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REVIEW

Systematic review: Carbohydrate supplementation on exercise performance or capacity of varying durations[1]

Trent Stellingwerff and Gregory R. Cox

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Abstract: This systematic review examines the efficacy of carbohydrate (CHO) supplementation on exercise performance of varying durations. Included studies utilized an all-out or endurance-based exercise protocol (no team-based performance studies) and featured randomized interventions and placebo (water-only) trial for comparison against exclusively CHO trials (no other ingredients). Of the 61 included published performance studies (n = 679 subjects), 82% showed statistically significant performance benefits (n = 50 studies), with 18% showing no change compared with placebo. There was a significant (p = 0.0036) correlative relationship between increasing total exercise time and the subsequent percent increase in performance with CHO intake versus placebo. While not mutually exclusive, the primary mechanism(s) for performance enhancement likely differs depending on the duration of the exercise. In short duration exercise situations (~1 h), oral receptor exposure to CHO, via either mouthwash or oral consumption (with enough oral contact time), which then stimulates the pleasure and reward centers of the brain, provide a central nervous system-based mechanism for enhanced performance. Thus, the type and (or) amount of CHO and its ability to be absorbed and oxidized appear completely irrelevant to enhancing performance in short duration exercise situations. For longer duration exercise (>2 h), where muscle glycogen stores are stressed, the primary mechanism by which carbohydrate supplementation enhances performance is via high rates of CHO delivery (>90 g/h), resulting in high rates of CHO oxidation. Use of multiple transportable carbohydrates (glucose:fructose) are beneficial in prolonged exercise, although individual recommendations for athletes should be tailored according to each athlete's individual tolerance.

Key words: carbohydrate, performance, duration, dose–response.

Résumé : Cette analyse documentaire systématique scrute l'efficacité de la supplémentation en hydrates de carbone (« CHO ») sur la performance physique de durée diverse. Les études retenues traitent d'effort à fond de train ou d'endurance (pas d'études sur la performance en équipe) et regroupent des approches aléatoires et des essais avec placebo (eau seulement) à des fins de comparaison avec des essais sur les CHO seulement (pas d'autres ingrédients). Parmi les 61 études sur la performance (n = 679 sujets), 82 % révèlent des gains de performance statistiquement significatifs (50 études) et 18 % ne révèlent aucune différence avec des groupes placebo. On note une corrélation significative (p = 0,0036) entre l'augmentation du temps total d'exercice et l'augmentation (%) subséquente de performance en présence de consommation de CHO comparativement à un placebo. Tout en n'étant pas mutuellement exclusifs, les principaux mécanismes d'amélioration de la performance diffèrent en fonction de la durée de l'exercice. Dans le cas des exercices de courte durée (~1 h), les récepteurs buccaux sont exposés aux CHO, au moyen de rince-bouche ou de la consommation per os (avec suffisamment de temps de présence en bouche) stimulant ainsi les centres nerveux du plaisir et de la récompense; cette exposition constitue un mécanisme du système nerveux central pour l'amélioration de la performance. Par conséquent, la nature et/ou la quantité de CHO pouvant être absorbés et oxydés n'a apparemment rien à voir avec l'augmentation de la performance dans les exercices de courte durée. Dans le cas des exercices de plus longue durée (>2 h) qui grèvent les réserves de glycogène musculaire, les principaux mécanismes d'amélioration de la performance consécutive à la supplémentation en sucres comportent un haut taux d'approvisionnement en CHO (>90 g/h) suivi d'un haut taux d'oxydation des CHO. L'utilisation de multiples CHO transportables (glucose:fructose) est bénéfique pour les exercices prolongés, mais les recommandations à l'intention des athlètes doivent être ajustées à la capacité de tolérance individuelle. [Traduit par la Rédaction]

Mots-clés : sucres, performance, durée, dose–réponse.

Introduction/approach

Beyond an individual athlete's genetic trainability and optimized training program, perhaps the largest single determinant of ensuring optimal performance during prolonged endurance events is through the intake of carbohydrate (CHO) and fluid. As endorsed by the 2007 American College of Sports Medicine Exercise and Fluid Replacement Position Stand (Sawka et al. 2007), it is clear that most studies show an improvement in endurance performance or capacity when subjects consume a CHO fluid as compared with water alone (Jeukendrup 2010). Furthermore, a recent meta-analysis on the performance effect sizes of CHO stated: "Carbohydrate supplements with an appropriate composition and administration regimen can have large benefits on endurance performance" (Vandenbogaerde and Hopkins 2011). However, no recent reviews have examined and analyzed both the performance magnitude of CHO intake on either exercise capacity or performance coupled with the mechanistic interpretation and practical recommendations from short duration CHO mouthwash studies to prolonged (>2 h) exercise interventions.

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T. Stellingwerff. Canadian Sport Institute – Pacific, 4371 Interurban Road, Victoria, BC V9E 2C5, Canada.
G.R. Cox. Australian Institute of Sport, Gold Coast, Queensland, Australia.
Corresponding author: Trent Stellingwerff (e-mail: tstellingwerff@csipacific.ca).

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To locate articles, a combination of several historical and contemporary reviews (Sawka et al. 2007; Jeukendrup 2010, 2011; Vandenbogaerde and Hopkins 2011) and searches in MEDLINE (PubMed) were analyzed and performed, respectively. The review focused only on studies that utilized an all-out or endurance-based exercise protocol (no team-based performance studies) and that featured randomized interventions and placebo (water only) trial for comparison against exclusively CHO trials (no other ingredients). With these criteria, the search resulted in examining 61 different published performance studies featuring 679 subjects. Each study was individually assessed according to the following criteria: exercise, performance description, and duration; CHO type; blinding; mean hourly CHO intake rate; exercise performance; or capacity effect (% difference) versus placebo. Of these 61 studies, 82% showed statistically significant performance benefits (n = 50 studies), with 18% showing no change compared with placebo.

Proposed performance mechanisms of CHO supplementation

The exact mechanism(s) of fatigue, and thus what limits performance, are multi-factorial in nature, and are different across different types and durations of sporting events. Furthermore, the impact that CHO supplementation can have on metabolism and performance depends on the length and intensity of the exercise, the CHO intake rate, CHO type/blend, athlete's fitness level, type of exercise mode/test (cycling vs. running; exercise performance vs. capacity tests), and whether the study was properly powered to show a performance difference. Therefore, the mechanisms and regulation involved with fuel metabolism and energy production during exercise are complex. However, there have been 2 major mechanisms that have emerged to primarily explain why CHO supplementation during exercise improves performance: (*i*) a mental/cognitive stimulation of the central nervous system (CNS) by oral exposure of CHO during shorter exercise durations (e.g., <1 h) when muscle glycogen stores are not limiting (e.g., CHO mouthwash studies); and (*ii*) direct contribution of CHO energy and exogenous CHO oxidation (CHO_{oxid}) during muscle glycogen limiting exercise situations (e.g., >2 h).

Exercise duration of less than ~60 min (nonglycogen limiting conditions)

Muscle glycogen is generally not limiting to performance when exercise durations are less than ~60 min. Historically it was generally hypothesized that exogenous carbohydrate supplementation may *not* improve performance in events less than 60 min in duration. However, several studies (n = 16 out of 23 total studies) have found that carbohydrate supplementation and (or) oral (mouth) exposure to carbohydrate can improve performance of tasks less than 1 h in duration (Table 1).

In 2004 a seminal paper was published showing that a carbohydrate mouthwash (swirling 25 mL of a 6% CHO beverage (only ~1.5 g of CHO in 25 mL) around in the mouth for ~10 s, every 7.5 min) significantly improved time trial (TT) performance by ~3% (Carter et al. 2004*a*). This effect of CHO mouthwashing to improve performance in events from 30–60 min has now been replicated in several other performance studies (10 of 13 studies; Table 1) using both cycling and running interventions and with both sweet (sucrose) and nonsweet (maltodextrin) caloric CHO sources, as compared with noncaloric artificial sweetener placebo trials showing no performance-enhancing effects. All these findings have been mechanistically supported with a functional magnetic resonance brain imaging study showing that CHO mouthwashing from both sweet tasting glucose and nonsweet maltodextrin can stimulate the brain areas of the insula/frontal operculum, orbitofrontal cortex, and striatum, which are involved with brain centers responsible for reward and motor control (Chambers et al. 2009). Interestingly, if the mouth (oral receptors) and gastrointestinal (GI) tract is bypassed by CHO infusion straight into the blood stream, then 1 h of cycling TT performance was unaltered as compared with no CHO supplementation (Carter et al. 2004*b*). Furthermore, a recent paper has also shown that a 10-s mouthwash resulted in superior 30 min of cycling TT performance compared with a 5-s mouthwash, suggesting a dose–response relationship between oral caloric sweet taste receptors activation, brain activation, and subsequent performance (Sinclair et al. 2014). It is well established that subjects pacing during a TT is closely linked to their individual ratings of perceived exertion (RPE), ultimately dictating performance outcomes (Eston 2012). Accordingly, CHO mouthwash studies have shown equivalent RPEs among subjects between placebo and intervention, despite the higher power outputs and enhanced performance in the mouthwash trials (Rollo et al. 2008, 2010; Pottier et al. 2010; Sinclair et al. 2014). And, as one would hypothesize, in the only study to undertake a time to exhaustion design, and thus equivalent power outputs between treatments, there was a reduced RPE in the CHO mouthwash trial compared with placebo (Fares and Kayser 2011).

Taken together, all of these data strongly suggests that oral receptor exposure to CHO, via either mouthwash or oral consumption (with enough oral contact time), which then stimulates the pleasure and reward centers of the brain, provide a CNS-based mechanism for enhanced performance when exercise is 1 h or less. Thus, in short duration exercise situations (<1 h) the type and (or) amount of CHO and its ability to be absorbed and oxidized appear completely irrelevant to enhancing performance (Carter et al. 2004*b*) as long as there is adequate oral exposure to CHO (~1.5 g in 25 mL for 5 to 10 s for every 8 to 10 min of exercise). Several practical barriers may prevent athletes from implementing these strategies during high-intensity endurance competitions. It can be difficult to strategically consume CHO fluids at critically tactical times (e.g., a break-away or an attack) as well as the difficulties with breathing while exposing your mouth to carbohydrate for approximately 10 s. Placing a sports confectionary in the cheek cavity may provide a more practical option for some athletes.

Exercise duration of greater than ~60 min (potentially glycogen limiting conditions)

Since the early studies by Coyle et al. (Coyle 1992*a*, 1992*b*) it has become well established and scientifically accepted that the intake of carbohydrate (glucose alone, and glucose + fructose blends) can significantly improve prolonged endurance capacity and performance (>60 min of exercise (Jeukendrup 2010)). Although there are many factors to prolonged endurance exercise fatigue, the apparent primary mechanism for this improved performance is an enhanced maintenance of plasma glucose (prevention of hypoglycemia) resulting in augmented CHO_{oxid} by the muscles. Recent data (Table 2) has clearly shown that a positive dose–response between increasing CHO intake rates being correlated to subsequent CHO_{oxid} (Smith et al. 2010) and performance (Smith et al. 2010, 2013; Watson et al. 2012). It is thought that the rate limiting step to exogenous CHO_{oxid} is at the level of the GI tract because of the intestinal CHO transport mechanisms; specifically the activity of the sodium-dependent glucose cotransporter 1 (SGLT1) transporter for glucose and the GLUT-5 transporter for fructose (Jeukendrup 2010).

Multi-transportable CHO: glucose:fructose (GLU:FRU) blends

In exercise situations of greater than 60 min, several recent papers have evaluated the CHO_{oxid} and performance effects of a combined ingestion of a sports drink containing GLU:FRU or maltodextrin:fructose (MALT:FRU) blends, otherwise known as multi-transportable CHOs, since they utilize both the SGLT1 and GLUT5 intestinal transporters. A plethora of data have shown that during prolonged exercise (>2 h) with high CHO ingestion rates (>~60 to 70 g/h) of GLU:FRU or MALT:FRU blends, this pattern of

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Table 1. Effects of carbohydrate supplementation during exercise lasting less than 1 h on exercise performance or capacity.

Study	*n*	Subject type	Exercise and performance description/duration	CHO type: study-dependent variable	Mean CHO intake rate (g/h)	Performance effect vs. P	% Difference	Significant performance effect?
CHO orally consumed								
Anantaraman et al. 1995	5	Moderately trained males (3) and females (2)	Total cycling work done for 1-h TT at self-selected PO of ~90% $\dot{V}O_{2max}$	1. 10% GLU pre-exercise with P during (G/P); 2. GLU pre-exercise with GLU during (GLU/GLU); 3. P before and during (P/P)	1. 30 g/h; 2. 120 g/h; 3. 0 g/h	1. GLU/P = 619 kJ; 2. GLU/GLU = 599 kJ; 3. P/P = 560 kJ	7.0% to 11.0% vs. P/P	Yes
Below et al. 1995	8	Endurance-trained males	Cycling at 80% of $\dot{V}O_{2max}$ for 50 min followed by ~10-min TT	1. Large volume (1330 mL) of 6% (GLU+SUC); 2. small volume (200 mL) of 40% (GLU+SUC); 3. large volume (1330 mL); 4. Small volume (200 mL)	1. 79 g/h; 2. 79 g/h; 3. 0 g/h; 4. 0 g/h	1. 9.93 min; 2. 10.5 min; 3. 10.5 min; 4. 11.3 min	14.0% vs. P	Yes
Bonen et al. 1981	8 G; 8 P	Moderately trained males	Cycling at 80% $\dot{V}O_{2max}$ to exhaustion/group design (not crossover)	P vs. 20% GLU ingestion during exercise	112 g total (over 30 min)	26.1 min (GLU) vs. 29.9 min (P)	15.0% vs. P	No
Desbrow et al. 2004	9	Endurance-trained males	Total cycling work done for ~1-h TT at self-selected PO	P vs. 6% GLU ingestion during warm-up and during exercise	~60 g/h	62.3 min (GLU) vs. 62.4 min (P)	0.2% vs. P	No
el-Sayed et al. 1997	8	Endurance-trained males	Total cycling work done for ~1-h TT at self-selected PO	P vs. 8% GLU right before the TT	25 g/h	277 W (GLU) vs. 269 W (P)	3.0% vs. P	Yes
Jeukendrup et al. 1997	19	Moderately trained males (17) and females (2)	Cycling total amount of work (J) predicted to be a 1-h TT	P vs. 8% GLU solution	~75 g/h	58.74 min (GLU) vs. 60.15 (P)	2.4% vs. P	Yes
Jeukendrup et al. 2008	12	Endurance-trained males	Cycling 16-km TT (~25 min)	P vs. 8% GLU+SUC CHO solution	35 g total (over 30 min)	25.63 min (GLU+SUC) vs. 25.50 min (P)	−0.3% vs. P	No
Nicholas et al. 1995	9	Trained male soccer players	75 min of intermittent exercise (running/sprinting) followed by intermittent running to fatigue (~8 min)	P vs. 7% GLU consumed in 2 mL/kg every 15 min	~66 g/h	8.9 min (GLU) vs. 6.7 min (P)	3.3% vs. P	Yes
Powers et al. 1990	9	Endurance-trained males	85% $\dot{V}O_{2max}$ until fatigue (~40 min)	210 mL every 15 min of P vs. 7% GLU vs. water	~66 g/h	39.2 min (GLU) vs. 40.2 min (water) vs. 35.8 min (P)	−8.7% vs. P	No
Sugiura and Kobayashi 1998	8	Moderately trained males	90 min of exercise over 6 trials of 3 continuous (65% $\dot{V}O_{2max}$; CONT) and 3 intermittent (65% $\dot{V}O_{2max}$ with 30-s sprints every 2.5 min; INT) with an all-out 40-s Wingate performance test	Halfway through trial subjects received 250 mL of either 1. 20% GLU; 2. 20% FRU; 3. P	~33 g/h	CONT: 614 W (GLU) vs. 574 W (P); INT: 629 W (GLU) vs. 596 W (P)	6.9% (GLU/CONT); 5.5% (GLU/INT) vs. P	Yes

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Table 1 (*continued*).

Study	*n*	Subject type	Exercise and performance description/duration	CHO type: study-dependent variable	Mean CHO intake rate (g/h)	Performance effect vs. P	% Difference	Significant performance effect?
CHO mouthwash only								
Beaven et al. 2013	12	Recreationally trained males	5 × 6-s sprints with 24-s recovery on a cycle ergometer	25 mL of 6% GLU or noncaloric P mouth rinse for 5 s prior to each sprint	na	Sprint 1: GLU +39 W vs. P	na	Yes
Beelen et al. 2009	14	Endurance-trained males	Total cycling work done for ~1-h TT at self-selected PO	25 mL of 6% GLU or noncaloric P mouth rinse for 5 s every 12.5% of the TT (5 times, ~12 min) after a standardized breakfast	na	68.14 min (GLU) vs. 67.52 min (P)	–0.9% vs. P	No
Carter et al. 2004*a*	9	Endurance-trained males (7) and females (2)	Total cycling work done for ~1-h TT at self-selected PO	25 mL of 6% GLU or noncaloric P mouth rinse for 5 s every 12.5% of the TT (5 times, ~12 min)	na	59.57 min (GLU) vs. 61.36 min (P)	3.0% vs. P	Yes
Chambers et al. 2009	8	Endurance-trained males	Total cycling work done for ~1-h TT at self-selected PO	25 mL of 6% GLU or noncaloric P mouth rinse for 5 s every 12.5% of the TT (5 times, ~12 min)	na	60.4 min (GLU) vs. 61.6 min (P)	2.0% vs. P	Yes
Fares and Kayser 2011	13	Recreationally trained for endurance (males)	60% W_{max} until exhaustion (~55 min) while morning fed and fasted	25 mL of 6% GLU or noncaloric P mouth rinse for 5 s every 10 min (5 times)	na	Fed: 56.6 min (GLU) vs. 54.7 min (P); fasted: 53.9 min (GLU) vs. 48.3 min (P)	Fed: 3.5% vs. P; fasted: 11.6% vs. P	Yes
Gam et al. 2013	10	Endurance-trained males	Time to complete 1000 kJ on a cycling ergometer as fast as possible (~65 min)	25 mL of 6% GLU or noncaloric P mouth rinse for 5 s every 10 min (5 times)	na	65.7 min (GLU) vs. 67.6 min (P)	2.9% vs. P	Yes
Lane et al. 2013	12	Endurance-trained males	Total cycling work done for 60-min TT at self-selected PO	20 mL of 10% maltodextrin (GLU) or noncaloric P mouth rinse for 10 s every 12.5% of the TT (8 times) in fasted and fed states	na	286 W (fed+GLU) vs. 281 W (fed+P) vs. 282 W (fasted+GLU) vs. 273 W (fasted+P)	1.8% vs. P in fed state; 3.4% vs P in fasted state	Yes
Painelli et al. 2011	12	Recreationally trained for strength (males)	Maximum strength testing (1RM) and 6 sets until failure at 70% of 1RM	25 mL of 6% GLU or noncaloric P mouth rinse for 10–15 s before every 1RM attempt	na	101 kg (GLU) vs. 101 kg (P)	0% vs. P	No
Pottier et al. 2010	12	Endurance-trained males	Time to complete ~975 kJ on a cycling ergometer as fast as possible (~60 min)	25 mL of 6% GLU or noncaloric P mouth rinse for 5 s every 10 min (5 times)	na	61.7 min (GLU) vs. 64.1 min (P)	3.9% vs. P	Yes
Rollo et al. 2008	10	Endurance-trained males	10-min warm-up at 60% $\dot{V}O_{2max}$ followed by 30-min treadmill running TT performance test (as far as possible in 30 min)	25 mL of 6% GLU or noncaloric P mouth rinse for 5 s (10 times) over warm-up and performance test	na	6584 m (GLU) vs. 6469 m (P)	1.7% vs. P	Yes
Rollo et al. 2010	10	Endurance-trained males	60-min treadmill running TT performance test (as far as possible in 60 min)	25 mL of 6% GLU or noncaloric P mouth rinse for 5 s at start and every 15 min (4 times)	na	14298 m (GLU) vs. 14086 m (P)	1.5% vs. P	Yes

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Table 1 (*concluded*).

Study	*n*	Subject type	Exercise and performance description/duration	CHO type: study-dependent variable	Mean CHO intake rate (g/h)	Performance effect vs. P	% Difference	Significant performance effect?
Sinclair et al. 2013	11	Recreationally trained males	30-min cycling performance TT test (as far as possible in 30 min)	25 mL of 6% GLU or noncaloric P mouth rinse for 5 s or 10 s at start and every 6 min (4 times)	na	155.6 W (10 s) vs. 152.4 W (5 s) vs. 145.7 W (P)	10 s: 6.8% vs. P; 5 s: 4.6% vs. P	Yes
Whitham and McKiney 2007	7	Recreationally trained males	15 min running warm-up at 65% $\dot{V}O_{2max}$ followed by 35 min treadmill running TT performance test (as far as possible in 45 min)	~25 mL of 6% GLU or 3% unsweetened lemon juice (P) mouth rinse for 5 s at start and every 6 min (10 times)	na	9333 m (GLU) vs. 9309 m (P)	0.3% vs. P	No

Note: CHO, carbohydrate; FRU, fructose; GLU, glucose; P, placebo; PO, power output; TT, time trial; 1RM, one-repetition maximum; SUC, sucrose; $\dot{V}O_{2max}$, maximal oxygen uptake; W_{max}, wattage maximum during $\dot{V}O_{2max}$ testing.

CHO ingestion results in ~20% to 50% higher CHO_{oxid} compared with the ingestion of a drink containing an isocaloric amount of glucose or maltodextrin only (Jeukendrup 2010). This increased CHO_{oxid} has shown an increase in prolonged endurance performance as compared with isocaloric glucose (Currell and Jeukendrup 2008; Triplett et al. 2010; O'Brien, W.J., and Rowlands 2011, 2013). However, intake rates of greater than 60–70 g/h of CHO are needed to show the added benefit of using GLU:FRU blends. A recent study confirmed this hypothesis, in that when a GLU:FRU blend was consumed at a rate of less than 60 g/h (thus, not saturating the SGLT1 transporter), the resultant CHO_{oxid} as compared with glucose alone was the same (Hulston et al. 2009). Therefore, GLU:FRU blends are equivalent to glucose only supplementation when intake rates are <60 g/h. These CHO_{oxid} results have also been shown to be consistent between males and females (Wallis et al. 2006), in hot and ambient temperatures (Carter et al. 2003), and similar between cycling and running (Pfeiffer et al. 2009).

CHO supplementation recommendations and performance intervention studies

Given the unique physiological mechanism(s) in place, which underlie the performance benefit of CHO intake during exercise, the following section will be segmented according to Table 3. This table outlines recommended CHO intake rates and CHO type (blend of CHO) for distinctive exercise durations. The physiological rationale for breaking the exercise continuum into these 3 temporal segments are based on the assumption that CHO-induced performance improvements in exercise durations of <1 h are primarily CNS driven. Improvements in 1 to 2 h of performance may be a combination of CNS stimulation and CHO fuel provision to maximize CHO_{oxid}. While the primary mechanism of exercise durations of >2 h, where muscle glycogen is certainly limiting, is CHO delivery and CHO_{oxid}. The recommended CHO intake ranges have been adapted from the 2010 International Olympic Committee (IOC) Nutrition Consensus meeting (Jeukendrup 2011) to reflect recent field data (Stellingwerff and Jeukendrup 2011; Pfeiffer et al. 2012; Stellingwerff 2012), suggesting large intake ranges that athletes tolerate (GI tolerance) to maximize individual performance across varying modes of exercise (cycling and running). Furthermore, these CHO recommendations highlight the fact that high intake rates of multi-transportable CHOs are required to induce maximal CHO_{oxid} and performance outcomes (Smith et al. 2010, 2013).

Figure 1 highlights the percent increase in TT performance when comparing CHO intake with placebo (generally water with artificial sweetener to blind subjects) of all studies over exercise durations of <1 h, 1 to 2 h, and >2 h, respectively. There was a significant (p = 0.0036) correlative relationship between increasing total exercise time and the subsequent percent increase in performance with CHO intake versus placebo. Perhaps, not surprisingly, as fuel (glycogen) becomes more and more limiting during prolonged exercise situations, the positive performance effect of CHO intake becomes larger. This is demonstrated in studies lasting longer than 2 h, showing an averaged of single source CHO and multi-transportable CHO of 6.2% ± 4.3% increase in performance compared with <1-h exercise durations that show only 2.6% ± 3.3%. The 1- to 2-h exercise durations showed an intermediate increase of 4.9% ± 4.9% (Fig. 1). The consistency of the performance benefit across studies also supports this effect of CHO having greater performance impacts during longer exercise durations (>2 h) with 95% of studies (19 of 20 studies) demonstrating a statistically significant performance benefit of CHO intake.

Less than 1 h of exercise

As mechanistically described above, just the presence of CHO in the mouth (i.e., zero consumption, zero calories) can serve to

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Table 2. Dose–response relationship between varying amounts of CHO supplementation and exercise performance or capacity.

Study	*n*	Subject type	Exercise and performance description/duration	CHO type: study-dependent variable	Mean CHO intake rate (g/h)	Performance effect vs. P	% Difference	Significant performance effect?
Smith et al. 2010	12	Recreationally trained for endurance (males)	Cycling at 77% $\dot{V}O_{2max}$ for 2 h followed by a 20-km TT	P vs. 15 g/h (15CHO), 30 g/h (30CHO) and 60 g/h (60CHO) as a 250-mL GLU solution every 15 min during exercise	P: 0 g/h; 15CHO: 15 g/h; 30CHO: 30 g/h; 60CHO: 60 g/h	34.7 min (60CHO) vs. 35.0 min (30CHO) vs. 35.2 min (15CHO) vs. 36.4 min (P)	60CHO: 4.8% vs. P; 30CHO: 4.0% vs. P; 15CHO: 3.4% vs. P	Yes (all trials vs. P)
Smith et al. 2013	51	Endurance-trained males	Cycling at 95% of the PO that elicits a 4-mmol/L blood lactate concentration for 2 h immediately followed by 20-km TT	0, 10, 20, 30, 40, 50, 60, 70, 80, 90, 100, 110, and 120 g/h CHO (1:1:1 GLU–FRU–maltodextrin) per hour during the 2-h constant load ride at a fluid intake rate of 1 L/h	0, 10, 20, 30, 40, 50, 60, 70, 80, 90, 100, 110, and 120 g/h	Raw data not given	1.0%, 2.0%, 3.0%, 4.0%, 4.7%, 4.0%, and 3.3% increase in perf vs. P for 19, 31, 48, 78, 108, and 120 g/h, respectively	Yes
Watson et al. 2012	24	Recreationally trained for endurance (males)	2 groups of 12 subjects cycling at 70% $\dot{V}O_{2max}$ until exhaustion in cool (n = 12; 10 °C) or 60% $\dot{V}O_{2max}$ until exhaustion in warm conditions (n = 12; 30 C)	P vs. 2% (2CHO), 4% (4CHO), or 6% (6CHO) solutions (SUC, GLU, and FRU in a ratio of 50:25:25) at start and every 10 min during exercise	COOL: P, 0 g/h; 2CHO, ~15 g/h; 4CHO, ~31 g/h; 6CHO, ~46 g/h. WARM: P, 0 g/h; 2CHO, ~16 g/h; 4CHO, ~33 g/h; 6CHO, ~50 g/h	COOL: 122.4 min (6CHO) vs. 121.0 min (4CHO) vs. 109.2 min (2CHO) vs. 102.6 min (P). WARM: 112.0 min (6CHO) vs. 105.5 min (4CHO) vs. 104.1 min (2CHO) vs. 94.5 min (P)	COOL: 6CHO, 19.3% vs. P; 4CHO, 17.9% vs. P; 2CHO, 6.4% vs. P. WARM: 6CHO, 18.5% vs. P; 4CHO, 11.6% vs. P; 2CHO, 10.2% vs. P	Yes (4CHO and 6CHO vs. 2CHO and P)

Note: CHO, carbohydrate; FRU, fructose; GLU, glucose; P, placebo; PO, power output; TT, time trial; SUC, sucrose; $\dot{V}O_{2max}$, maximal oxygen uptake.

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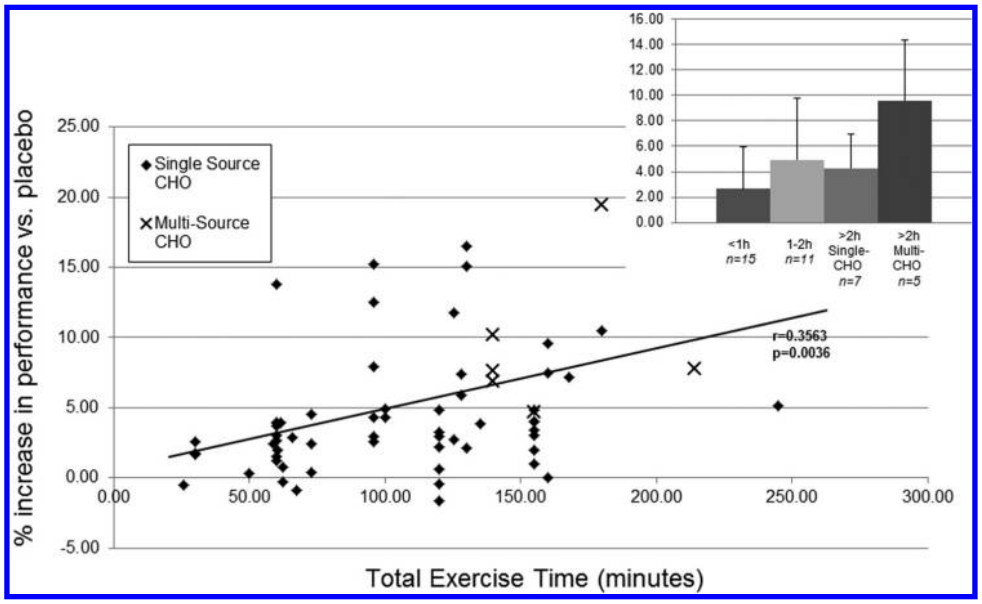
Table 3. CHO intake recommendations based on the duration of sporting event or training bout. Data is summarized from n = 555 subjects from 56 different studies.

Event time duration	General amount of CHO required for optimal performance while minimizing negative energy balance and GI issues	Recommended intake	CHO type	Single source CHO (e.g., GLU or maltodextrin)	Multiple transportable CHOs (e.g., GLU:FRU combo)
<1 h	Very small amounts	Mouth rinse to minimal amounts (up to 30 g/h)	Most forms of CHO	●	●
1–2 h	Small to moderate amounts	30 to 60 g/h	Most forms of CHO	●	●
>2 h	Moderate to large amounts	40 to 110 g/h	CHOs that are rapidly oxidized (e.g. GLU or maltodextrin), at intake rates above 60 g/h, use multiple transportable CHOs	○ (if <60 g/h)	●

Note: When absolute exercise intensity is low (<4 kcal/min) these recommendations should be scaled back. Large ranges of CHO intake recommendations are given to reflect that individual athletes have individual GI tolerance to fluid and CHO intake during exercise (Stellingwerff and Jeukendrup 2011; Pfeiffer et al. 2012). ●, Ideal/optimal for maximizing performance outcomes and minimizing negative GI side effects; ○, less than ideal, but better than nothing. CHO, carbohydrate; FRU, fructose; GI, gastrointestinal; GLU, glucose.

Fig. 1. Overview of all studies examining carbohydrate (CHO) intake and exercise performance versus a noncaloric placebo. Data in Fig. 1 represents studies undertaking time trial (TT) protocols only, with all time to exhaustion trials omitted. Percent change calculations were undertaken with all data converted to minutes for each trial/treatment intervention. With studies undertaking a set amount of work (e.g., kJ), conversions were made to wattage outcomes, based on the average reported subject body mass, so that the placebo trial exactly equalled the TT duration (min) with the exact conversions made to the treatment trial to compare all effects in minutes.



enhance physical performance. In exercise situations of less than ~60 min, where muscle glycogen is not limiting, the type and (or) amount of CHO and its ability to be absorbed and oxidized appears to be completely irrelevant to enhancing exercise performance. Accordingly, several studies (n = 16) have found that CHO supplementation or oral exposure (CHO mouthwash) can improve performance of less than 1 h in duration (Table 1). Some of the inconsistencies in the data might have to do with the amount of oral exposure (time duration) to CHO to trigger the brain reward and motor centres. A recent study seems to support this, as Sinclair et al. (2014) found a slightly greater performance effect with a 10-s CHO mouthwash (+6.8%) versus just a 5-s mouthwash (+4.6%). So, perhaps some of the previous studies' findings of no effect, regardless of whether CHO was consumed or not, just did not expose the oral receptors long enough, or with enough frequency, to induce a performance benefit. Another confounding factor is whether or not subjects are overnight fasted or morning fed prior to their experimental trial. Interestingly, Beelen et al. did not find any effect of CHO mouthwash when subjects were given a standardized breakfast (Beelen et al. 2009). In direct contrast, Fares and Kayser (2011) showed a significant performance effect of CHO mouthwash after a morning breakfast (Fares and Kayser 2011; Table 1). Furthermore, Lane et al., using a Latin-square design, showed an additive effect of being fed before the exercise trial with mouth rinsing with CHO (Lane et al. 2013). Of note, the effect of mouth rinsing with CHO was more pronounced in the fasted trial (+3.4%) compared with the fed trial (+1.8%). So the effects of CHO mouthwash on performance require more research to fully elucidate the mechanisms involved and whether or not it is likely to offer a performance benefit to athletes completing high-intensity endurance exercise lasting ~1 h.

1 to 2 h of exercise

Table 4 outlines the 18 studies where exercise performance or capacity was assessed over 1 to 2 h of exercise (either a TT or with

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Table 4. Effects of CHO supplementation during exercise lasting 1 to 2 h on exercise performance or capacity.

Study	*n*	Subject type	Exercise and performance description/duration	CHO type: study-dependent variable	Mean CHO intake rate (g/h)	Performance effect vs. P	% Difference	Significant performance effect?
Bjorkman et al. 1984	8	Recreationally trained for endurance (males)	Cycling at 68% $\dot{V}O_{2max}$ until exhaustion	P vs. 7% GLU vs. 7% FRU	~53 g/h	137 min (GLU) vs. 116 min (FRU) vs. 116 min (P)	GLU: 18.1% vs. FRU+P	Yes (GLU vs. FRU and P)
Davis et al. 1988*a*	15	Endurance-trained males	2 consecutive 60-min cycling bouts at 60% $\dot{V}O_{2max}$, each followed time to complete a 270-revolution TT (~3 min) immediately after and 20 min after	275 mL every 20 min of water P vs. 6% GLU (LC) vs. 12% GLU (HC)	LC: ~50 g/h; HC: ~100 g/h	153.9 s (LC) vs. 158.7 s (HC) vs. 163.7 s (P)	LC: 6.4% vs. P; HC: 3.2% vs. P (strong positive trend)	No
Flynn et al. 1987	8	Endurance-trained males	Total cycling work done for 2-h TT at self-selected PO	150 mL prior to and every 20 min during exercise of: 5% GLU (MG); 5% GLU + 5% FRU (MF); 7.7% GLU + 2.3% HFCS (MHF; >60% FRU)	MG: 23 g/h; MF: 45 g/h; MHF: 45 g/h	184 W (MG) vs. 178 W (MF) vs. 189 W (MHF) vs. 186 W (P)	MG: −1.1% vs. P; MF: −4.3% vs. P; MHF: 1.6% vs. P	No
Maughan et al. 1989	6	Recreationally trained for endurance (males)	4 repeated trials of running at 70% $\dot{V}O_{2max}$ to exhaustion	100 mL prior to exercise and 100 mL every 10 min throughout 1. 4% GLU (LGLU); 2. 34% GLU + 15% FRU (GLU+FRU); 3. 36% GLU (HGLU); 4. 34% FRU + 2% GLU (HFRU) vs. water P[a]	1. LGLU: 29.3 g/h; 2. GLU+FRU: 240 g/h; 3. HGLU: 262 g/h; HFRU: 229 g/h; 4. 0 g/h (P)	90.8 min (LGLU) vs. 79.5 min (GLU+FRU) vs. 79.0 min (HGLU) vs. 65.6 min (HFRU) vs. 70.2 min (P)	LGLU: 29.3% vs. P; GLU+FRU: 12.5% vs. P; HGLU: 12.5% vs. P; HFRU: −6.5% vs. P	Yes (LGLU vs. P); no for rest of comparisons
Maughan et al. 1996	12	Recreationally trained for endurance (males)	Cycling at 70% $\dot{V}O_{2max}$ to exhaustion	100 mL prior to exercise and 100 mL every 10 min throughout 2.3% GLU (LGLU); 3.1% GLU (HGLU); vs. P	LGLU: 16 g/h; HGLU: 22 g/h	110 min (LGLU) vs. 107 min (HGLU) vs. 93 min (P)	LGLU: 18.3% vs. P; HGLU: 15.1% vs. P	Yes
McConell et al. 2000	13	Endurance-trained males	Cycling at 83% $\dot{V}O_{2max}$ to exhaustion	P vs. 6% GLU solution	81 g/h	68.1 min (GLU) vs. 69.6 min (P)	−2.2% vs. P	No
Mitchell et al. 1988	8	Endurance-trained males	84 min of cycling at 70% $\dot{V}O_{2max}$ followed by 12-min TT	P vs. 5% CHO (5CHO) vs. 6% CHO (6CHO) vs. 7.5% CHO (7.5CHO) solutions	5CHO: 33.5 g/h; 6CHO: 39.4 g/h; 7.5CHO: 50.1 g/h	1.98NM (5CHO) vs. 1.96NM (6CHO) vs. 2.05NM (7.5CHO) vs. 1.83NM (P)	5CHO: 7.1% vs. P; 6CHO: 6.6% vs. P; 7.5CHO:7.1% vs. P	Yes
Mitchell et al. 1989	10	Endurance-trained males	105 min of cycling at 70% $\dot{V}O_{2max}$ followed by 15-min TT	P vs. 6% CHO (6CHO) vs. 12% CHO (12CHO) vs. 18% CHO (18CHO) solutions	6GLU: 37 g/h; 12GLU: 74 g/h; 18GLU: 111 g/h	213 kJ (6CHO) vs. 228 kJ (12CHO) vs. 217 kJ (18CHO) vs. 201 kJ (P)	6CHO: 6% vs. P; 12CHO: 13.4% vs. P; 18CHO: 8.0% vs. P	Yes (12CHO vs. P); no for rest of comparisons

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Table 4 (*concluded*).

Study	*n*	Subject type	Exercise and performance description/duration	CHO type: study-dependent variable	Mean CHO intake rate (g/h)	Performance effect vs. P	% Difference	Significant performance effect?
Murray et al. 1987	13	Untrained males	~90 min of intermittent cycling at 55%–65% $\dot{V}O_{2max}$ followed by a ~6-min TT sprint	P vs. 5% GLU (5CHO) vs. 4% SUC + 2% GLU (6CHO) vs. 5% GLU + 2% FRU (7CHO) solutions	5CHO: 24 g/h; 6CHO: 29 g/h; 7CHO: 34 g/h	400 s (5CHO) vs. 384 s (6CHO) vs. 375 s (7CHO) vs. 432 s (P)	5CHO: 8.0% vs. P; 6CHO: 12.5% vs. P; 7CHO: 15.2% vs. P	Yes (6CHO and 7CHO vs. P); no for 5CHO
Murray et al. 1989*b*	12	Moderately trained males (7) and females (5)	3 × 20-min cycling at 65% $\dot{V}O_{2max}$ with 5-min rest followed by a ~13-min TT sprint	P vs. 6% SUC (6CHO) vs. 8% SUC (8CHO) vs. 10% SUC (10CHO) solutions	6CHO: 31 g/h; 8CHO: 41 g/h; 10CHO: 52 g/h	13.03 min (6CHO) vs. 13.30 min (8CHO) vs. 13.57 min (10CHO) vs. 13.62 min (P)	6CHO: 4.5% vs. P; 8CHO: 2.4% vs. P; 10CHO: 0.4% vs. P.	Yes (6CHO vs. P); no for rest of comparisons
Murray et al. 1989*a*	12	Untrained males	~115 min of intermittent cycling at 65%–80% $\dot{V}O_{2max}$ followed by a ~7-min TT sprint	6% GLU (GLU) vs. 6% SUC (SUC) vs. 6% FRU (FRU) solutions[b]	38 g/h	424 s (GLU) vs. 419 s (SUC) vs. 488 s (FRU)	GLU: 15.1% vs. FRU; SUC: 16.5% vs. FRU	Yes (GLU and SUC vs. FRU)
Neufer et al. 1987	10	Endurance-trained males	45 min of cycling at 77% $\dot{V}O_{2max}$ followed by total work done during a ~15-min TT	P vs. 45 g of liquid CHO (LCHO) vs. 45 g of solid CHO bar (SCHO)	45 g/h	175204NM (LCHO) vs. 176013 (SCHO) vs. 159143NM (P)	LCHO: 10.1% vs. P; SCHO: 10.6% vs. P	Yes
Too et al. 2012	11	Endurance-trained males	80 min of running at 80% $\dot{V}O_{2max}$ followed by a 5-km TT	P vs. raisins (R) vs. commercial sport chews/blocks (B) at the start and every 20 min during exercise	~65 g/h	20.6 min (R) vs. 20.7 min (B) vs. 21.6 min (P)	R: 4.9% vs. P; B: 4.3% vs. P	Yes
Tsintzas et al. 1993	7	Endurance-trained males	30-km running road race	P vs. 5.5% CHO (GLU polymer+GLU+FRU)	50 g/h (first hour only)	128.3 min (CHO) vs. 131.2 min (P)	CHO: 2.1% vs. P	Yes
Tsintzas et al. 1996*a*	8	Endurance-trained males	Running at 70% $\dot{V}O_{2max}$ until exhaustion	P vs. 5.5% CHO (GLU+FRU)	~41 g/h	132.4 min (CHO) vs. 104.3 min (P)	CHO: 2.3% vs. P	Yes
Tsintzas et al. 1996*b*	11	Recreationally trained for endurance (males)	Running at 70% $\dot{V}O_{2max}$ until exhaustion	P vs. 5.5% CHO (5CHO) vs. 6.9% CHO (6CHO; first hour only for CHO treatments, water thereafter)	5CHO: ~55 g/h; 6CHO: ~69 g/h	124.5 min (5CHO) vs. 121.4 min (6CHO) vs. 109.6 min (P)	5CHO: 13.6% vs. P; 6CHO: 10.8% vs. P	Yes
Wilber and Moffatt 1992	10	Endurance-trained males	Running at 80% $\dot{V}O_{2max}$ until exhaustion	P vs. 7% GLU	41 g/h	115.4 min (GLU) vs. 92.0 min (P)	GLU: 25.4% vs. P	Yes
Zachwieja et al. 1992	8	Endurance-trained males	105 min of cycling at 70% $\dot{V}O_{2max}$ followed by total work done during a ~15-min TT	P vs. 4% GLU + 6% FRU (GLU+FRU)	63 g/h	264 W (GLU+FRU) vs. 242 W (P)	GLU+FRU: 9.1% vs. P	Yes

Note: CHO, carbohydrate; FRU, fructose; GI, gastrointestinal; GLU, glucose; HFCS, high-fructose corn syrup; NM, no measurement; P, placebo; PO, power output; TT, time trial; SUC, sucrose; $\dot{V}O_{2max}$, maximal oxygen uptake.

[a]Reported adverse GI symptoms in all treatments except LGLU.

[b]Reported adverse GI symptoms in FRU-alone treatment.

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Table 5. Effects of CHO supplementation during exercise lasting longer than 2 h on exercise performance or capacity.

Study	*n*	Subject type	Exercise and performance description/duration	CHO type: study-dependent variable	Mean CHO intake rate (g/h)	Performance effect vs. P	% Difference	Significant performance effect?
CHO vs. P								
Angus et al. 2000	8	Endurance-trained males	Time to complete 35 kJ/kg on cycle ergometer (~100-km TT)	P vs. 6% CHO (GLU+SUC) ingestion during exercise	60 g/h	166 min (CHO) vs. 178 min (P)	7.2% vs. P	Yes
Carter et al. 2003	8	Endurance-trained males	Cycling at 60% (LOW) and 73% (HI) $\dot{V}O_{2max}$ to exhaustion	P vs. 6% CHO (GLU) ingestion during exercise at both LOW and HI	~65 g/h	145.6 min (GLU) vs. 123.1 min (P)	18.3% vs. P	Yes
Coggan and Coyle 1987	7	Endurance-trained males	Cycling at 73% $\dot{V}O_{2max}$ to exhaustion (~170 min), followed by 20-min recovery and again cycling at 73% $\dot{V}O_{2max}$ to exhaustion	P vs. 3 g/kg GLU (~210 g GLU) consumed during 20 min recovery	na (taken between exercise bouts)	26 min (GLU) vs. 10 min (P)	160% vs. P	Yes
Coyle et al. 1983	10	Endurance-trained males	Cycling at 74% $\dot{V}O_{2max}$ until exhaustion	P vs. 7% GLU	~51 g/h	157 min (GLU) vs. 134 min (P)	17.2% vs. P	Yes
Coyle et al. 1986	7	Endurance-trained males	Cycling at 71% $\dot{V}O_{2max}$ until exhaustion	P vs. GLU polymer (GLU)	~114 g/h	4.02 h (GLU) vs. 3.02 h (P)	33.1% vs. P	Yes
Davis et al. 1988*b*	19	Endurance-trained males	Cycling at 75% $\dot{V}O_{2max}$ for 130 min, followed by ~30-min rest, followed by 30-min TT at ~75% $\dot{V}O_{2max}$	P vs. 2.5% CHO (LCHO) vs. 6% CHO (HCHO) as SUC+GLU	LCHO: 23 g/h; HCHO: 56 g/h	31.3 min (HCHO) vs. 31.9 min (LCHO) vs. 34.3 min (P)	HCHO: 9.6% vs. P; LCHO: 7.5% vs. P	Yes (HCHO vs. P)
Fielding et al. 1985	9	Recreationally trained for endurance (males)	240-min cycling followed by a sprint at 100% $\dot{V}O_{2max}$ to exhaustion	P vs. 5% CHO solution (SUC)	21.5 g/h	121 s (SUC) vs. 81 s (P)	49.4% vs. P	Yes
Hargreaves et al. 1984	10	Endurance-trained males	4 h of intermittent intensity cycling followed by a sprint at 100% $\dot{V}O_{2max}$ to exhaustion	P vs. candy bar (C) having 43 g SUC, 6 g fat, and 3 g protein	43 g/h	127 s (C) vs. 87 s (P)	46.0% vs. P	Yes
Ivy et al. 1983	10	Healthy males	Walking at 45% $\dot{V}O_{2max}$ until exhaustion	P vs. 20% GLU polymer	24 to 29 g/h	299 min (C) vs. 268 min (P)	11.6% vs. P	Yes
Madsen et al. 1996	9	Endurance-trained males	100-km cycling TT	P vs. 5% CHO solution (CHO)	66 g/h	160 min (CHO) vs. 160 min (P)	0%	No
McConell et al. 1996	8	Endurance-trained males	2 h of cycling at 70% $\dot{V}O_{2max}$ followed by total work done over a 15-min TT	P vs. 7% CHO solution (CHO)	79 g/h	268 kJ (CHO) vs. 242 kJ (P)	10.7% vs. P	Yes
Wright et al. 1991	9	Endurance-trained males	Cycling at 70% $\dot{V}O_{2max}$ until exhaustion	P vs. 8% CHO (5%GLU + 3%SUC) after both a 3- and 10-h pre-exercise fast	~40 g/h	3-h fast: 289 min (CHO) vs. 237 min (P); 10-h fast: 266 min (CHO) vs. 201 min (P)	3 h fast: 21.9% vs. P/10 h fast: 32.3% vs. P	Yes

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Table 5 (*concluded*).

Study	*n*	Subject type	Exercise and performance description/duration	CHO type: study-dependent variable	Mean CHO intake rate (g/h)	Performance effect vs. P	% Difference	Significant performance effect?
GLU:FRU CHO combinations vs. GLU alone								
Currell and Jeukendrup 2008	8	Endurance-trained males	Cycling at 55% W_{max} (~65% $\dot{V}O_{2max}$) for 2 h followed by a total work done in ~1-h TT	P vs. GLU vs. GLU:FRU (2:1 ratio)	108 g/h	3367 s (GLU:FRU) vs. 3641 s (GLU) vs. 4022 s (P)	GLU:FRU: 19.5% vs. P/GLU: 8.1% vs. P/GLU:FRU: 10.5% vs. GLU	Yes
Langenfeld et al. 1994	14	Endurance-trained males	128-km cycling time trial	P vs. 7% CHO (5% maltodextrin + 2% FRU)	37 g/h	241.0 min (CHO) vs. 253.2 min (P)	CHO: 5.1% vs. P	Yes
O'Brien and Rowlands 2011	10	Endurance-trained males	Cycling at 50% W_{max} for 150 min immediately followed by an incremental test to exhaustion	P vs. 2:1 GLU:FRU (2 to 1) vs. 1.25:1 GLU:FRU (1.25 to 1) vs. 0.8:1 GLU:FRU (0.8 to 1)[a]	108 g/h	545 s (2 to 1) vs. 594 s (1.25 to 1) vs. 578 s (0.8 to 1) vs. 549 s (P)	2 to 1: −0.7% vs. P; 1.25 to 1: 8.2% vs. P; 0.8 to 1: 5.3% vs. P	Yes (for 1.25 to 1 and 0.8 to 1)
O'Brien et al. 2013	12	Endurance-trained males	Cycling at 57% W_{max} for 2 h followed by 10 performance sprints (~2 min each sprint with ~5-min recovery)	P vs. 2:1 GLU:FRU (2 to 1) vs. 1.25:1 GLU:FRU (1.25 to 1) vs. 0.8:1 GLU:FRU (0.8 to 1)[a]	108 g/h	294 W (2 to 1) vs. 303 W (1.25 to 1) vs. 296 W (0.8 to 1) vs. 275 W (P)	2 to 1: 6.9% vs. P; 1.25 to 1: 10.2% vs. P; 0.8 to 1: 7.6% vs. P	Yes (for all CHO vs. P)
Triplett et al. 2010	9	Endurance-trained males	100-km cycling TT on ergometer	GLU vs. GLU:FRU (1:1 ratio)	108 g/h	204 min (GLU:FRU) vs. 220 min (GLU)	GLU:FRU: 7.8% vs. GLU	Yes

Note: CHO, carbohydrate; FRU, fructose; GLU, glucose; HI, high intensity; LOW, low intensity; P, placebo; TT, time trial; SUC, sucrose; $\dot{V}O_{2max}$, maximal oxygen uptake; W_{max}, wattage maximum during $\dot{V}O_{2max}$ testing.

[a]No glucose-alone treatment.

a preload). Of the 18 studies, 83% (n = 15) showed a positive benefit of CHO intake on performances.

Greater than 2 h of exercise

It is generally accepted that the American College of Sports Medicine's (ACSM's) CHO intake recommendations (ACSM 2000; Sawka et al. 2007) for exercise 2 h or longer needs to be reexamined, as commented in the 2010 IOC Sports Nutrition Consensus meeting's paper on nutrition for endurance athletes (Jeukendrup 2011). Currently, the consensus statement on Nutrition and Athletic performance (published in 2000 and 2007 by ACSM (ACSM 2000; Sawka et al. 2007)) recommends the consumption of approximately 30–60 g/h at a CHO concentration of 4% to 8% for athletes during prolonged exercise. However, the majority of data for the review is prior to 2007, and based on single source CHO intake (mainly just glucose or maltodextrin alone). Given the long and demanding nature of performance when exercise durations are greater than 2 h, it should not be surprising that 16 of 17 studies have shown a significant performance benefit with an average percent increase in performance (either time or power outputs) of 6.2% ± 4.3% when subjects consume any type of carbohydrate source (Table 5). More recently, several studies provide strong evidence that for hard exercise bouts longer than 2 h, upwards of 90 g/h or more of >8% CHO solutions appear to be optimal, as long as they are comprised of multi-transportable CHOs (for reviews see Jeukendrup 2010, 2011). It should be duly noted, however, that individual recommendations for athletes should be tailored according to the athletes individual tolerance, which appears to be varied (Pfeiffer et al. 2012).

GLU:FRU combinations increase CHO oxidation and performance greater than glucose alone

Several studies have now shown that high intake rates (>70 g/h) of GLU:FRU blends during moderate-intensity, prolonged (>2 h) exercise results in ~8% improvement in endurance performance over both a 1-h TT (Currell and Jeukendrup 2008) and over 100 km of cycling (Triplett et al. 2010) compared with glucose alone, and 19.5% versus water (Table 5). Another research group has shown further increases in performance with GLU:FRU blends over multiple sprints after an endurance preload (O'Brien and Rowlands 2011; O'Brien et al. 2013).

Carbohydrate dose–performance response studies

Table 2 highlights the CHO dose–response studies that further solidify the link between CHO delivery, CHO_{oxid}, and performance. To date, the most comprehensive CHO dose–performance response study undertaken was a large-scale multi-center study by Smith et al. (2013). In this study, 51 endurance-trained cyclists or triathletes across 4 research sites completed 4 randomized treatments featuring a 2-h constant load ride at moderate intensity, followed by a 20-km TT. Thirteen different beverages (4 at each site) were tested, providing athletes 0, 10, 20, 30, 40, 50, 60, 70, 80, 90, 100, 110, and 120 g of CHO/h during the 2-h constant-load ride. The CHO given was a 1:1:1 glucose:maltodextrin:fructose blend. Results indicated incremental performance improvements of 1.0%, 2.0%, 3.0%, 4.0%, and 4.7% at 9, 19, 31, 48, and 78 g CHO/h, respectively, with diminishing performance enhancement seen at CHO levels >78 g/h. The optimal amount for performance (+4.7%) was 78 g/h, with a range of 68 to 88 g/h. However, even at 10 g/h, a 1.0% increase in performance was observed, showing that even a small amount of carbohydrate has the potential to positively impact performance.

Practical carbohydrate supplementation considerations

Athlete body mass (BM)

Recent data summarized from 9 individual studies (n = 63 subjects), from the same laboratory and under similar conditions, has

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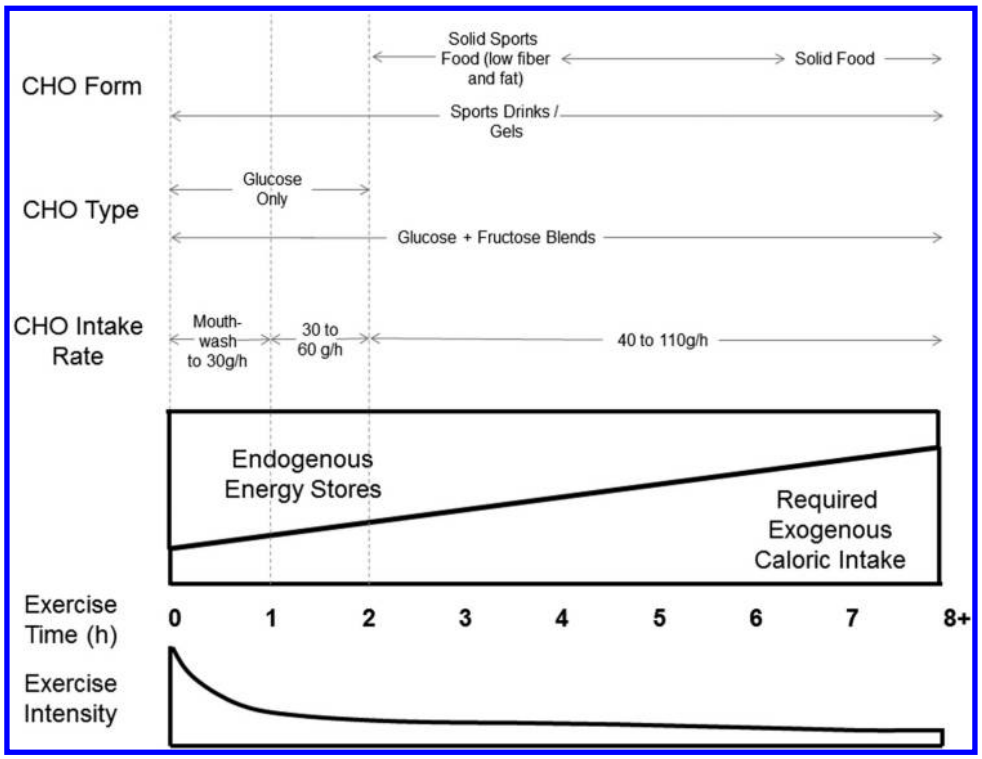
Fig. 2. Schematic overview of key recommendations highlighted in this review for carbohydrate (CHO) intake rate, CHO type, and form over varying exercise durations and intensities.



demonstrated no correlation between BM and CHO_{oxid} with the same CHO intake rates (Jeukendrup 2010). This suggests that the quality and quantity of CHO transporters, not the length of the GI tract or number of muscle GLUT4 transporters, ultimately dictates exogenous CHO delivery and CHO_{oxid}. Therefore, unlike daily CHO or carbohydrate loading recommendations, which are adapted to individual BM because it scales to lean muscle tissue and total muscle glycogen contents, exercise CHO intake recommendations do not need to be adjusted for individual BM.

Individual GI tolerance

Data has shown a highly variable response in individual CHO_{oxid} (Jeukendrup 2010) and GI tolerance (Pfeiffer et al. 2012), with a between-subject coefficient of variation of measurement for CHO_{oxid} of ~15%–20% in well-controlled studies with the same CHO intake rates conducted in similar subjects (endurance trained males). Furthermore, ~15%–20% of endurance athletes have a chronic history of GI problems during exercise (Pfeiffer et al. 2012). It is thought that having a high uptake and oxidation efficiency of supplemented CHO beverages should reduce the accumulation of CHO in the GI tract and in turn reduce the potential for GI distress during exercise (Jeukendrup 2010). This point is not trivial given that minor GI distress is associated with negative endurance performance outcomes (Thorburn et al. 2006). Also, recent evidence in rodents suggests that these CHO transporters in the GI tract appear to be "trainable" (Margolskee et al. 2007; Lambert et al. 2008); in other words, repeated GI exposure to CHO can increase SGLT transporter density and enhance CHO uptake, which suggests greater GI transporter protein density. In support of this, a 4-week endurance training study featuring 2 groups that consumed either a high-CHO (~8.5 g CHO/(kg·day)) or a moderate-CHO (~5.3 g CHO/(kg·day)) diet, including ~100 g CHO/h training in the high-CHO group, showed significant 16% increase in CHO_{oxid} post-training in the high-CHO vs. low-CHO group (Cox et al. 2010). Interestingly, this study did not show differences in muscle GLUT4 concentrations, but suggested the role of the gut and its possible trainability in determining CHO_{oxid} rates as the primary mechanism for their finding. Practically speaking, each athlete will have a unique CHO and fluid intake "sweet spot" where they are able to absorb and oxidize the maximum amount of exogenous carbohydrate/fluids to improve endurance performance versus a mismatch of fluids and CHO, which will cause GI distress, resulting in decreased performance. It is likely that an individual's sweet spot for carbohydrate and fluid will be influenced by environmental conditions, exercise intensity, and exercise mode (running vs. cycling).

Summary

Figure 2 is a schematic overview of key recommendations highlighted in this review for CHO intake rate, CHO type, and form over varying exercise durations and intensities. For shorter duration exercise situations (<1 h) when exercise intensity is high, small amounts (mouthwashing to 30 g/h) of liquid CHO sources provides a convenient and practical option to elicit a performance benefit of CHO supplementation. CHO strategies should provide adequate oral exposure (~1.5 g in 25 mL for 5 to 10 s every 8 to 10 min of exercise) to stimulate the pleasure and reward centers of the brain. While the majority of studies (16 of 23) have shown that CHO supplementation improves exercise performance by 2.6% ± 3.3% during <1 h exercise situations, the challenge for athletes undertaking such activities will be to access liquid CHO sources regularly throughout the exercise bout. As the duration of exercise is increased (1–2 h), moderate amounts of CHO supplementation (30–60 g/h) consumed frequently throughout exercise appears to maximize the performance advantage of CHO supplementation. Given the intensity of the exercise, the opportunity for intake and the athlete's individual tolerance, liquid CHO sources are recommended. Of the 18 studies included in this review, 83% (n = 15) showed a positive benefit of CHO intake on performance during exercise situations of 1–2 h. An intermediate

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improvement (4.9% ± 4.9%) of CHO supplementation was observed in the studies included in this review.

As the exercise duration is extended beyond 2 h and exercise intensity is reduced, a greater variety of CHO foods and fluids can be included to meet high hourly CHO intake recommendations of 40 to 110 g/h. CHO supplementation during prolonged exercise will provide an alternate substrate to the active muscle and maintain high rates of CHO_{oxid}. A unique finding of this review was that the positive performance effect of CHO intake becomes larger during prolonged exercise situations. In studies lasting longer than 2 h, the average increase in performance of single-source CHO and multi-transportable CHO was 6.2% ± 4.3%. The type of CHO becomes an important consideration as high intake rates of multi-transportable CHOs are required to induce maximal CHO_{oxid} and performance outcomes in prolonged exercise situations. Ultimately, the amount of CHO consumed will be influenced by the athlete's individual tolerance, which appears both variable and trainable.

Taken together, this systematic review clearly demonstrates the positive performance impact that CHO consumption has on varying exercise durations. Furthermore, contemporary CHO and performance research, including dose–response data, CHO blends, and CHO mouthwash studies, showcase the complex mechanisms supporting these performance benefits — from peripheral exogenous energy provision to central cognitive benefits.

Conflict of interest statement

The authors have no conflicts of interest to declare.

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