Curvilinear Dose–Response Relationship of Carbohydrate (0–120 g·h^{-1}) and Performance

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ABSTRACT

SMITH, J. W., D. D. PASCOE, D. H. PASSE, B. C. RUBY, L. K. STEWART, L. B. BAKER, and J. J. ZACHWIEJA. Curvilinear Dose–Response Relationship of Carbohydrate (0–120 g·h^{-1}) and Performance. *Med. Sci. Sports Exerc.*, Vol. 45, No. 2, pp. 336–341, 2013. **Background**: There is a lack of consensus regarding the optimal range of carbohydrate (CHO) ingestion rates recommended for endurance athletes. **Purpose**: This study investigated the relationship between CHO dose and cycling time trial performance to identify an optimal range of CHO ingestion rates for endurance performance. **Methods**: Fifty-one cyclists and triathletes (28 ± 7 yr, mean ± SD) across four research sites completed four trials. Each trial consisted of a 2-h constant load ride at 95% of the workload that elicited a 4-mmol·L^{-1} blood lactate concentration immediately followed by a computer-simulated 20-km time trial, which subjects were asked to complete as quickly as possible. Twelve CHO electrolyte (18 mmol·L^{-1} Na, 3 mmol·L^{-1} K, and 11 mmol·L^{-1} Cl) beverages (three at each site) were tested in a double-blind manner, providing subjects 10, 20, 30, 40, 50, 60, 70, 80, 90, 100, 110, and 120 g CHO (1:1:1 glucose–fructose–maltodextrin) per hour during the 2-h constant load ride at a fluid intake rate of 1 L·h^{-1}. All subjects also consumed a noncaloric placebo on one counterbalanced test occasion. Data were natural log transformed, subjected to a mixed-model analysis, and are reported as adjusted treatment means. **Results**: We estimate incremental performance improvements of 1.0%, 2.0%, 3.0%, 4.0%, and 4.7% at 9, 19, 31, 48, and 78 g·h^{-1}, respectively, with diminishing performance enhancement seen at CHO levels >78 g·h^{-1}. **Conclusions**: CHO beverage ingestion and endurance (~160 min) performance appear to be related in a curvilinear dose–response manner, with the best performance occurring with a CHO (1:1:1 glucose–fructose–maltodextrin) ingestion rate of 78 g·h^{-1}. **Key Words:** CYCLING, TIME TRIAL, CARBOHYDRATE INGESTION RATE

Research has consistently demonstrated the ergogenic effect of consuming carbohydrate (CHO) during endurance exercise (7,13,14). Such studies indicate that, when CHO is consumed during exercise, time to exhaustion is prolonged (5,8,9,31,35,36) and the time required to complete a set distance or work volume is reduced (1,2,23,24). Accordingly, the American College of Sports Medicine (ACSM) and National Athletic Trainers' Association (NATA) position stands recommend CHO ingestion during prolonged exercise to maintain performance (5,31).

Both the ACSM and NATA recommend a CHO ingestion rate of 30–60 g·h^{-1} (5,31). However, improvements in exercise performance have also been reported with CHO intakes below (as little as 22 g·h^{-1}) and above (up to 180 g·h^{-1}) this range (8,9,17,20,21,24,36). While several studies have investigated the effect of CHO ingestion rate on performance, variations in CHO type, delivery form, delivery schedule, and testing protocol make it difficult to compare dosage benefits across studies (1,7,13,23,25,29,34,36). A number of other studies have addressed the question of whether a dose–response relationship exists between CHO intake and performance (18,20,21,23,24,34). However, because of confounding factors in these studies, such as varying the ratio of CHO types and/or electrolyte composition across beverages, a consensus on the CHO dose–performance response has not been reached (14,23). In addition, most previous dose–response studies have compared a limited number of doses and/or a relatively narrow range of CHO ingestion rates.

Research using tracer techniques has demonstrated that when glucose alone is ingested, the body is able to use it at a rate of about 1 g·min^{-1} (60 g·h^{-1}) (3,11,16,33) and about 1.5 g·min^{-1} (90 g·h^{-1}) when multiple CHO types (i.e., glucose and fructose) are consumed (3,10,11,15,16,33). These results lead one to speculate that a range of 60–90 g·h^{-1} may facilitate optimal performance. By contrast, higher CHO ingestion rates have not always been associated with improved

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exercise performance (18,20,30), due in part to an increased incidence of stomach discomfort and a reduction in intestinal CHO and fluid absorption (30).

The purpose of the present study was to investigate the relationship between 0 and 120 $g \cdot h^{-1}$ (at 10-$g \cdot h^{-1}$ increments) CHO ingestion rates (with a consistent 1:1:1 ratio of glucose, maltodextrin, and fructose across beverages) and performance during a 20-km time trial preceded by a 2-h constant load ride in cyclists and triathletes. The aim in using this study design was to quantify the CHO dose–performance response relationship across a wide range of CHO doses. We hypothesized that there would be a curvilinear relationship between 0 and 120 $g \cdot h^{-1}$ CHO ingestion and performance, such that performance would progressively improve from zero to moderate CHO ingestion rates, reach an apex in the range of 60–90 $g \cdot h^{-1}$, and then progressively decline as CHO ingestion rate increased above 90 $g \cdot h^{-1}$.

METHODS

Subjects. Four separate exercise physiology laboratories collaborated to test 51 recreationally trained, healthy male cyclists or triathletes (12–15 subjects at each laboratory) for this study. Before testing, each subject signed an informed consent, which was approved by the human subject ethics committee at each testing site. Mean and SD age, height, body mass, and peak oxygen uptake ($\dot{V}O_{2peak}$) were 28.4 ± 6.7 yr, 1.82 ± 0.07 m, 77.7 ± 8.4 kg, and 59.1 ± 5.6 $mL \cdot kg^{-1} \cdot min^{-1}$, respectively.

Preliminary testing. During the subjects' first visit to the laboratory, $\dot{V}O_{2peak}$ was determined using an incremental multistage cycling test adapted from Robergs et al. (28). After a 10-min warm-up at 100 W, athletes cycled at 150 W for 5 min. Then the workload was increased by 50 W every 3 min until 250 W, after which the workload was increased by 25 W every minute until volitional exhaustion. On a second occasion, separated from the $\dot{V}O_{2peak}$ test by at least 7 d, the subjects completed an incremental lactate test to identify the workload that would elicit a 4-$mmol \cdot L^{-1}$ blood lactate concentration (onset of blood lactate accumulation, OBLA). The workloads used for the OBLA test corresponded to 55%, 60%, 65%, 70%, 75%, 80%, 85%, and 90% $\dot{V}O_{2peak}$ and were calculated from the linear relationship between wattage and $\dot{V}O_2$ measured in the first three stages of the $\dot{V}O_{2peak}$ test. During the OBLA test, subjects exercised for 4 min at each workload. Blood samples were collected during the final 30 s of each stage for analysis of blood lactate concentration with an i-STAT whole blood analyzer (Abbott Point of Care, Inc., Princeton, NJ) using the i-STAT CG4+ test cartridge. The $\dot{V}O_{2peak}$ and OBLA tests were performed with the subjects exercising on their own bicycles affixed to a bicycle trainer (CompuTrainer™ Pro; RacerMate, Inc., Seattle, WA).

Familiarization. Before the experimental trials, subjects performed three familiarization trials. During the first familiarization, subjects completed the computer-simulated 20-km time trial course. The second familiarization consisted of a 2-h ride at 95% OBLA while drinking *ad libitum* followed by the computer-simulated 20-km time trial. The third familiarization was a 2-h ride at 95% OBLA while drinking 250 mL of water every 15 min followed by a computer-simulated 20-km time trial. Each familiarization trial was separated by at least 7 d. Data from the three familiarization trials were not used in subsequent analyses.

Experimental procedures. Subjects completed four randomized experimental trials with at least 7 d between trials. For each trial, subjects reported to the laboratory after a 10-h overnight fast, having maintained a consistent diet and abstained from exercise during the 24-h preceding each trial. Before the initiation of the experimental trial, subjects voided and had their body weight recorded. Subjects were required to have a preexperiment urine specific gravity (USG) ≤1.025. After a 10-min warm-up at 100 W, subjects began the 2-h constant load ride at 95% OBLA (average workload sustained = 228.1 ± 27.3 W; 70.8% ± 6.6% $\dot{V}O_{2peak}$) on their own bicycles affixed to a bicycle trainer (CompuTrainer™ Pro; RacerMate, Inc.). HR (Polar Electro, Inc., Lake Success, NY) was measured every 15 min. The CHO ingestion rates were altered by providing the subjects beverages with different CHO concentrations. During each 2-h ride, subjects ingested a total of 2000 mL of one of 13 beverages (0%, 1%, 2%, 3%, 4%, 5%, 6%, 7%, 8%, 9%, 10%, 11%, and 12% CHO) with electrolytes (18 $mmol \cdot L^{-1}$ Na, 3 $mmol \cdot L^{-1}$ K, and 11 $mmol \cdot L^{-1}$ Cl). The beverage was consumed in 250-mL aliquots every 15 min (beginning at minute 15 and ending at minute 120) for an overall ingestion rate of 1 $L \cdot h^{-1}$. The CHO ingestion rates of the drinks were blinded to both the subjects and the researchers. The code was not revealed until the data were submitted for statistical analysis. The placebo beverage provided 0 g $CHO \cdot h^{-1}$ but was the same sweetness (use of noncaloric sweeteners) flavor and taste and contained the same electrolyte composition as the CHO beverages. Each research site tested the placebo condition and three of the twelve CHO beverages (test site 1: 0%, 1%, 5%, and 9% CHO; test site 2: 0%, 2%, 6%, and 10% CHO; test site 3: 0%, 3%, 7%, and 11% CHO; test site 4: 0%, 4%, 8%, and 12% CHO). Consequently, the analysis will focus on aggregate performance (combining average performance at each CHO level from all laboratory sites) as a measure of the effect of CHO on performance. The CHO beverages were formulated with a ratio of 1:1:1 of glucose, maltodextrin, and fructose (2:1 ratio of glucose and fructose units). The 13 beverages were formulated to be similar in flavor and sweetness to minimize differences in taste. Beverages were given to the subjects in opaque plastic bottles and were presented in a random, balanced order. After completing the 2-h ride, the HR monitor was removed, and subjects were allowed off the bike for 1.5 min to void their bladder (if necessary).

Performance time trial. Two minutes after the cessation of the 2-h ride, subjects began the simulated 20-km time trial on a custom-designed computer-simulated undulating

course and were asked to complete the course as quickly as possible. The course elevation change included 9.04 km of incline at a 2.00% average slope (~180 m uphill) and 10.96 km of decline at a −1.95% average slope (~213 m downhill). Resistance varied with the inclination of the course, during which subjects altered their speed and gearing throughout the time trial. Subjects were aware of their position on the course, but no verbal stimuli, times, or other information was given. No fluids were ingested during the 20-km performance time trial. Environmental conditions during the experimental trials varied across research sites (18°C–22°C and 32%–55% relative humidity), but conditions remained consistent within each site for all trials.

Data analysis. All data are expressed as mean ± SD. Statistical significance was set at $P \leq 0.05$. Confidence intervals (CI) and exact P values are reported when possible. Time-to-complete time trial data were log transformed (natural logs) to facilitate interpretation of percent change in performance and were back transformed as appropriate. We used the Linear Mixed Model procedure (Version 15.0.1; SPSS, Armonk, NY) to quantify performance relative to CHO treatment condition. CHO treatment condition was coded as grams per hour (0, 10, 20, 30, 40, 50, 60, 70, 80, 90, 100, 110, and 120) and laboratory site was coded in an arbitrary sequential fashion (1, 2, 3, 4), and both were included in the model as fixed effects. Subject was included in the model as a random effect. Aggregate data (adjusted means of performance associated with each of the 13 treatment conditions) were then modeled (a polynomial curve fit to 13 means), and the optimum CHO level was estimated from this curve (point on quadratic curve corresponding to fastest performance). The mean regression formula from the bootstrap (nonparametric identically distributed resampling procedure) applied to the treatment means using 10,000 iterations was then used to estimate performance at CHO levels from 0 to 120 $g \cdot h^{-1}$ in increments of 1 $g \cdot h^{-1}$. The CHO level corresponding to the optimum performance on this curve was then used as an estimate of optimum CHO intake level. Mean performance and 95% CI at the quadratic minimum (inflexion point of the curve), which corresponds to the fastest time to complete time trial, was determined using the following formula applied to the 10,000 iterations of the bootstrap: $Y_M = [4(B_{2.1})(B_0) - (B^2{}_{1.2})]/4(B_{2.1})$, where Y_M is the predicted maximum/minimum of the quadratic curve, $B_{2.1}$ is the quadratic term, $B^2{}_{1.2}$ is the linear term, and B_0 is the Y intercept (6). A separate analysis of treatment order effects was conducted using a mixed-model analysis, with order of treatment and laboratory site included as fixed effects and subject included as a random effect.

RESULTS

Laboratory comparison. The subjects' body masses, 2-h workloads, and times to complete time trial at the 0% CHO beverage condition at each testing site are shown in Table 1. Treatment order effect was not significant. Baseline USG varied significantly among sites (1.009 to 1.014); however, all sites had average USG values <1.020, which indicates that subjects at all four sites began their trials in a well-hydrated state (5).

TABLE 1. Body mass, 2-h workload, and time-to-complete time trials with 0% CHO placebo for time-to-complete-time trial data for the 0% CHO placebo condition for each testing site.

		Testing Site				ANOVA
		1 (n = 12)	2 (n = 12)	3 (n = 15)	4 (n = 12)	P
Body weight (kg)	Mean	81	77	76	77	0.35
	SD	10	5	9	6	
2-h workload (W)	Mean	236	210	231	234	0.07
	SD	23	18	25	35	
Time-to-complete time trial: 0% CHO (min)	Mean	36.1	35.4	37.0	34.0	0.18
	SD	3.1	3.0	3.3	4.6	

CHO dose–performance relationship. Individual performance relative to CHO intake is shown in Figure 1 with fitted quadratic (R^2 = 0.05). Mean time to complete time trial at the 0% CHO placebo condition was 35.43 min (95% CI = 34.58–36.30 min). A significant treatment effect was seen in the mixed model ($P < 0.001$). Adjusted mean performance at each CHO intake level with fitted quadratic curve is shown in Figure 2. The predicted time to complete time trial for the 0% CHO placebo condition from the mean regression formula (based on bootstrap of values in Fig. 2) was 35.48 min (95% CI = 34.37–36.62 min), a difference of about 0.1%. Using the mean regression formula from the bootstrap, we also estimated incremental performance improvements of 1.0%, 2.0%, 3.0%, 4.0%, and 4.7% at 9, 19, 31, 48, and 78 $g \cdot h^{-1}$, respectively. Increasing CHO beyond 78 $g \cdot h^{-1}$ did not produce any further performance improvement. Moreover, 4.0% and 3.3% performance improvements over the 0-$g \cdot h^{-1}$ placebo condition were observed at 108 and 120 $g \cdot h^{-1}$, respectively (suggesting a progressive decrement in performance beyond 78 $g \cdot h^{-1}$). The curve minimum (Fig. 2) corresponding to the fastest time to complete time trial was 33.80 min (95% CI = 32.82–35.30 min; mean and 95% CI based on bootstrap of log

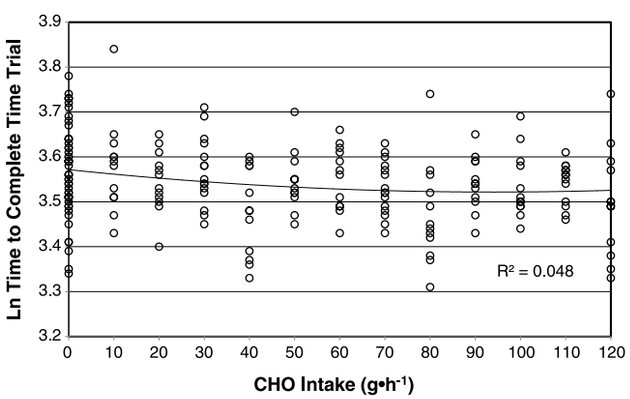

FIGURE 1—Individual performance (natural log of time to complete time trial) relative to CHO intake ($g \cdot h^{-1}$) with fitted quadratic. Differences × 100 represent change in performance.

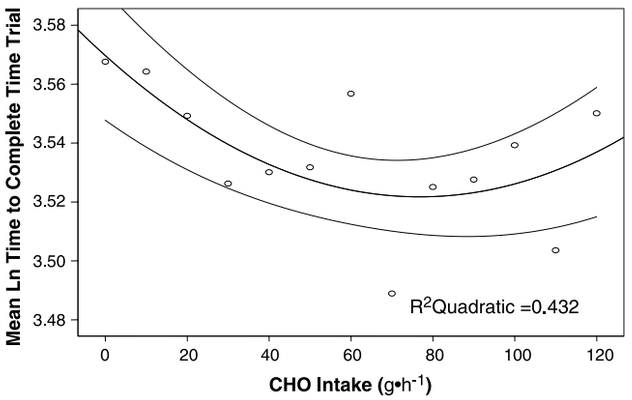

FIGURE 2—Mean log time to complete time trial (natural) as function of CHO treatment condition with fitted quadratic curve (with 95% CI of mean curves). Differences × 100 represent percent change in performance. The quadratic function relating CHO ingestion rate to time complete time trial for 43% (95% CI = 11%–75%, *P* = 0.059) of the variation in mean performance scores.

time-to-complete time trial data shown in Figure 2 with back transformation of the mean and 95% CI values). The 95% CI curves (of the mean) in Figure 2 suggest uncertainty in the optimum of approximately 68–88 g·h^{-1}.

DISCUSSION

In agreement with previous research, we found that the ingestion of a CHO (1:1:1 glucose–fructose–maltodextrin) beverage during a 2-h constant load cycling bout at ~70% $\dot{V}O_{2peak}$ significantly improved performance compared to placebo during a subsequent 20-km simulated cycling time trial. The novel finding from the present study was a significant curvilinear dose–response relationship between 0 and 120 g·h^{-1} and exercise performance. The estimated optimal CHO dose was 78 g·h^{-1}.

Previous studies have not supported the notion of a dose–response relationship between CHO ingestion rate and performance (20,21,23). Mitchell et al. (21) compared 0, 34, 39, and 50 g·h^{-1} and found that each of the CHO ingestion rates improved performance over 0 g·h^{-1}, but there were no differences among CHO ingestion rates. In another study by Mitchell et al. (20), subjects ingested CHO at 0, 37, 74, and 111 g·h^{-1} and only the 74-g·h^{-1} dose elicited an ergogenic affect compared to 0 g·h^{-1}. Murray et al. (23) compared 0, 26, 52, and 78 g·h^{-1}, and their results suggested a lack of dose–response relationship between CHO and performance as 26 and 78 g·h^{-1} improved cycling performance, but 52 g·h^{-1} did not. Perhaps the discrepancy in findings between our results and that of previous investigations is due in part to differences in study design (continuous in the present study vs intermittent exercise in Mitchell et al. [20,21]) and/or CHO types/electrolyte content of the beverages (inconsistent across beverages in Mitchell et al. [20,21]). By contrast, a previous study in our laboratory suggested that the chance of an athlete experiencing a meaningful improvement in performance increased as the CHO dose increased from 15 to 30 to 60 g·h^{-1} (32). A recent study by Watson et al. (34) has demonstrated a trend for improvements in performance as CHO dose increased from approximately 15 to 45 g·h^{-1}, with only doses of approximately 30 and 45 g·h^{-1} being significantly different from placebo in a cool environment and a dose of 45 g·h^{-1} being significantly different from placebo in a warm environment. The present study corroborates the results of these two studies and also provides insight on the CHO dose–performance response relationship from 60 to 120 g·h^{-1}.

The CHO ingestion rate that elicited the greatest performance improvement in the present study was 78 g·h^{-1}. As CHO ingestion rates increased above this range, performance progressively decreased. The finding that higher CHO ingestion rates do not provide an advantage over 78 g·h^{-1} is in agreement with Mitchell et al. (21) who showed a performance improvement with 74 g·h^{-1} but no improvement above placebo when 111 g·h^{-1} of CHO was ingested. In addition, Maughan et al. (18) found that 225 g·h^{-1} did not provide an ergogenic effect over water. Similarly, a recent study demonstrated greater endurance capacity when ingesting moderate-CHO solutions as compared to low- and high-CHO solutions (26).

Our study results suggested that low rates of CHO ingestion had a small, but beneficial effect on performance. This finding is consistent with Maughan et al. (17) and Murray et al. (23) who found a significant performance benefit with CHO ingestion at a rate of 22 and 26 g·h^{-1}, respectively. Furthermore, previous work from our laboratory has shown that, compared to placebo (0 g·h^{-1}), a significant improvement in endurance performance can be obtained with a CHO ingestion rate as low as 15 g·h^{-1} (32).

The performance improvements observed with CHO ingestion could be due to a combination of several factors. It has been suggested that the beneficial effect of CHO ingestion during exercise could be due in part to the stimulation of CHO receptors in the oral cavity modulating central neural drive and reducing perceived exertion (4). The ergogenic affect could also be attributed to better maintenance of plasma glucose concentration and/or the associated changes in fuel selection. The increased availability of blood glucose could result in a higher rate of CHO oxidation, particularly late in the exercise period (13). When a single type of CHO is ingested, peak oxidation rates are approximately 1 g·min^{-1} (12,16,33). However, exogenous CHO oxidation rates have been reported to exceed 1.2 g·min^{-1} (72 g·h^{-1}) when multiple forms of CHO are ingested at high rates (10,11,15). The increase in exogenous oxidation rate with ingestion of multiple CHO types may be the result of the ability to use both glucose and fructose intestinal transporters (10). Accordingly, multiple CHO types were used in the beverages in the present study to maximize CHO absorption and oxidation.

In the present study, cycling performance progressively decreased as CHO ingestion rates increased above 78 g·h^{-1}. Limitations in gastric emptying (19,22), intestinal absorption (27), and CHO oxidation (30) rates have been identified

as potential reasons why large CHO intakes during exercise do not provide additional performance benefits. Previous findings of a threshold in CHO absorption and CHO oxidation could possibly explain the decrease in performance with CHO ingestion rates above 78 $g \cdot h^{-1}$ in the present study.

Limitations and future directions. Four sites were used in the present study to allow testing across such a broad range of CHO ingestion rates. Ideally, the same subjects would have seen all 13 treatments. However, this approach was not used because of the concern that subjects would lose desire/ability to perform at a high level as a result of training fatigue or changes in training status over the course of 13 weeks. To help control for potential differences among laboratory sites, the low- to high-CHO range at all sites overlapped with two of the interventions at all other sites and improvements were compared to a common placebo (Table 1). We believe this provided a realistic view of the changes that would have occurred if all subjects experienced all CHO doses. However, we are limited in our ability to model the effects of CHO ingestion rates in individual subjects because no subject was exposed to the full range of CHO treatments. As a result, curve fitting of the individual data was inappropriate because the quadratics for many of the subjects did not yield valid estimates of optimum performance within the range of treatment conditions experienced by the individual. Therefore, given that a significant treatment effect was found in the mixed-model analysis, a quadratic curve fit was applied to the aggregate data (the 13 treatment means) to estimate the inflexion point on the curve, thereby identifying the CHO level corresponding to optimum performance. While the quadratic curve fit accounted for a substantial amount of variation in mean performance, the observed significance level of this regression approached but did not meet our prechosen hurdle of 0.05. Inspection of Figure 2 suggests that variation in the model from apparent outlier values at 60–70 $g \cdot h^{-1}$ is contributing to the quadratic fit not reaching traditional statistical significance. We are unsure as to why these values may be outliers. An additional caveat relates to the use of the bootstrap method with small numbers of values, which could compromise our ability to estimate variation. However, this study does provide an estimate of optimum CHO level and expected performance enhancement over a range of treatment conditions never before attempted. Future research that focuses on CHO intake levels around the point estimate of optimum from this study (68–88 $g \cdot h^{-1}$) will benefit from designs that allow more complete modeling of individual data so as to generate estimates of individual variation of estimates of optimum, something not possible in the current design.

The present study's beverages contained CHO in the form of maltodextrin, glucose, and fructose in a 1:1:1 ratio, with the goal of providing glucose and fructose units in a 2:1 ratio while trying to maintaining osmolality as close as possible across all beverages. Despite this, differences in osmolality among beverages (range ~ 90–520 mOsm) could have affected intestinal absorption, CHO oxidation, and ultimately exercise performance. Unfortunately, the effect of carbohydrate on osmolality is an unavoidable consequence of altering beverage CHO concentration. Emerging research on new forms of CHO and CHO "creation" may allow the ability to reduce osmolality while providing greater amounts of CHO. However, research needs to be conducted to determine how these new forms are used by the body during exercise.

The results of the present study demonstrated the potent ergogenic affect of CHO ingestion on performance during ~2.5 h of cycling without measures to assess the mechanism by which the performance enhancements occurred. Future studies should be conducted to test the CHO dose–performance response relationship during exercise of varying durations and modes of exercise, as well as potential mechanisms leading to these changes.

Summary and practical implications. In summary, this study found that prolonged exercise performance can be enhanced across a wide range of CHO ingestion rates and that a CHO ingestion rate of 78 $g \cdot h^{-1}$ will likely result in an endurance athletes' optimal performance. The goal of each training/race session should be taken into consideration when determining the appropriate amount of CHO to ingest. This study has demonstrated that the ingestion of small amounts of CHO (~10–60 $g \cdot h^{-1}$) can provide some performance benefit. In most training situations, this level of performance enhancement is likely sufficient. This study also suggests that in competitive race settings the athlete would benefit from a CHO ingestion rate of 78 $g \cdot h^{-1}$ (the optimal range is estimated to be 68–88 $g \cdot h^{-1}$). However, higher CHO ingestion rates have diminishing returns as the performance benefit progressively decreases above ~78 $g \cdot h^{-1}$.

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