Carbohydrate supplementation improves time-trial cycle performance during energy deficit at 4,300-m altitude

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Fulco, C. S., K. W. Kambis, A. L. Friedlander, P. B. Rock, S. R. Muza, and A. Cymerman. Carbohydrate supplementation improves time-trial cycle performance during energy deficit at 4,300-m altitude. *J Appl Physiol* 99: 867–876, 2005. First published May 5, 2005; doi:10.1152/japplphysiol.00019.2005.—Carbohydrate supplementation (CHOS) typically improves prolonged time-trial (TT) performance at sea level (SL). This study determined whether CHOS also improves TT performance at high altitude (ALT; 4,300 M) despite increased hypoxemia and while in negative energy balance ($\sim$1,250 kcal/day). Two groups of fasting, fitness-matched men performed a 720-kJ cycle TT at SL and while living at ALT on *days 3* (ALT3) and *10* (ALT10). Eight men drank a 10% carbohydrate solution (0.175 g/kg body wt) and eight drank a placebo (PLA; double blind) at the start of and every 15 min of the TT. Blood glucose during each TT was higher ($P < 0.05$) for CHOS than for PLA. At SL, TT duration ($\sim$59 min) and watts ($\sim$218 or $\sim$61% of peak watts; %SL Wpeak) were similar for both groups. At ALT, the TT was longer for both groups ($P < 0.01$) but was shorter for CHOS than for PLA on ALT3 (means $\pm$ SE: 80 $\pm$ 7 vs. 105 $\pm$ 9 min; $P < 0.01$) and ALT10 (77 $\pm$ 7 vs. 90 $\pm$ 5 min; $P < 0.01$). At ALT, %SL Wpeak was reduced ($P < 0.01$) with the reduction on ALT3 being larger for PLA (to 33 $\pm$ 3%) than for CHOS (to 43 $\pm$ 2%; $P < 0.05$). On ALT3, O_2 saturation fell similarly from 84 $\pm$ 2% at rest to 73 $\pm$ 1% during the TT for both groups ($P < 0.05$), and on ALT10 O_2 saturation fell more ($P < 0.02$) for CHOS (91 $\pm$ 1 to 76 $\pm$ 2%) than for PLA (90 $\pm$ 1 to 81 $\pm$ 1%). %SL Wpeak and O_2 saturation were inversely related during the TT for both groups at ALT ($r \geq -0.76$; $P \leq 0.03$). It was concluded that, despite hypoxemia exacerbated by exercise, CHOS greatly improved TT performance at ALT in which there was a negative energy balance.

endurance performance; glucose; hypoxemia; prolonged exercise; ergogenic

CARBOHYDRATE (CHO) supplementation (CHOS) during prolonged ($>$2 h) exercise prevents declines in blood glucose concentration and CHO oxidation (3, 11, 16, 17, 24) and typically reduces the time to complete tasks requiring that a fixed amount of work be completed as quickly as possible [e.g., maximum-effort cycle time trial (TT)] (3, 17, 36). The relationship between CHOS and prolonged exercise performance is well described at sea level (11) but not at high altitude (e.g., 4,300 m). Moreover, some physiological responses to intense exercise at high altitude make it difficult to determine a priori whether CHOS will benefit TT performance at high altitude.

Mean power output during a prolonged TT at sea level can usually be maintained at a higher level during CHOS compared with placebo (PLA), thereby improving performance (3, 17).

At high altitude, similar attempts to maintain a higher mean power output during exercise with CHOS will reduce arterial oxygen saturation (Sa_{O_2}) (34) and require compensatory increases in cardiac output, arterial oxygen content, muscle blood flow, and/or oxygen extraction across the working limbs to maintain oxygen transport to tissues (29, 30, 35). An increase in cardiac output, for example, will exacerbate an already widened alveolar to arterial P_{O_2} difference and result in more severe hypoxemia (35, 37) and perhaps a greater feeling of respiratory distress due to hyperventilation (33). Sustained time at higher power outputs, therefore, may be limited such that the durations of prolonged cycle TTs at high altitude may not be shortened by CHOS.

The purpose of this study was to determine whether CHOS could improve cycling performance during prolonged TTs conducted on *days 3* and *10* while living at 4,300 m. The TTs were performed while undergoing a daily energy deficit and weight loss that are common during high-altitude residence (38). It was hypothesized that the potential benefit of CHOS on TT performance at altitude would be offset by hypoxemia exacerbated by attempts to increase mean power output during exercise.

METHODS

Study Design Overview

The study used a double-blind, PLA-controlled prospective design in which two groups of healthy men performed a two-segment endurance test at sea level and then on *days 3* and *10* of residence at 4,300 m. Just before the sea-level endurance test, a staff member not directly involved with any exercise testing assigned the volunteers for the rest of the study to either a group receiving a CHOS ($n = 8$) or a group receiving a PLA ($n = 8$) that was similar in taste and appearance. Individuals between groups were matched as closely as possible ($P > 0.10$) on age, body weight, height, and sea-level peak O_2 uptake before the endurance tests, as illustrated in Table 1.

Volunteers

The men were recruited using advertisements and fliers placed in local newspapers and universities in and around the Palo Alto/San Jose, CA area ($<$50 m). In response to a questionnaire regarding daily physical activity, the men reported exercising 6.3 $\pm$ 0.3 days/wk (median: 7 days/wk) or 11.9 $\pm$ 1.9 h/wk (median: 12 h/wk) in activities such as bicycling ($n = 11$), running ($n = 9$), weightlifting ($n = 8$), basketball ($n = 3$), Stanford University varsity crew ($n = 2$) or wrestling ($n = 1$) team, rock climbing ($n = 1$), and ultimate frisbee ($n = 1$). All were nonsmokers, normal weight for height (i.e., body

Table 1. *Baseline physical characteristics of the volunteers*

Group	Age, yr	Weight, kg	Height, cm	$\dot{V}O_{2\ peak}$, ml·min^{-1}·kg^{-1}	$\dot{V}O_{2\ peak}$, ml/min
PLA	25.1±6	79.8±11	176.8±6	54.0±6	4,270±504
CHOS	25.3±6	75.1±6	180.6±6	58.4±6	4,395±682

Values are means ± SD (*N* = 8). PLA, placebo group; CHOS, carbohydrate supplement group; $\dot{V}O_{2\ peak}$, peak O_2 uptake.

mass index = 20–27), able to perform strenuous cycle exercise for 1 h at 75% of their age-predicted peak heart rate (HR), and not born or residing within the previous 6 mo at altitudes of >2,000 m. All subjects voluntarily provided verbal and written consent to participate after being fully informed of the nature of the study and its possible risks and benefits. The study was approved by the institutional review boards of the US Army Research Institute of Environmental Medicine, The Office of the Surgeon General of the Army, Veterans' Administration Palo Alto Health Care System, and The College of William and Mary. The investigators adhered to policies of the US Code of Federal Regulations, Part 46 and US Army Regulations AR 40-25 for the protection of volunteers.

Study Outline

The volunteers initially participated in a 7-day "stabilization phase" at the Clinical Studies Unit at the Veterans' Administration Hospital (SL; 50 m) during which time they were fed a controlled and well-balanced diet to attain energy and nitrogen balance and body weight stability. During the stabilization phase, a peak O_2 uptake ($\dot{V}O_{2\ peak}$) test and an endurance test were conducted using cycle ergometry on *days 2* and *4*, respectively. They remained on the diet and lived at the Veterans' Administration Hospital during the subsequent 5 days ("baseline phase"). During this time, a $\dot{V}O_{2\ peak}$ test and endurance test were repeated on *days 9* and *10*, respectively. The volunteers were told not to perform any nonstudy-related leg exercise for 24 h before each test session.

After completing the SL baseline phase, the volunteers were flown to Colorado Springs, CO (1,800 m), where they spent the first afternoon and night in an apartment under staff supervision. To facilitate study needs, the volunteers traveled to Colorado Springs either singularly or in groups of two every 1–3 days. From the time they arrived until they departed the next morning to the US Army Research Institute of Environmental Medicine High Altitude Research Laboratory at the summit of Pikes Peak (4,300 m), they breathed medical grade O_2 (>96%) via a nasal cannula connected to an O_2 concentrator. Flow rate was adjusted to maintain SL Sa_{O_2} (i.e., >96%), as measured by finger pulse oximeter.

At 0530 (*day 1*; ALT1), they were driven in ~1 h to the laboratory while breathing from nasal cannulas connected to small O_2 tanks (100% O_2) with a flow rate that maintained Sa_{O_2} at >96%, as measured by the pulse oximeter. Supplemental breathing of O_2 was terminated on arrival where the volunteers lived continuously without supplemental O_2 for 12 days. The volunteers performed $\dot{V}O_{2\ peak}$ tests on *days 2* and *9* of altitude residence (ALT2 and ALT9, respectively) and endurance tests on *days 3* and *10* at altitude (ALT3 and ALT10, respectively).

While living on the summit, they were asked to increase their energy expenditure by 30–40% more (or by 1,200–1,600 kcal/day) than their expenditure during the SL baseline phase when their body weight was stable. They also were asked to maintain energy intake throughout the SL and altitude phases. Such requirements helped simulate the increased expenditure and rate of weight loss that are typical of prolonged, outdoor activities in mountainous terrain (38). To facilitate the increased energy expenditure, a large heated tent [18 ft. (width) × 36 ft. (length) × 8.5 ft. (height)] was set up next to the laboratory in which the volunteers had unlimited access to treadmills, cycle ergometers, rowing and ski machines, and barbells. They could

also play basketball, soccer, and hacky sack, or play catch with a football, baseball, or frisbee just outside of the facilities. They also participated in one to three hikes lasting from 1 to 4 h during their tenure on the mountain. The hiking routes were within 8 km from the summit and were no less than 3,600-m elevation.

Energy Intake

During the SL and altitude phases, volunteers were fed a standardized, healthy diet that consisted of whole foods and liquid supplements provided in individualized amounts. Each individual's energy intake was initially estimated during *day 1* of the SL stabilization phase using the Harris-Benedict equation (20), corrected for typical activity level estimated by volunteer recall, and was then adjusted, if warranted, to maintain body weight, which was measured daily. Protein content of the diet was held constant (1.2–1.3 g·kg body wt^{-1}·day^{-1}). Total energy intake was adjusted by adding or subtracting fat- and CHO-containing foods so that the energy ratio of these nutrients remained at ~1:2, respectively. The diet provided ~14% of energy from protein, 23% from fat, and 63% from CHO.

Energy Expenditure

Daily energy expenditure was estimated from self-reported activity logs maintained in real time. Each volunteer recorded in 15-min segments all activities for each 24-h period (midnight to midnight) throughout the study. Activities were estimated by the same investigator (1). On several occasions, HR for each volunteer was monitored for some activities (e.g., running, hiking) to more accurately assess energy expended. For all volunteers, total daily expenditures were corrected by actual measurement of basal metabolic rate (via open-circuit spirometry) determined on the mornings of ALT2 to ALT6 and on ALT10. Volunteers were provided daily continuous feedback on energy expended so that they could adjust their activity levels as needed.

Acute Mountain Sickness Assessment

Acute mountain sickness (AMS) was assessed each morning using the Environmental Symptoms Questionnaire. The Environmental Symptoms Questionnaire is a self-reported, 68-item inventory typically used to document symptoms induced by altitude. A 0- to 5-point weighted average of scores from "cerebral" symptom items (AMS-c) was used to determine AMS severity (0 = none to 5 = severe) and incidence (e.g., AMS-c > 0.7 indicates AMS), as previously described (32).

$\dot{V}O_{2\ peak}$

An incremental progressive exercise bout to volitional exhaustion on an electromagnetically braked cycle ergometer (Sensormedics, model 800s, Yorba Linda, CA) was used to assess $\dot{V}O_{2\ peak}$ at SL and altitude. Volunteers pedaled at 70–100 rpm for 2 min at 50, 100, and 150 W, and then in 30-W increments thereafter until O_2 uptake failed to increase or they stopped the test despite strong encouragement. During the $\dot{V}O_{2\ peak}$ test, O_2 uptake (via metabolic cart, True Max 2400, ParvoMedics, Salt Lake City, UT) and HR (via HR watch, Polar, Hempstead, NY) were monitored continuously. Some of the results of the $\dot{V}O_{2\ peak}$ tests were used to determine peak HRs, peak power outputs, 48 and 68% $\dot{V}O_{2\ peak}$ steady-state power outputs, and energy costs of the self-selected power outputs used during the time-trial performance assessment.

Bicycle Ergometer Endurance Test

The endurance test consisted of two distinct segments: a fasting steady-state exercise segment having a low- and high-intensity stage, and a CHOS or PLA-supplemented, self-paced maximal effort TT segment. Steady-state exercise was used to assure group similarity before CHO or PLA supplementation and to document physiological

responses during exercise at SL and in response to altitude exposure and acclimatization. The TT segment was used to assess performance changes due to supplementation at SL and altitude and those due to altitude exposure and acclimatization.

Endurance tests were performed using electromagnetically braked cycle ergometers (Sensormedics, model 800s, Yorba Linda, CA or Warren C. Collins, Pedalmate, Braintree, MA) on 4 separate days: twice at SL and on ALT3 and ALT10. Each volunteer was always tested using the same ergometer throughout the study. Volunteers were encouraged to provide maximum effort during the four TT performance tests. Water was provided ad libitum during all endurance tests.

During steady-state exercise, volunteers warmed up for 5 min at 50 W and then exercised for 20 min at a low intensity and 20 min at a high intensity of their altitude-specific $\dot{V}_{O_2 peak}$ (48 ± 5 and $68 \pm 5\%$, respectively). Because of the ~25–28% expected reduction in $\dot{V}_{O_2 peak}$ from SL to 4,300 m (18), the work rate used for low-intensity, steady-state exercise at SL was calculated to become the work rate used for high-intensity, steady-state exercise at altitude. Doing so allowed SL-to-altitude comparisons at the same absolute work rates in addition to the same relative percentages of $\dot{V}_{O_2 peak}$. After the steady-state segment, the volunteers had a 5-min rest period to allow bathroom use and "stretching out." They then began the TT performance segment and were required to complete 720 kJ of total work as fast as possible. They were allowed to alter pedaling speed and to adjust their work rate at any time during cycling by any desired increment. All were provided real-time feedback (via computer screen graphics) of total work performed and total work remaining. The volunteers were not informed of any of their TT performance durations until the study was completed. A TT performance test was chosen because of its high test-retest reproducibility and low coefficient of variance (22).

All four endurance tests were conducted using the same protocol. The only exception was that, during the first SL endurance test, there were no blood samples drawn and that, in the TT performance segment, in addition to ad libitum water, the volunteers were required to drink water at the exact volume, times, and frequency that the CHOS or PLA would be consumed during the remaining three endurance tests.

The second endurance test was conducted during the SL baseline phase, and the third and fourth tests were conducted on ALT3 and ALT10, respectively. All three were conducted in the mornings after fasting overnight, placement of a forearm venous catheter, and the drawing of a resting fasting blood sample. Exercise blood samples were obtained during steady-state exercise (i.e., while fasting) and during CHO or PLA supplementation during the TT.

CHO and PLA supplementation. CHOS was a previously tested and highly acceptable (26) tropical punch-flavored blend of maltodextrin (mass/volume, 9%), glucose (2%), and fructose (1%) (Ergo Drink, US Army Soldier Systems Command, Natick, MA). Each powdered serving was reconstituted with water to a 10% CHO solution. At the start of the TT and every 15 min thereafter until completion, volunteers consumed either 0.175 g/kg body wt (e.g., 80-kg body weight = 14 g CHO, 56 kcals, and 140 ml/serving) of reconstituted Ergo Drink or an equal volume of indistinguishable PLA having no nutritive value. A staff member not directly involved with the endurance tests mixed and assigned the CHO and PLA drinks. The volunteers and the investigators participating in the study remained blinded to the supplement assignment until the entire study was completed. The rate of CHO ingested during exercise (i.e., 56 g/h for an 80-kg body weight) was within established CHOS guidelines (2).

To assure that the CHOS group did not receive a disproportionate amount of CHO on the TT test days, each volunteer was required to receive the exact volume of the opposite supplementation after each TT. In other words, if a volunteer had four drinks of 13 g of CHO per drink (total of 52 g or 208 kcals of CHO in 520 ml of H_2O), he would receive 520 ml of PLA and be required to drink it within 1 h of completing the TT and vice versa.

Blood measures. Blood glucose, lactate, glycerol (Analox GM7 Micro-Stat, Hammersmith, London, UK), and free fatty acids (Elan Diagnostics, ATAC 8000, Smithfield, RI) were determined at rest to validate a fasting state, and after 15 min of cycling at 48% and then at 68% of $\dot{V}_{O_2 peak}$ during steady-state exercise to assure that all volunteers had normal metabolic responses to exercise. Blood samples also were obtained during the TT after the volunteer completed 25% (i.e., 180 kJ), 50% (i.e., 360 kJ), 75% (i.e., 540 kJ), and 100% (i.e., 720 kJ) of total work to validate CHO/PLA supplementation. For each endurance test, <10 ml of blood were withdrawn. Blood glucose and lactate were analyzed within minutes of collection; whereas glycerol and free fatty acids were frozen for later analyses.

Other measures. During rest and all endurance tests, Sa_{O_2} via noninvasive finger pulse oximetry (model N-200, Nellcor, Pleasanton, CA; measurement error: $\pm 2\%$ in the range of 70–100% Sa_{O_2}, validated against a hemoximeter as per manufacturer communication) and HR via HR watch (Polar, Hempstead, NY) were recorded continuously for determination of possible between-group differences in hypoxemia level and exercise intensity, respectively. Ratings of perceived exertion [RPE; 6–20 Borg Scale (5)] were obtained every 5 min for determination of possible between-group differences in perceived effort. O_2 uptake data via metabolic cart (True Max 2400, ParvoMedics, Salt Lake City, UT) were collected at rest and within *minutes 10–15* during the 48 and 68% $\dot{V}_{O_2 peak}$ stages of steady-state exercise to determine the O_2 cost of cycle exercise at the same absolute and relative exercise intensities at SL and altitude.

Statistics

A two-factor (days × group) or three-factor (days × times × group) analysis of variance with repeated measures on one (days) or two (days and times) factors was utilized for performance, physiological, and blood values comparisons (Statistica version 7.0, Statsoft, Tulsa, OK). All values collected during the TT were analyzed at 25, 50, 75, and 100% of TT work completion to assure intra- and intersubject data compatibility among TTs and between groups. Post hoc analyses (Newman-Keuls) were performed when appropriate. Independent *t*-tests were used to compare specific characteristics (e.g., age, height, etc.) between groups. Regression analyses were used to determine relationships between physiological measures (e.g., Sa_{O_2}) and exercise performance (e.g., TT duration). Statistical significance was accepted when $P < 0.05$. All values are expressed as means $\pm$ SE unless otherwise indicated.

RESULTS

Energy Intake and Energy Expenditure

There were no differences in mean daily intakes of energy, CHO, protein or fat, energy expenditure, energy deficit, or body weight loss between the CHOS and PLA groups at SL or altitude. Throughout SL, body weight remained stable for all subjects at ~77.5 ± 2 kg due to the similarity in energy intake ($3,879 \pm 91$ kcal/day) and energy expenditure ($4,057 \pm 153$ kcal/day).

On the summit, unlimited and convenient access to a wide variety of physical activities resulted in daily energy expenditures at altitude being consistently higher than at SL. Energy expenditure at altitude averaged $4,567 \pm 169$ kcal/day (or ~500 kcal/day more than at SL; $P < 0.01$). At altitude, despite strong encouragement to maintain daily energy intake similar to that at SL, energy intake was voluntarily reduced to an average of $3,140 \pm 165$ kcal/day (or ~750 kcal/day less than at SL; $P < 0.01$). At ALT compared with SL, CHO consump-

Table 2. $\dot{V}_{O_2 \, peak}$ change at altitude

	Day 2				Day 9			
	$\dot{V}_{O_2 \, peak}$, ml/min	SL, %	$\dot{V}_{O_2 \, peak}$, ml·min^{-1}·kg^{-1}	SL, %	$\dot{V}_{O_2 \, peak}$, ml/min	SL, %	$\dot{V}_{O_2 \, peak}$, ml·min^{-1}·kg^{-1}	SL, %
PLA	3,134±79	74±1	39.9±2	74±1	3,140±91	74±1	41.2±2	77±2
CHO	3,211±193	73±2	43.0±2	74±2	3,081±158	70±2	42.5±2	77±3

Values are means ± SE. SL, sea level; ALT2, ALT9, *days 2* and *9* at Pikes Peak.

tion was reduced by 102 g/day (662 ± 33 to 560 ± 19 g/day; $P < 0.01$) or by 1.0 g·kg^{-1}·day^{-1} (8.6 ± 0.01 to 7.6 ± 0.01 g·kg^{-1}·day^{-1}; $P < 0.02$). The resulting energy deficit contributed to the body weight decline from 77.0 ± 2 kg on ALT3 to 74.7 ± 2 kg on ALT10 ($P < 0.01$).

AMS

Five volunteers in the PLA group and 5 volunteers in the CHO group had AMS before the TT on ALT3. Because the AMS-c score was 1.38 ± 0.52 for the PLA group and 1.26 ± 0.35 for the CHO group, the severity of AMS was determined to be equal and "slight" for both groups. Before the TT on ALT10, none of the volunteers had AMS. Thus the incidence and severity of AMS for volunteers in both groups were nearly identical before each of the TTs.

$\dot{V}_{O_2 \, peak}$, Peak Watts, and Peak HR

Both groups (matched on $\dot{V}_{O_2 \, peak}$ at SL) had similar declines in $\dot{V}_{O_2 \, peak}$ and peak watts (Wpeak) resulting from altitude exposure. For both groups, $\dot{V}_{O_2 \, peak}$ and Wpeak declined ~25% from SL to ALT2 ($P < 0.01$) and did not change ($P > 0.05$) with continued exposure (~26% on ALT9; Tables 2 and 3). Peak HR was lower on ALT2 (177 ± 2 beats/min) compared with SL (187 ± 2 beats/min; $P < 0.01$). It was also lower on ALT9 (156 ± 3 beats/min) compared with ALT2 and SL ($P < 0.01$). These results are consistent with normal altitude acclimatization (18).

Bicycle Ergometer Endurance Test

Steady-state exercise responses. Because volunteers were matched as closely as possible at SL on $\dot{V}_{O_2 \, peak}$ and other physical characteristics, it was anticipated that there would be no between-group differences during the fasting, steady-state exercise for work rate, % $\dot{V}_{O_2 \, peak}$, or any of the other measurements made. Our results indicate that there were no between-group differences in wattages, % $\dot{V}_{O_2 \, peak}$, HR, % Sa_{O_2}, respiratory exchange ratio (RER), RPE, and blood values for glucose, lactate, free fatty acids, or glycerol used at the low (48% $\dot{V}_{O_2 \, peak}$) and high (68% $\dot{V}_{O_2 \, peak}$) steady-state exercise intensities at SL or on either test day at altitude. The steady-state exercise data were then pooled to confirm that the values

Table 3. *Wpeak at SL and altitude*

	SL Wpeak, W	ALT2 Wpeak, W	ALT2 Wpeak, %SL Wpeak	ALT9 Wpeak, W	ALT9 Wpeak, %SL Wpeak
PLA	349±19	259±13	75±3	251±11	73±4
CHO	364±20	270±14	75±3	266±14	74±3

Values are means ± SE. Wpeak, peak wattage determined during $\dot{V}_{O_2 \, peak}$ test.

obtained on ALT3 and ALT10 were typical for SL residents undergoing normal acclimatization to 4,300 m (18, 19).

From SL to ALT3, power outputs were reduced during low-intensity exercise (48% $\dot{V}_{O_2 \, peak}$, 142 ± 6 to 94 ± 4 W; $P < 0.01$) and high-intensity exercise (68% $\dot{V}_{O_2 \, peak}$, 205 ± 9 to 142 ± 6 W; $P < 0.01$). Doing so allowed low-intensity and high-intensity steady-state exercise to be conducted at similar ($P > 0.05$) altitude-specific relative exercise intensities, respectively. Because identical individual steady-state low and high power outputs were used on ALT3 and ALT10, and Wpeak did not change with time at altitude (see Table 3), the low and high relative exercise intensities remained similar during steady-state exercise between testing days.

HR for both intensities was higher on ALT3 than for either SL or ALT10 ($P < 0.01$). HR during exercise was maintained ~25 beats/min higher at 68% $\dot{V}_{O_2 \, peak}$ than for 48% $\dot{V}_{O_2 \, peak}$ throughout the study ($P < 0.01$). There was a reduction ($P < 0.01$) in HR for both exercise intensities of ~15 beats/min from ALT3 to ALT10. Steady-state exercise Sa_{O_2} decreased from SL (97 ± 0.3%; range: 94–99%) to ALT3 (73 ± 1.6%; range: 63–83%; $P < 0.01$) and then increased on ALT10 (81 ± 1.2%; range: 68–89%; $P < 0.01$) but remained lower compared with SL ($P < 0.01$). For each of the altitude test days, Sa_{O_2} during 68% $\dot{V}_{O_2 \, peak}$ was ~2% lower than during 48% $\dot{V}_{O_2 \, peak}$ ($P < 0.03$). For 48% $\dot{V}_{O_2 \, peak}$, RER decreased from 0.91 ± 0.01 at SL to 0.81 ± 0.01 on ALT3 ($P < 0.01$) and to 0.80 ± 0.01 on ALT10 ($P < 0.01$). There was no difference between the two altitude test days. Similar changes occurred for 68% $\dot{V}_{O_2 \, peak}$ from SL to ALT3 (0.93 ± 0.01 to 0.85 ± 0.01; $P < 0.01$) and to ALT10 (0.84 ± 0.01; $P < 0.01$), with no difference from ALT3 to ALT10. There also was no difference from SL to altitude in RPE. Steady-state exercise at 48% $\dot{V}_{O_2 \, peak}$ was rated as a 10 to 11 ("fairly light"), and exercise at 68% $\dot{V}_{O_2 \, peak}$ was rated as a 13 to 14 ("somewhat hard" to "hard") throughout the study.

Blood glucose was higher during exercise on ALT3 (5.69 ± 0.16 mM) compared with SL (5.02 ± 0.13 mM) and ALT10 (5.16 ± 0.11 mM) ($P < 0.01$). On all test days, blood lactate was higher at 68% $\dot{V}_{O_2 \, peak}$ (3.69 ± 0.46 mM) compared with 48% $\dot{V}_{O_2 \, peak}$ (1.94 ± 0.52 mM; $P < 0.01$). Lactate during exercise also was higher ($P < 0.03$) on ALT3 (3.61 ± 0.42 mM) than at SL (2.78 ± 0.44 mM) or ALT10 (2.06 ± 0.14 mM). Free fatty acids were higher on ALT3 (0.68 ± 0.05 mM) and ALT10 (0.59 ± 0.06 mM) compared with SL (0.30 ± 0.05 mM; $P < 0.01$) but were not affected by a change from 48% $\dot{V}_{O_2 \, peak}$ (0.55 ± 0.07 mM) to 68% $\dot{V}_{O_2 \, peak}$ (0.49 ± 0.06 mM) on any testing day. Glycerol was higher for ALT3 (0.22 ± 0.03 mM) and ALT10 (0.21 ± 0.03 mM) compared with SL (0.11 ± 0.02 mM, $P < 0.01$) and also was higher at 68% $\dot{V}_{O_2 \, peak}$ (0.22 ± 0.03 mM) compared with 48% $\dot{V}_{O_2 \, peak}$ (0.14 ± 0.02 mM; $P < 0.01$).
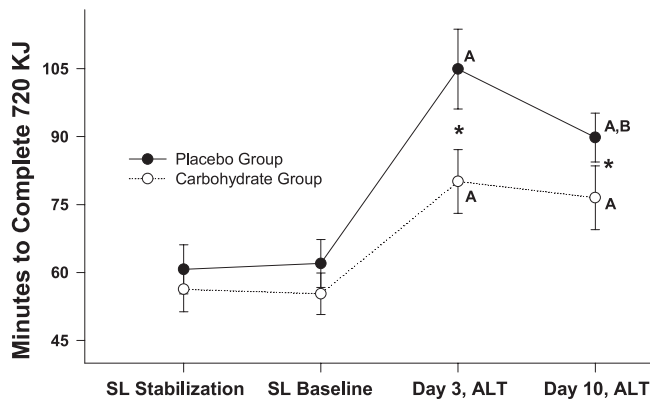
Fig. 1. Time trial (TT) performance at sea level (SL) and altitude (ALT). [A]$P <$ 0.01 from SL. *$P < 0.01$ between groups. [B]$P < 0.01$ reduced from *day 3* at ALT (ALT3).

Collectively, the volunteers had typical and expected physiological responses to the steady-state exercise segment at SL and altitude. Also, the decreases in HR and RER, the increase in Sa_{O_2}, and the blood value responses from ALT3 to ALT10 during exercise at the same power output, %Wpeak, and % $\dot{V}_{O_2\ peak}$ on both days are consistent with a normal pattern of altitude acclimatization (6, 19).

TT Performance

CHOS during the TT. The total amount of energy provided by CHO during the TT was a function of body weight and TT duration. Although the calories in each drink ingested every 15 min were similar among TT testing days (52 ± 1.3 kcal at SL, 52 ± 1.6 kcal on ALT3, and 51 ± 1.6 kcal on ALT10), total calories consumed during the TTs differed. Total energy intake was 200 ± 16 kcal at SL, 290 ± 16 kcal on ALT3 ($P < 0.01$ from SL), and 262 ± 17 kcal on ALT10 ($P < 0.01$ from SL or ALT3). At SL, the amount of CHO consumed during the TT was, as a percentage of daily CHO intake, 8 ± 1% at SL, 13 ± 1% on ALT3 (<0.01 from SL), and 12 ± 1% on ALT10 ($P < 0.01$ from SL).

TT performance durations. CHOS made no difference in TT performance at SL but improved performance at altitude (Fig. 1). During the SL stabilization phase (in which none of the volunteers was yet supplemented), the TT was completed by the CHOS group in 56.3 ± 5 min and by the PLA group in 60.7 ± 5 min ($P = 0.55$). During the SL baseline phase, the TT was completed by the CHOS group in 55.3 ± 5 min and by the PLA group in 62.0 ± 5 min ($P = 0.36$). The coefficient of variation (standard deviation/mean) from the stabilization phase to the baseline phase was 5.2% for the CHOS group and 4.6% for the PLA group (and 4.9% for both groups combined). These values are close to the 3.4% coefficient of variation previously reported for trained cyclists completing TTs of

similar durations (22). These results clearly indicate that the test-retest variation in TT performance was small for each group and that there was no within- or between-groups effect of CHOS on SL performance.

Performance durations were impaired (i.e., completion time was longer) for both groups ($P < 0.01$) on ALT3 and ALT10 compared with SL. There was no significant relationship between the decline from SL in $\dot{V}_{O_2\ peak}$ and performance duration either for ALT3 ($r = 0.26$) or for ALT10 ($r = 0.22$). Performance duration and mean power output during the TTs were, however, similarly inversely related at SL ($r = -0.93$, $P < 0.001$), ALT3 ($r = -0.91$, $P < 0.001$), and ALT10 ($r = -0.97$, $P < 0.001$). Also, for both groups, performance time was improved on ALT10 compared with ALT3 (main effect, $P < 0.01$). The data also indicate that the time on ALT3 for the PLA group was much longer (i.e., performance worse) than for the CHOS group (104.9 ± 9 vs. 80.1 ± 7 min; $P < 0.01$). From ALT3 to ALT10, performance time for the PLA group improved ($P < 0.01$), whereas that for the CHOS group did not improve ($P > 0.05$). Despite the performance improvement of the PLA group from ALT3 to ALT10, their time on ALT10 was still worse than that of the CHOS group (89.8 ± 5 vs. 76.5 ± 7 min; $P < 0.01$).

% $\dot{V}_{O_2\ peak}$. There was no statistically significant difference between groups in self-selected, altitude-specific % $\dot{V}_{O_2\ peak}$ used during the TT performance tests between SL baseline and ALT3 for either group (Table 4). By ALT10, both groups exercised at a higher altitude-specific % $\dot{V}_{O_2\ peak}$ compared with SL baseline ($P < 0.03$) and ALT3 ($P < 0.01$).

The difference in altitude-specific % $\dot{V}_{O_2\ peak}$ used during the TTs for the eight matched pairs of CHOS and PLA volunteers was 2% at SL baseline but increased to 14% on ALT3 ($P < 0.03$) due to those in the CHO group tending ($P = 0.061$) to exercise at a higher % $\dot{V}_{O_2\ peak}$ than those in the PLA group. The matched pair difference in altitude-specific % $\dot{V}_{O_2\ peak}$ by ALT10 tended to be lower than on ALT3 ($P = 0.06$) but similar to SL baseline. Because a similar inverse relationship between altitude-specific % $\dot{V}_{O_2\ peak}$ used during the TT and performance duration existed for both groups at SL ($r = -0.79$; $P < 0.01$), ALT3 ($r = -0.74$, $P < 0.01$), and ALT10 ($r = -0.82$, $P < 0.01$), those who were able to maintain a higher altitude-specific % $\dot{V}_{O_2\ peak}$ completed the TT more quickly. Overall, these findings are consistent with the TT performance times.

Exercise intensity and Sa_{O_2}. Exercise intensity (expressed as %SL Wpeak) and Sa_{O_2} measured during the TT are illustrated in Fig. 2, *top* and *bottom*, respectively. Both groups exercised at a lower exercise intensity at altitude than at sea level ($P < 0.01$), with the CHOS group exercising on ALT3 and ALT10 at a higher %SL Wpeak than the PLA group ($P < 0.05$). For the CHOS group, there was no difference between ALT3 and ALT10 in %SL Wpeak, whereas for the PLA group %SL

Table 4. *Percentage $\dot{V}_{O_2\ peak}$ during the time-trial performance segment*

Group	SL Stabilization	SL Baseline	*Day 3*, Altitude	*Day 10*, Altitude
PLA	61.3 ± 4	60.3 ± 4	55.1 ± 5§	66.0 ± 3*†
CHOS	65.2 ± 3	64.9 ± 3	66.9 ± 3	71.8 ± 4*†
Matched pair difference	4 ± 4%	2 ± 5%	14 ± 5%*	6 ± 6%‡

Values are means $\pm$ SE. *$P < 0.03$ from SL. †$P < 0.01$ from *day 3*. ‡$P = 0.06$ from *day 3*. §$P = 0.061$ from CHOS, *day 3*.

Fig. 2. Percentage of SL peak power output used to complete the time trial (*top*) and arterial O_2 saturation (Sa_{O_2}) (*bottom*) during the time trials. For each group, the percentage of SL peak power output (%SL Wpeak) used during the TT on ALT3 (■) and *day 10* at ALT (ALT10; ▲) was lower than at SL (●) (*$P < 0.01$). Although there was no difference between groups at SL, %SL Wpeak was higher for the carbohydrate (CHO) supplementation (CHOS) group than for the placebo (PLA) group on each altitude day ($^{C}P < 0.05$). %SL Wpeak also was lower on ALT3 than on ALT10 for the PLA group ($^{D}P < 0.03$) but not for the CHOS group. For each group, Sa_{O_2} during the TT on ALT3 and ALT10 was lower than at SL (*$P < 0.01$). Sa_{O_2} also was lower on ALT10 compared with ALT3 for the PLA group (**$P < 0.01$) but not for the CHOS group. There was no difference during the TT in Sa_{O_2} between groups at SL or ALT3. However, throughout the TT on ALT10, Sa_{O_2} was lower for the CHOS group (76.4 ± 2%) than for the PLA group (81.3 ± 2%; $^{E}P < 0.01$). There were significant inverse relationships between %SL Wpeak and Sa_{O_2} for both groups during the TT at ALT3 ($r = 0.76$, $P < 0.03$) and ALT10 ($r = 0.90$, $P < 0.01$).
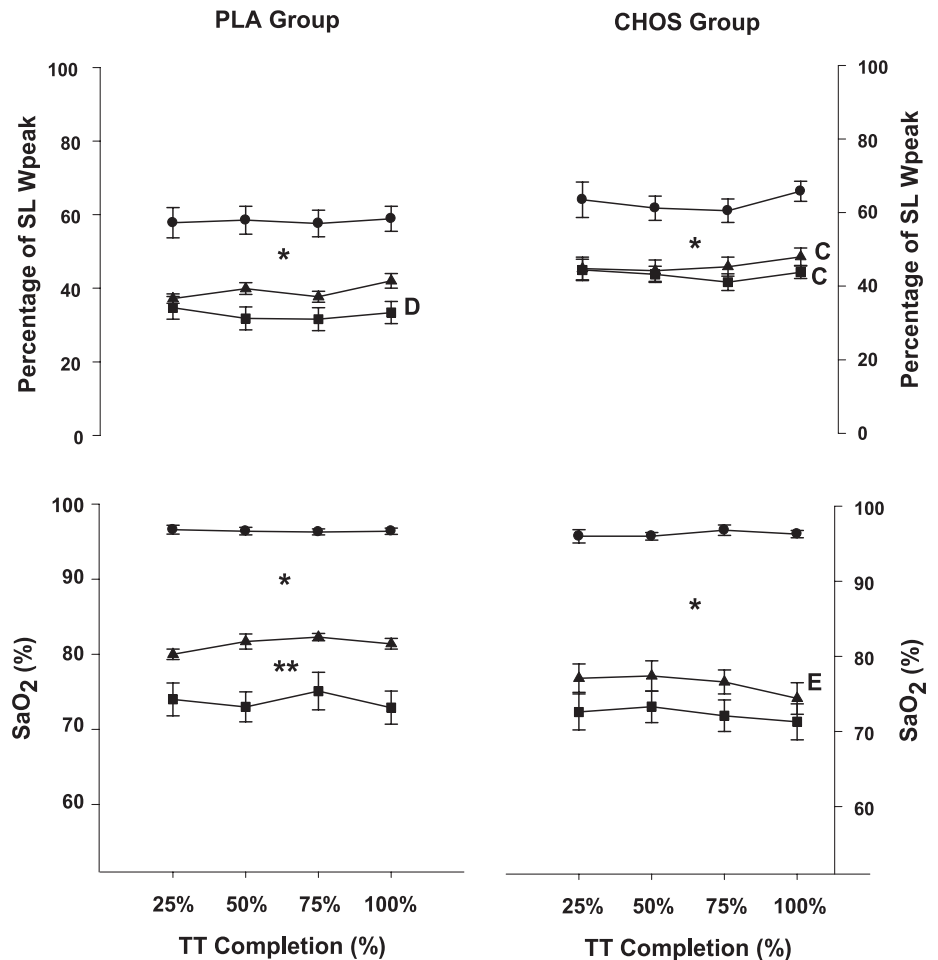
Wpeak was lower on ALT3 than on ALT10 ($P < 0.03$). Sa_{O_2} did not differ between groups at SL (PLA: 96 ± 0.4%, range: 94–98%; CHO: 96 ± 0.5%, range: 95–99%) and ALT3 (PLA: 74 ± 1.9%, range: 64–79%; CHO: 72 ± 2.0%, range: 65–79%) but was reduced similarly for both groups from SL to ALT3 ($P < 0.01$). However, throughout the TT on ALT10, Sa_{O_2} was lower ($P < 0.01$) for the CHOS group (76 ± 1.7%, range: 68–83%) than for the PLA group (81 ± 0.6%, range: 78–83%). For both groups, Sa_{O_2} was inversely related to %SL

Wpeak throughout the TTs on ALT3 ($r = -0.76$, $P < 0.03$) and ALT10 ($r = -0.90$, $P < 0.01$). TT duration and mean absolute level of Sa_{O_2} during the TT were not, however, related at ALT3 ($r = -0.18$, $P =$ not significant) and ALT10 ($r = 0.17$, $P =$ not significant). Collectively, these results indicate that Sa_{O_2} level closely tracked changes in exercise intensity throughout the TTs at altitude but had little impact on overall TT performance.

HR and RPE. Percentage of HR peak (%HRpeak) and RPE are illustrated in Figs. 3 and 4, respectively, for SL baseline,

Fig. 3. Percentage of peak heart rate (%HRpeak) used during the TT. Overall, the CHOS group used a higher %HRpeak than the PLA group (main effect, $^{A}P < 0.01$). For both groups, a higher %HRpeak was used on ALT10 (▲) compared with SL baseline (●) and ALT3 (■) ($^{B}P < 0.01$). Also for both groups, for all test days (with the exception of the PLA group on ALT3), the %HRpeak used was higher toward the end of exercise compared with the beginning of exercise ($^{C}P < 0.01$).
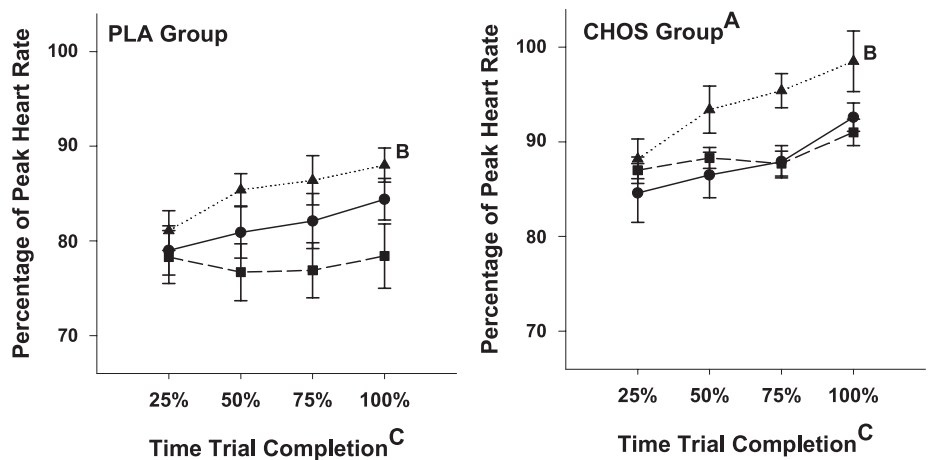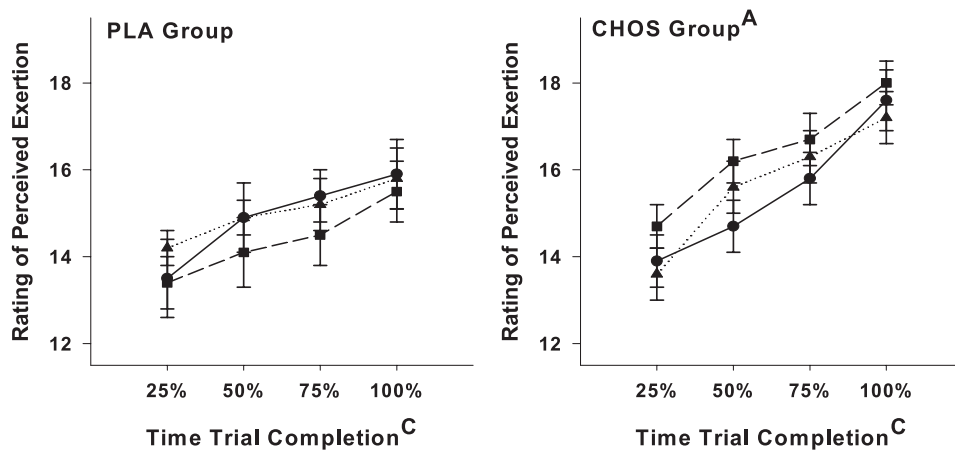
Fig. 4. Ratings of perceived exertion (RPE) during the TT. For both groups at SL and altitude, RPE increased progressively with exercise duration ($^CP < 0.05$). For each group, RPE did not differ among test days ($P > 0.05$). However, at all time periods after 25% completion of the TT, the CHOS group reported higher RPE values than the PLA group for both altitude days ($^AP < 0.01$).

ALT3, and ALT10. In general, %HRpeak and RPE differed between groups during exercise, with the CHOS group having higher values for %HRpeak and RPE compared with the PLA group.

Blood measures. Figures 5–8 show blood glucose, lactate, free fatty acids, and glycerol values, respectively, for the PLA and CHOS groups at rest and during the TT. For several of the volunteers during the TT segment on each testing day, we were unsuccessful in drawing all samples after ~50% of the TT duration due to problems such as blood clotting and catheter displacement. For these volunteers, blood sampling was postponed until the completion of exercise. Therefore, data represented are the fasting, pre-TT resting values and exercise values after 25%, 50%, and completion of the TT at SL baseline, ALT3, and ALT10.

Throughout the study, resting values were similar for both groups. In contrast, exercise values for glucose and lactate were generally higher and values for free fatty acid and glycerol were generally lower for the CHOS group compared with the PLA group.

DISCUSSION

The results clearly indicate that CHOS enhances cycle TT performance of SL residents during the first 10 days at 4,300 m that is accompanied by negative energy balance. Performance on ALT3 compared with that at SL was reduced by 73% for the PLA group but only by 46% for the closely matched CHOS group. By ALT10, the between-group performance gap had

narrowed but was still 9% better for the CHOS group. It is noteworthy that performance improved from ALT3 to ALT10 for the PLA group but not for the CHOS group. These results are consistent with the notion that TT performance for the CHOS group may have been optimized at altitude and that it was influenced more by CHOS than the salutary physiological effects associated with the first 10 days of altitude acclimatization.

Sa_{O_2} during the TTs was reduced similarly for both groups on ALT3 and was lower for the CHOS group than for the PLA group on ALT10. Yet, during the TTs for both days at altitude, exercise intensity, HR, and RPE for the CHOS group were higher than those for the PLA group. These results are interpreted to mean that CHOS enabled exercise to be performed voluntarily at a higher intensity despite severe hypoxemia. Thus, contrary to our hypothesis, the magnitude of the exercise-induced hypoxemia sustained during the TTs at altitude is inconsequential relative to the performance benefit resulting from CHOS.

At least four major experimental design and measurement outcome features of this study provide assurance that such a difference in performance at altitude between groups was related directly to CHOS during exercise. First, matching groups on SL $\dot{V}_{O_2\ peak}$ minimized the possibility that the performance disparity could be attributed to differences in fuel utilization linked to a difference in fitness level (7). Moreover, the similar altitude-induced decline in % $\dot{V}_{O_2\ peak}$ and fall in HRpeak from SL to altitude indicated that aerobic capacity of

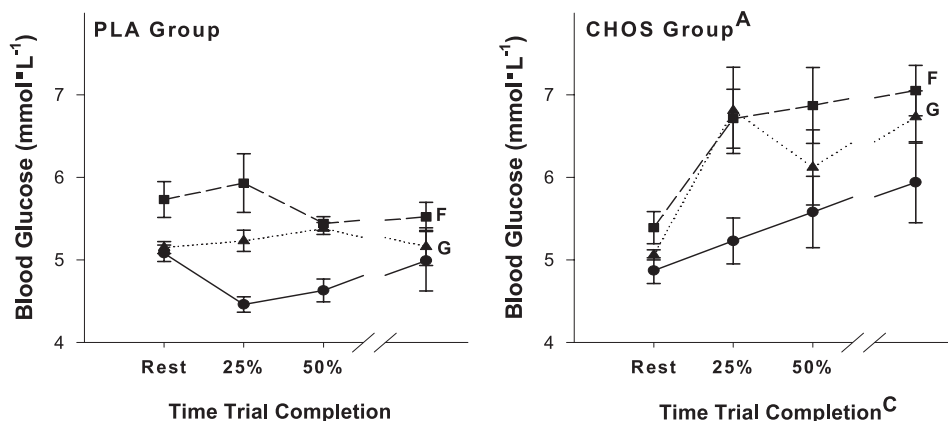Fig. 5. Blood glucose during the TT. At SL and ALT, blood glucose during exercise was higher for the CHOS group than for the PLA group ($^AP < 0.03$). Blood glucose for the PLA group did not differ from rest ($P > 0.05$), whereas for the CHOS group blood glucose was always higher throughout exercise compared with rest ($^CP < 0.02$). When the data were pooled, blood glucose was higher on ALT3 (■) compared with SL (●) and ALT10 (▲) (main effect, $^FP < 0.01$). In addition, blood glucose was higher on ALT10 compared with SL (main effect, $^GP < 0.01$).

Fig. 6. Blood lactate during the TT. At SL and ALT, blood lactate was higher for the CHOS group than for the PLA group ([A]$P < 0.04$). Pooled data indicate that blood lactate during exercise was similar at SL (●) and ALT3 (■) but was lower on ALT10 (▲) ([H]$P < 0.01$). Although blood lactate tended to rise with exercise duration ($P < 0.07$), that for the CHOS group rose to a higher level compared with the PLA group ([C]$P < 0.03$).
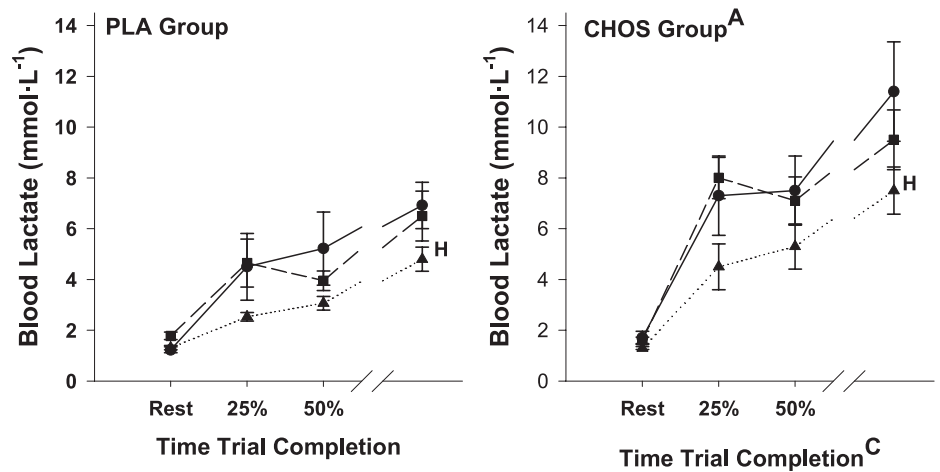
both groups was affected equally at altitude. Second, both groups began the steady-state segment of the endurance tests after an overnight fast to minimize the acute effects of the last meal on exercise metabolism and performance. Third, there were striking similarities of physiological (e.g., HR, RER, and Sa_{O_2}), perception (e.g., RPE), and metabolic (e.g., blood glucose and lactate) responses to steady-state exercise on each testing day at altitude. Such results strongly indicate a similar rate of altitude acclimatization for both groups. And fourth, experimental bias in favor of the CHOS group was avoided by having a disinterested third party make the volunteer assignments to each group. Results of the group assignments were not revealed to the other staff or volunteers until the entire study was completed. Moreover, while at altitude, volunteers from both groups lived together, participated jointly in the same activities, and ate the same foods.

Previous studies at SL reported that, when resting muscle glycogen stores are replete, the rate of total CHO oxidation is similar for the CHOS and PLA or control groups for up to ~2 h of cycling at ~70% $\dot{V}o_{2 \text{ peak}}$ (15). After this exercise duration, with no CHOS, muscle glycogen stores are reduced ~60% and plasma glucose levels decline relative to resting levels (10, 14). Throughout the SL phase of the present study, energy intake nearly equaled energy expenditure, and the diet was high in CHO (i.e., 63% of total energy or 8.6 g $CHO \cdot kg^{-1} \cdot day^{-1}$). This suggests that, at the start of the endurance performance tests for both groups, resting muscle

glycogen stores were not greatly reduced from fully replete levels. In addition, each group exercised at >60% $\dot{V}o_{2 \text{ peak}}$ for less than a total of 0.5 h (i.e., 20 min at 68% $\dot{V}o_{2 \text{ peak}}$ during the steady-state segment and TT segment combined), and, for the PLA group, blood glucose was maintained at resting levels throughout the endurance test. In such a scenario, CHO availability is not limited to SL performance, and CHOS during exercise may not enhance exercise performance (4, 9, 16). The lack of change in the intra- and intergroup performance at SL in the present study is consistent with this interpretation. In contrast, however, there are other reports indicating that CHOS improves cycle TT performance of 1-h duration, although the mechanism has not been established (8, 21).

$\dot{V}o_{2 \text{ peak}}$ at altitude was reduced from SL for both groups, and as a result the self-selected power outputs that could be used during the TT performance tests also were reduced from SL (18). Because the total amount of work performed at SL and altitude was identical at 720 kJ, the duration of the TT was necessarily longer at altitude than at SL for both groups. However, in contrast to the similarity in performance between groups at SL, the performance of the CHOS group was superior to that of the PLA group on both test days at altitude. It appears there are several factors that, when combined, could at least partly explain this difference.

One factor is the observed SL vs. altitude difference in energy balance and its relationship to resting muscle glycogen stores. At SL, both groups were nearly in energy balance,

Fig. 7. Free fatty acids (FFA) during the TT. At SL and ALT, blood FFA for the CHOS group was lower than for the PLA group ([A]$P < 0.01$). For pooled data, blood FFA was higher on ALT3 (■) compared with SL (●) and ALT10 (▲) ([I]$P < 0.01$). Also, blood FFA was highest at the end of exercise compared with rest and 25 and 50% completion ([C]$P < 0.01$). However, at SL and ALT, FFA for the PLA group was higher during exercise compared with rest ([C]$P < 0.01$) in direct contrast to the CHOS group, whose level was lower during exercise than at rest ([J]$P < 0.01$).
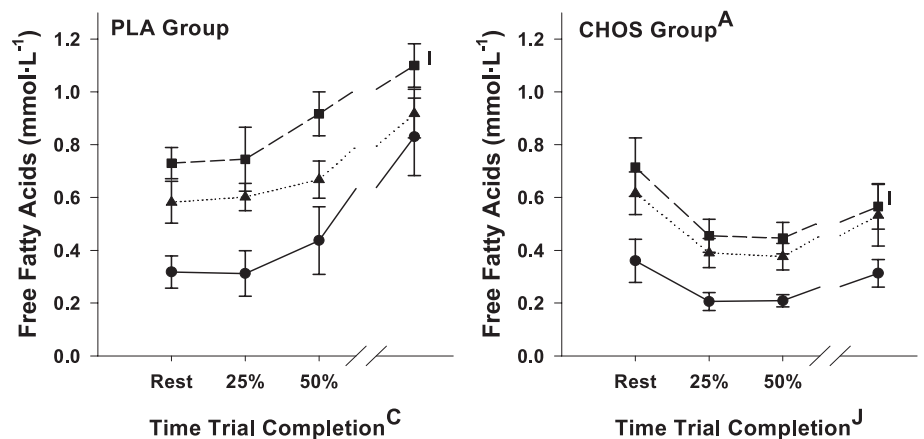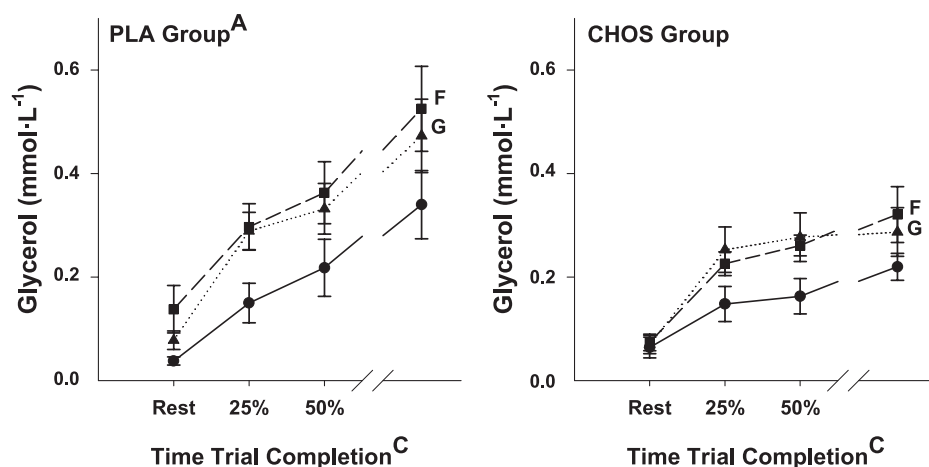
Fig. 8. Blood glycerol during the TT. There was no overall difference in blood glycerol between groups during rest or exercise at SL or ALT. For pooled data, blood glycerol was higher on ALT3 (■) and ALT10 (▲) than at SL (●) ([F,G] $P < 0.01$) and, for each test day, higher during exercise than at rest ([C] $P < 0.01$). Although blood glycerol rose with exercise duration ($P < 0.04$), that for the PLA group rose to higher levels compared with the CHOS group ([A] $P < 0.01$).

whereas at altitude both groups had greatly increased energy expenditures and reduced energy intakes that amounted to a daily energy deficit of ~1,250 kcal/day compared with SL. Significantly increasing daily energy expenditure likely increased muscle glycogen utilization (12). Moreover, it is important to note that to expend the necessary extra amount of daily energy required 20–40% more time at 4,300-m altitude than it would have at SL (18) and therefore reduced the daily rest time available for muscle glycogen restoration (23). Furthermore, the reduced daily energy intake may have been insufficient to provide adequate CHO for full muscle glycogen repletion (13) despite the daily CHO intake remaining relatively high at altitude (560 g/day or 7.6 g $CHO \cdot kg^{-1} \cdot day^{-1}$). Thus it is possible that muscle glycogen was lower at altitude than at SL before each TT.

In addition to the possibility that both groups at altitude started exercise with less than optimal resting muscle glycogen stores and with a greater proportion of fat being oxidized (based on lower steady-state exercise RER values), each group exercised via their own volition at approximately similar % $\dot{V}_{O_2 peak}$ at SL and altitude during the TT performance tests. Because muscle glycogen utilization is related more to % $\dot{V}_{O_2 peak}$ than to absolute work rate (31) and the volunteers exercised for longer periods of time at altitude than at SL, it is likely that muscle glycogen stores fell to lower levels at altitude than at SL during the TT. The implication is that, as muscle glycogen progressively declined during the prolonged TT, the reliance on blood glucose to maintain total CHO oxidation steadily increased (11).

In the present study, blood glucose level for the CHO group was higher than for the PLA group during the TTs at SL and altitude, and performance was superior for the CHO group at altitude. Because glucose is transported via facilitated diffusion down a concentration gradient (25) and glucose is the most O_2-efficient fuel under conditions of acute and chronic hypoxia (28), our findings are consistent with the notion that CHOS increased glucose availability that resulted in increased glucose utilization during the TTs at altitude. Previous studies at sea level have shown that, when endogenous CHO stores are less than optimal and/or if exercise duration is 2 h or longer, CHOS typically benefits performance (3, 11, 17, 27, 36). From this perspective, the benefit of CHOS on prolonged intense exercise may not appear to be unique to altitude exposure. However,

what was difficult to determine a priori was whether the severe hypoxemia resulting from maximal effort exercise during the first 10 days of high-altitude exposure would minimize or even mask the performance benefits otherwise associated with CHOS. We conclude that, despite hypoxemia exacerbated by higher intensity exercise, increasing availability of glucose as a metabolic fuel greatly improved TT performance during high-altitude residence in which there was a negative energy balance.

In summary, two groups of eight men closely matched by SL $\dot{V}_{O_2 peak}$, age, body weight, and height performed cycle endurance tests at SL and on *days 3* and *10* while living at 4,300-m altitude and experiencing daily negative energy balance and weight loss. The endurance test consisted of two distinct parts: a steady-state exercise segment (i.e., 20 min each at 48 and 68% $\dot{V}_{O_2 peak}$) that assessed physiological changes due to altitude acclimatization while fasting and a 720-kJ TT segment that assessed the effects of CHOS (10% solution, 0.175 g/kg body wt every 15 min) on prolonged, maximal-effort performance. Both groups had similar physiological responses to the steady-state exercise segment at SL and high altitude and acclimatized similarly with altitude residence. In contrast, TT exercise performance at altitude was far superior for the CHOS group than for the PLA group despite hypoxemia exacerbated by higher intensity exercise. We conclude that increased availability of glucose as a metabolic fuel greatly improved endurance performance in SL residents during the first 10 days at altitude that was accompanied by a daily negative energy balance and weight loss.

not be construed as an official Department of the Army position, policy or decision unless so designated by other documentation.

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