	236 \pm 24	305 \pm 32	69 \pm 32

† Values are means \pm SEM. CHO-PRO represents carbohydrate-protein beverage containing \sim 15 g carbohydrate and \sim 4 g protein per 100 ml. The sports beverage contained \sim 6 g carbohydrate per 100 ml. Recovery lasted 4 hours. Δ represents the difference between postexercise and postrecovery glycogen levels. It also reflects the difference in functional glycogen following recovery.

* Indicates significant difference across treatments ($p < 0.05$).

0.79 $\text{mmol}\cdot\text{L}^{-1}$. Blood lactate concentrations were not different between treatments immediately after exercise or during the 4-hour recovery period.

Muscle Glycogen Storage. Muscle glycogen concentrations were similar for both treatments immediately after exercise (Table 3). During the 4-hour recovery period, the rate of muscle glycogen storage was $33.7 \pm 4.5 \mu\text{mol}\cdot\text{g}^{-1}$ dry weight $\cdot\text{h}^{-1}$ for the CHO-PRO treatment and $17.4 \pm 5.2 \mu\text{mol}\cdot\text{g}^{-1}$ dry weight $\cdot\text{h}^{-1}$ for the SB treatment. Thus, the rate of glycogen storage during the CHO-PRO treatment was 128% greater than that of the SB treatment ($p < 0.05$).

Discussion

Fallowfield et al. (12) were the first to demonstrate that supplementing with a carbohydrate-electrolyte beverage after prolonged exercise enhances the recovery

process. Their subjects were provided with either 1 g CHO $\cdot\text{kg}^{-1}$ body wt of a 6.9% CHO-electrolyte beverage or equal volume of placebo immediately and 2 hours after a 90-minute run at 70% $\dot{V}\text{O}_2\text{max}$. Subjects were allowed to recover for 4 hours before a subsequent run at 70% $\dot{V}\text{O}_2\text{max}$ to fatigue. During the run to fatigue, the subjects who received the CHO-electrolyte beverage ran approximately 22 minutes longer than those who received the placebo. A similar finding was later reported by Wong et al. (34). Thus, the ingestion of a CHO-electrolyte beverage is an effective means of restoring endurance capacity when recovery time is limited.

In the present study, we compared the effects of a high CHO-PRO beverage containing electrolytes on short-term exercise recovery with that of a traditional 6% CHO-electrolyte SB. Providing a beverage containing a high concentration of carbohydrate and protein can accelerate the recovery process. This was evidenced by our finding that subjects were able to ride 55% longer after receiving the CHO-PRO beverage as opposed to the traditional SB. The results, therefore, extend the findings of Fallowfield et al. (12) and Wong et al. (34) and suggest that the recovery process can be accelerated beyond that produced by a traditional SB if additional carbohydrate is provided.

The intensity of the performance ride was 85% $\dot{V}\text{O}_2\text{max}$. This exercise intensity is significant because it cannot be sustained unless sufficient muscle glycogen is present (3, 6), and it suggests that the greater performance time after the CHO-PRO supplementation was because of a greater restoration of the muscle glycogen stores. To test this hypothesis, a second study was designed to compare the effects of supplementing with the high CHO-PRO beverage with that of the 6% CHO SB on muscle glycogen restoration. Muscle glycogen replenishment was in excess of 125% greater after the CHO-PRO treatment as compared with the SB treatment. Therefore, in light of the strong relationship between aerobic endurance and muscle glycogen stores, the improvement in performance after recovery with the CHO-PRO beverage may be directly related to the greater muscle glycogen concentration.

The CHO-PRO beverage used in the present study contained 2.7 times the amount of carbohydrate (106 g \cdot 740 ml $^{-1}$) found in the SB (40 g \cdot 740 ml $^{-1}$). Thus, the CHO-PRO supplement provided \sim 0.8 g of CHO $\cdot\text{kg}^{-1}$ body wt immediately and 2 hours after exercise, whereas the SB provided \sim 0.3 g of CHO $\cdot\text{kg}^{-1}$ body wt. In addition to the greater carbohydrate concentration, the CHO-PRO supplement contained protein and arginine, which are strong insulin secretagogues (10, 24, 29, 32, 35). The effectiveness of a carbohydrate supplement to enhance muscle glycogen recovery after exercise is related to the carbohydrate concentration of the supplement and also to the pancreatic insulin response elicited (32, 35). Indeed, in the present study,

ingestion of the CHO-PRO beverage resulted in a 17% greater plasma glucose and 92% greater plasma insulin response compared with the SB treatment. Thus, the greater rate of muscle glycogen storage during the CHO-PRO treatment compared with the SB was likely the consequence of great carbohydrate availability as well as a greater insulin response.

Whether the addition of protein contributed to the greater rate of glycogen storage is equivocal at this time (5, 31, 32, 35). However, there is an additional advantage to adding protein and amino acids to a carbohydrate recovery supplement, which is the stimulation of protein accretion (20, 26, 30). This occurs by virtue of the stimulation of protein synthesis by amino acids (20, 30) and the inhibition of postexercise protein degradation by insulin (26).

It is important to note that although total muscle glycogen concentration after the 4-hour recovery period was statistically different between the CHO-PRO and SB treatments, it represented only a 26% difference in total glycogen (Table 3). However, total glycogen does not represent functional glycogen, which may be defined as the glycogen concentration that can actually be used. Functional glycogen can be ascertained by determining the difference between total glycogen and the glycogen remaining after fatigue. Therefore, before the performance trial there appeared to be approximately twice as much functional glycogen available during the CHO-PRO treatment as compared with the SB treatment (Table 3).

The current findings differ from those of Fallowfield and Williams (11) and Wong and Williams (33). Fallowfield and Williams (11) found no difference in postrecovery exercise performance when 1.0 or 3.0 g CHO·kg⁻¹ body wt were provided immediately and 2 hours after exercise during a 4-hour recovery period. Likewise, Wong et al. (34) reported that subjects provided with 50 or 167 g CHO during a 4-hour recovery period had similar postrecovery exercise performances. Regarding the study by Fallowfield and Williams (11), there may be no difference in the postrecovery muscle glycogen stores. The rate of glycogen storage after exercise is essentially the same when 1.0 or 3.0 g CHO·kg⁻¹ body wt is provided at 2-hour intervals (19). Thus, recovery should not be differentially affected by carbohydrate supplements in excess of 1.0 g·kg⁻¹ body wt. This explanation, however, cannot explain the finding of Wong and Williams (33) because differences in muscle glycogen storage is expected between supplements of 50 and 167 g of CHO. One possibility for the different results between the present study and that of Wong and Williams (33) may reside in the exercise intensities used to assess the degree of recovery. To sustain the exercise intensity used in the present study, muscle glycogen is essential (3, 6). However, for the exercise intensity used by Wong and Williams (33), which was 70% $\dot{V}O_{2max}$, exercise can be sustained by simply

maintaining plasma glucose within a normal range even when muscle glycogen stores have been depleted (8). Thus, the difference in results between the present study and that of Wong and Williams (33) may be explained by a difference in dependency on muscle glycogen as substrate during the performance rides.

In addition to restoring the body's carbohydrate stores, sports recovery beverages are formulated to offset the effects of dehydration, i.e., replacement of fluid and electrolytes lost in sweat. Addition of carbohydrate and electrolytes, i.e., sodium, chloride, and potassium, to a recovery beverage will increase the fraction of the ingested fluid which is retained, attenuate large urine outputs, and result in a greater restoration of plasma volume than water alone (7, 13, 21–23). In the present study, ingestion of 740 ml of the CHO-PRO beverage or 740 ml of the SB resulted in similar electrolyte and fluid replenishment with no significant differences in plasma volume or body weight during recovery. Thus, consumption of the CHO-PRO supplement provided glycogen restoration and greater performance compared with the traditional SB without preventing rehydration and electrolyte replenishment. Whether the CHO-PRO supplement would be as effective as the traditional SB after exercise that resulted in a substantially greater state of dehydration is presently unknown.

Practical Applications

The effectiveness of a high CHO-PRO, electrolyte supplement to promote recovery from prolonged, aerobic exercise was compared with a traditional SB. The rate of recovery was significantly faster after the intake of the CHO-PRO supplement as compared with the SB. This increase in recovery appeared to be related to an increased rate of muscle glycogen restoration, but other possibilities cannot be dismissed at this time. Although it has been proposed that increasing the rate of muscle glycogen restoration after exercise will enhance the recovery process, to our knowledge this is the first study to support such a hypothesis. Thus, our results strongly suggest that recovery from prolonged aerobic exercise is best served by a supplement that can rapidly increase the muscle glycogen stores while also replacing lost water and electrolytes. It should be emphasized that rehydration is of primary concern if substantial water and electrolytes are lost during exercise. However, this can be solved by consuming additional fluid-electrolyte supplements after initiating the glycogen resynthesis process.

A CHO-PRO supplement may also provide a substantial anabolic stimulus by virtue of its ability to promote muscle protein synthesis and slow muscle protein degradation after exercise. This increases net protein accretion and possibly speeds repair of damaged tissue because of sustained intense exercise.

It should be emphasized that CHO-PRO supple-

ments like the one used in this study are best used after exercises that result in a substantial depletion of the muscle glycogen stores. Exercises that do not stress the muscle fuel stores or result in muscle damage do not require this amount of carbohydrate or protein for recovery.

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Acknowledgments

We wish to thank Zhenping Ding for his excellent technical assistance. The study was supported by a research grant from Pacific Health Laboratories, Inc., Woodbridge, NJ.

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