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Carbohydrate Ingestion during Team Games Exercise

Current Knowledge and Areas for Future Investigation

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Abstract

There is a growing body of research on the influence of ingesting carbohydrate-electrolyte solutions immediately prior to and during prolonged intermittent, high-intensity exercise (team games exercise) designed to replicate field-based team games. This review presents the current body of knowledge in this area, and identifies avenues of further research. Almost all early work supported the ingestion of carbohydrate-electrolyte solutions during prolonged intermittent exercise, but was subject to methodological limitations. A key concern was the use of exercise protocols characterized by prolonged periods at the same exercise intensity, the lack of maximal- or high-intensity work components and long periods of seated recovery, which failed to replicate the activity pattern or physiological demand of team games exercise. The advent of protocols specifically designed to replicate the demands of field-based team games enabled a more externally valid assessment of the influence of carbohydrate ingestion during this form of exercise. Once again, the research overwhelmingly supports carbohydrate ingestion immediately prior to and during team games exercise for improving time to exhaustion during intermittent running.

While the external validity of exhaustive exercise at fixed prescribed intensities as an assessment of exercise capacity during team games may appear questionable, these assessments should perhaps not be viewed as exhaustive exercise tests *per se*, but as indicators of the ability to maintain high-intensity exercise, which is a recognized marker of performance and fatigue during field-based team games. Possible mechanisms of exercise capacity enhancement include sparing of muscle glycogen, glycogen resynthesis during low-intensity exercise periods and attenuated effort perception during exercise. Most research fails to show improvements in sprint performance during team games exercise with carbohydrate ingestion, perhaps due to the lack of influence of carbohydrate on sprint performance when endogenous muscle glycogen concentration remains above a critical threshold of ~200 mmol/kg dry weight. Despite the increasing number of publications in this area, few studies have attempted to drive the research base forward by investigating potential modulators of carbohydrate efficacy during team games exercise, preventing the formulation of optimal carbohydrate intake guidelines. Potential modulators may be different from those during prolonged steady-state exercise due to the constantly changing exercise intensity and frequency, duration and intensity of rest intervals, potential for team games exercise to slow the rate of gastric emptying and the restricted access to carbohydrate-electrolyte solutions during many team games.

This review highlights fluid volume, carbohydrate concentration, carbohydrate composition and solution osmolality; the glycaemic index of pre-exercise meals; fluid and carbohydrate ingestion patterns; fluid temperature; carbohydrate mouthwashes; carbohydrate supplementation in different ambient temperatures; and investigation of all of these areas in different subject populations as important avenues for future research to enable a more comprehensive understanding of carbohydrate ingestion during team games exercise.

1. Introduction

The ergogenic effects of ingesting carbohydrate-electrolyte solutions prior to and during prolonged (≥45 min) moderate to high-intensity (>75% maximal oxygen uptake [$\dot{V}O_{2max}$])[1] steady-state exercise (sub-maximal exercise requiring a constant power output and a stable heart rate [HR] and oxygen uptake [$\dot{V}O_2$])[2] have been known for several decades.[1,3] During steady-state cycling, exogenous carbohydrate ingestion appears to maintain euglycaemia and high carbohydrate oxidation rates, and during steady-state running it has been demonstrated to reduce net muscle glycogen breakdown in type I muscle fibres.[1] Carbohydrate ingestion can improve both exercise performance, defined as distance covered in a set time or the time to complete a set distance/amount of work,[4] and exercise capacity, defined as time to exhaustion at a fixed exercise intensity.[5]

The mean whole-game exercise intensity during adult field-based team games (soccer, rugby and field hockey) has been estimated at 70–80% $\dot{V}O_{2max,}$ similar to prolonged steady-state exercise,[1,6] and appears sufficient to promote significant muscle glycogen depletion,[7] although this is not a consistent finding.[8] Muscle glycogen availability during prolonged intermittent, high-intensity exercise (hereafter referred to as 'team games exercise') can influence work output, distance covered and sprinting frequency, particularly in the later stages of exercise.[7,9] Therefore, ingesting carbohydrate-electrolyte solutions during field-based team games may prove beneficial by attenuating performance decrements that can occur towards the end of a game. In their earlier review on fluid and carbohydrate replacement during intermittent exercise, Shi and Gisolfi[10] provided recommendations for the optimal carbohydrate concentration, composition and osmolality of a carbohydrate-electrolyte solution for use before and during team games exercise. Since this review, a large number of publications have specifically addressed the ingestion of carbohydrate-electrolyte solutions immediately prior to and during team games exercise, and an updated synthesis of current knowledge in this field is required.

The aim of this review is to present the current state of knowledge on carbohydrate ingestion immediately prior to and during laboratory and field exercise typical of field-based team games. Suggestions are provided for further research that would increase knowledge in this area in both breadth and depth.

2. Methodology

To locate articles focusing on the effect of carbohydrate supplementation on team games exercise performance and capacity, searches in MEDLINE (PubMed) were performed using the terms 'carbohydrate prolonged intermittent exercise', 'carbohydrate intermittent exercise', 'carbohydrate team games', 'carbohydrate endurance exercise', 'carbohydrate exercise capacity' and 'carbohydrate sprint performance'. For the influence of carbohydrate supplementation on mental function and skill performance, the following MEDLINE (PubMed) searches were performed: 'carbohydrate skill team games', 'carbohydrate shooting passing performance', 'carbohydrate skill performance', 'carbohydrate mental function team games', 'carbohydrate cognitive function exercise', 'carbohydrate effort perception exercise'. The 'related citations' service in PubMed was explored for each highlighted abstract to locate additional relevant articles. The reference list of each article was also hand searched for other appropriate studies. These searches yielded a total of 36 articles for the influence of carbohydrate on team games exercise performance and capacity, and 25 articles for mental function and skill performance. Searches were not date limited, as the total research output in this area is manageable without using this limitation and the authors wanted to retrieve the earliest papers in the field. Only studies related to soccer, rugby and field hockey were incorporated, leading to the exclusion of 27 articles. Studies using additional supplementations (i.e. carbohydrate with caffeine, carbohydrate with protein) that did not include a direct comparison between a carbohydrate-electrolyte solution and a placebo solution were excluded. Discussion of these articles would have shifted the focus of the review, which is solely on the effect of carbohydrate supplementation. Using this exclusion criterion, four articles were removed. This review focuses on the acute effects of carbohydrate supplementation in team games; therefore, studies that supplemented the first bolus of carbohydrate >1 hour prior to the start of exercise were discounted. As a result, three articles were removed. Articles investigating the influence of carbohydrate on immune function during team games exercise were incorporated into the discussion of the physiological and metabolic responses to team games exercise with carbohydrate supplementation, but the influence on immune function was not discussed. A sufficiently in-depth review of this literature is outside the aims of this article. Based on these criteria, a total of 21 articles were included in the discussion of team games exercise performance and capacity, and 11 in the discussion of mental function and skill performance.

3. Carbohydrate Supplementation Immediately before and during Prolonged Intermittent Exercise

The following sections discuss early research that supplemented carbohydrate during prolonged intermittent exercise atypical of team games activity, followed by the more recent body of work that attempted to utilize team games-specific protocols and practices. The influence of carbohydrate supplementation on mental function and skill performance, and on physiological and metabolic responses during team games exercise is also discussed.

3.1 Early Laboratory Work

All studies in this section were placebo controlled and are summarized in table I. This initial body of work demonstrated that (i) consuming carbohydrate-electrolyte solutions during prolonged intermittent exercise can significantly improve exercise performance and capacity; (ii) consuming carbohydrate-electrolyte solutions may significantly attenuate muscle glycogen utilization during prolonged intermittent exercise; (iii) solid carbohydrate is not significantly different from a carbohydrate-electrolyte solution in improving intermittent exercise capacity; and (iv) the efficacy of carbohydrate-electrolyte solutions during prolonged intermittent exercise may be influenced by the intensities at which exercise is performed. However, prevalent methodological issues must be discussed prior to interpreting these conclusions.

Murray et al.[11] and Coggan and Coyle[12] were among the first to study the effects of carbohydrate supplementation during prolonged intermittent exercise. It is unclear why Murray et al.[11] conducted their study in a high ambient temperature. A thermoneutral trial should have been included for comparison due to the possibility of increased glycogen breakdown in high ambient temperatures.[16-18] Although both protocols were intermittent, neither was consistent with the activity pattern or physiological demand of intermittent exercise 'in the field' due to the nature of the recovery provided, the lack of a maximal- or high-intensity component, the structured and prolonged duration of the workloads and the use of a cycle ergometer. However, at this early stage of study, the authors may have been more concerned with establishing a baseline of data using controlled research designs rather than maximizing external validity.

Research by Murray et al.[13] and Yaspelkis et al.,[14] while again supporting carbohydrate supplementation, is subject to similar methodological issues. The regimented and specifically timed exercise intensities, with no maximal work and long periods of seated recovery, did not accurately reflect the physiological demand of team games. Additionally, exercise performance and capacity was assessed using steady-state rather than intermittent exercise. Yaspelkis et al.[14] did not provide body mass (BM)-standardized volumes of the carbohydrate or placebo solutions, meaning subjects of lower BM received a larger relative carbohydrate intake. Furthermore, muscle biopsy data were not collected during the solid carbohydrate trial, preventing full data interpretation and hindering the ability to understand the mechanisms behind the improvement in exercise capacity.

The lack of improvement in intermittent exercise capacity with carbohydrate supplementation shown by Nassis et al.[15] is in contrast with the literature discussed to this point. As the authors stated, the protocol probably made large demands on muscle glycogen stores; therefore, it would be expected that carbohydrate ingestion would have improved exercise capacity. However, while the volume of fluid ingested during exercise was similar to most related studies (2 mL/kg BM), the lower pre-exercise bolus (3 mL/kg BM) facilitated a lower overall carbohydrate intake during the protocol than most related work. The total amount of carbohydrate ingested during the trial (~36 g/hour) was above the minimum intake of 16 g/hour that is required for performance enhancement,[1] but was notably lower than the recommended intake for maximizing carbohydrate delivery (60–70 g/hour).[19] Furthermore, the lower volume of fluid entering the stomach may have

Table I. Summary of early laboratory studies on the effects of carbohydrate (CHO) supplementation immediately before and during prolonged intermittent exercise on the exercise performance and capacity of adults[a]

Study	No. of subjects and training level	Protocol	Supplementation	Significant findings	Limitations
Murray et al.[11]	13 untrained	5×15 min cycle at 55–65% $\dot{V}O_{2max}$, 480 rev TT (33°C)	5% glucose polymer solution 6% glucose/fructose solution 7% glucose polymer/fructose solution 2 mL/kg BM during each recovery period	Similar physiological function between trials Significantly faster TT with 6% and 7% solutions	No thermoneutral trial Design of study protocol is not externally valid to demands of team sports training or competition
Coggan and Coyle[12]	7 endurance-trained cyclists	Alternating 15 min cycle at 65% and ~85% $\dot{V}O_{2max}$ to exhaustion	50% CHO (1 g/kg BM) solution at 10 min, 20% CHO (0.6 g/kg BM) solution every 30 min thereafter	Significantly higher intensity during third h of exercise 18% longer time to fatigue 19% more work completed	Design of study protocol is not externally valid to demands of team sports training or competition
Murray et al.[13]	12 (5 F) untrained	3×20 min cycle at 65% $\dot{V}O_{2max}$, 1200 rev TT	6%, 8% and 10% sucrose solution 2.5 mL/kg BM before exercise and during each recovery	Similar physiological function between trials Significantly faster TT with 6% solution	Design of study protocol is not externally valid to demands of team sports training or competition
Yaspelkis et al.[14]	7 endurance-trained cyclists	3.3 h intermittent (45–80% $\dot{V}O_{2max}$) cycle: 30 min at 45% $\dot{V}O_{2max}$ 6×16 min (8 min at 75%, 8 min at 45% $\dot{V}O_{2max}$) 12 min seated rest 5 min at 45%, 5 min at 60% $\dot{V}O_{2max}$ 9×6 min (3 min at 75%, 3 min at 45% $\dot{V}O_{2max}$) 12 min seated rest cycle at 80% $\dot{V}O_{2max}$ to exhaustion	Two trials: 180 mL of 10% CHO polymer solution every 20 min 25 g CHO bar every 30 min	Significantly reduced muscle glycogen use with CHO solution Significant increase in time to exhaustion in both trials No difference between liquid and solid CHO	Design of study protocol is not externally valid to demands of team sports training or competition Solutions not standardized to BM Muscle biopsies not taken during solid CHO trial
Nassis et al.[15]	9 endurance-trained runners	Repeated 15 sec run at 80% $\dot{V}O_{2max}$ for 60 min, 85% $\dot{V}O_{2max}$ for 60–100 min, 90% $\dot{V}O_{2max}$ from 100 min to exhaustion, separated by 10 sec slow running	6.9% CHO-E solution 3 mL/kg BM prior to exercise 2 mL/kg BM every 20 min during exercise	Similar physiological function between trials No difference in time to exhaustion	Design of study protocol is not externally valid to demands of team sports training or competition Volume of CHO ingested may be insufficient for improving exercise capacity Intensity of exercise during final period of exercise may have been too intense

a All studies were placebo controlled.

BM = body mass; **CHO-E** = CHO-electrolyte; **F** = females; **rev** = revolutions; **TT** = time trial; $\dot{V}O_{2max}$ = maximal oxygen uptake.

resulted in a suboptimal rate of gastric emptying (GE), possibly further attenuating the delivery of carbohydrate to the intestine. Therefore, carbohydrate may not have been systemically present in sufficient amounts to alter metabolism. This is supported by no significant between-trials difference in blood glucose concentration (with the exception of one timepoint), blood lactate concentration or respiratory exchange ratio (RER). However, due to the variable intensities of the protocol, RER may not have been a valid method of assessing metabolism. Buffering of H^+ ions produced during the high-intensity periods of the protocol leads to greater production of CO_2 requiring removal at the lungs, thereby over-inflating RER.[15] It is also possible that the exercise intensity in the final part of the protocol (90% $\dot{V}O_{2max}$) was too intense, possibly causing fatigue to occur as a result of factors other than glycogen availability, such as phosphocreatine depletion.[20,21] If so, this negates the goal of the study and may help to explain the result being somewhat out of step with other research in the area.

3.2 Team Game-Specific Laboratory and Field Work

All studies discussed in this section are summarized in table II. Leatt and Jacobs[22] attempted to expand the research base by investigating, for the first time, the effect of carbohydrate ingestion on muscle glycogen depletion during an exhibition soccer match. Unfortunately, in an independent study design comprising two groups, only five subjects per group were used, placing the rigour of any statistical analyses under question. The authors attempted to control the between-groups physical demand of the game by using players from the same positions on the field. However, significant variations in exercise intensity and distance covered and, hence, muscle glycogen utilization, could have occurred between groups due to factors including team tactics, the activity profile of the opposing team[37] and the score in the game. This could have influenced the reported efficacy of the carbohydrate-electrolyte solution. However, Leatt and Jacobs[22] attempted to control the influence of team tactics and activity profile by analysing an intra-squad match. A time-motion analysis of each player would have been useful to confirm the physical demand experienced. Solutions were administered in a single-blind fashion, suggesting the potential for experimenter bias. However, the investigators had no direct contact with subjects during the match. All subjects consumed 0.5 L of the carbohydrate (containing 35 g carbohydrate) or placebo solution rather than a volume matched to individual BM. The authors stated that post-match blood samples and muscle biopsies were taken within 20 minutes and 45 minutes of the match ending, respectively. If these tests were administered at different times between subjects, the reliability of the results could have been affected due to inter-subject differences in lactate dynamics[38] and the onset of rapid glycogen resynthesis, particularly in the carbohydrate group.[39,40] While this may be speculative, it would have been beneficial to standardize these measurements. It may also have been prudent to collect some performance measures during the match to investigate whether glycogen sparing in the carbohydrate trial facilitated any improvement or maintenance of performance compared with placebo.

In a defining study, Nicholas et al.[23] demonstrated, for the first time, a 33% improvement in intermittent exercise capacity when a carbohydrate-electrolyte solution was consumed immediately prior to and during the Loughborough Intermittent Shuttle Test (LIST), a protocol specifically designed to replicate the physiological demand of soccer.[41] Carbohydrate supplementation did not significantly improve sprint performance during the protocol. Solutions were prescribed relative to BM and in a double-blind, counterbalanced fashion, ensuring equal fluid and carbohydrate (0.90 g/kg BM) intake across all subjects. These strengths are in direct comparison to the issues highlighted in section 3.1.

Most subsequent research investigating carbohydrate supplementation during team games exercise employed the LIST protocol or a slight modification of it. Almost without exception, this research demonstrates that carbohydrate supplementation improves intermittent exercise capacity[24,26,27,30,32,33] or promotes physiological

Table II. Summary of team games-specific laboratory and field studies on the effects of carbohydrate (CHO) supplementation immediately before and during team games exercise on the intermittent exercise performance and capacity of adults[a]

Study	No. of subjects and training level	Protocol	Supplementation	Significant findings	Limitations
Leatt and Jacobs[22]	10 highly trained soccer players	90 min outdoor friendly soccer match, 10 min interval Treatment (n = 5) and PLA (n = 5) group	7% glucose polymer solution 0.5 L ~10 min before match and at half-time	~39% reduction in muscle glycogen use with CHO ingestion	Low subject numbers Single-blind design Solutions not standardized to BM Variable timing of post-match blood and muscle samples No performance measurements made
Nicholas et al.[23]	9 trained games players	Standard LIST Double-blind design	6.9% CHO-E solution 5 mL/kg BM prior to exercise 2 mL/kg BM every 15 min during exercise	33% longer time to exhaustion Sprint performance unchanged	No notable limitations
Davis et al.[24]	10 active	Standard LIST Double-blind design	20% CHO solution 20% CHO + BCAA solution 5 mL/kg BM 1 h and 10 min before exercise 2 mL/kg BM every 15 min during exercise (CHO only)	Significant increase in time to exhaustion (52% CHO, 42% CHO + BCAA) No difference between treatments	Sprint performance not assessed
Nicholas et al.[25]	6 trained games players	Extended LIST (part A only, 90 min duration)	6.9% CHO-E solution 5 mL/kg BM prior to exercise 2 mL/kg BM every 15 min during exercise	Sprint performance unchanged 22% reduction in muscle glycogen use	Exercise capacity not assessed Blinding procedures used were not stated
Davis et al.[26]	8 active	Standard LIST Double-blind design	6% CHO-E solution 5 mL/kg BM 10 min before exercise 2 mL/kg BM every 15 min during exercise	32% longer time to exhaustion	Sprint performance not assessed
Welsh et al.[27]	10 (5 F) trained games players	Modified LIST: 4 × modified part A, with a 20 min recovery between the second and third set Modified part A: 3 × 20 m walking 2 vertical jumps at 80% maximum height 1 × 20 m sprint 3 × 20 m run at 120% $\dot{V}O_{2max}$ 2 vertical jumps at 80% maximum height	18% and 6% CHO-E solution 5 mL/kg BM prior to exercise 3 mL/kg BM every 15 min (6% only) 5 mL/kg BM at half-time (18% only)	37% longer time to exhaustion Significantly faster sprint performance during final 15 min Similar physiological function between trials	No validity or reliability testing of modified LIST protocol

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Table II. Contd

Study	No. of subjects and training level	Protocol	Supplementation	Significant findings	Limitations
		3 × 20 m jogging at 55% $\dot{V}O_{2max}$ Double-blind design Motor skill, jumping, cognitive and emotion tests undertaken before, during, and after protocol			
Morris et al.[18]	9 active	Modified LIST in 30°C heat: 5 × part A, followed by 60 sec run/60 sec rest until exhaustion	6.5% CHO-E solution 6.5 mL/kg BM prior to exercise 4.5 mL/kg BM every 15 min during exercise	No difference in sprint performance or time to exhaustion Similar physiological function between trials	Subjects were not acclimatized to exercise in the heat An order effect was reported for distance run Very low number of subjects completed the protocol Blinding procedures used were not stated
Winnick et al.[28]	20 (10 F) active	Modified LIST: 4 × 15 min modified part A, 5 min interval after set 1 and 3, 20 min interval after set 2 Modified part A, see Welsh et al.[27] Double-blind design Motor skill, jumping, force sensation, cognitive and emotion tests undertaken before, during and after protocol	6% CHO-E solution 5 mL/kg BM prior to exercise and at beginning of 20 min interval 3 mL/kg BM beginning of each 5 min interval, 10 min into 20 min interval, and immediately after fourth set	Significantly faster sprint performance during final 15 min Similar physiological function between trials	No validity or reliability testing of modified LIST protocol
Ali et al.[29]	16 trained games players	Extended LIST (part A only, 90 min duration) following glycogen-depleting exercise Shooting and passing tests undertaken before and after exercise	6.4% CHO-E solution 5 mL/kg BM prior to exercise 2 mL/kg BM every 15 min during exercise	Significantly faster mean sprint performance during protocol	Exercise capacity was not assessed Blinding procedures used were not stated
Patterson and Gray[30]	7 trained games players	Standard LIST Double-blind design	CHO gel 0.89 mL/kg BM prior to exercise 0.35 mL/kg BM every 15 min during exercise	45% longer time to exhaustion Similar physiological function between trials	CHO gel was compared with a PLA solution, rather than a PLA gel

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Table II. Contd

Study	No. of subjects and training level	Protocol	Supplementation	Significant findings	Limitations
Clarke et al.[31]	12 trained games players	Soccer-specific motorized treadmill protocol (2 × 45 min with 15 min recovery)	6.9% CHO-E solution 7 mL/kg BM prior to exercise and during recovery (trial 1) Same total volume as trial 1 at 15 min intervals (trial 2)	Similar physiological function and metabolic response between trials Significant attenuation in gut fullness in trial 2	No performance variables measured
Davison et al.[32]	10 untrained	Modified LIST: Part A for 60 min followed by incremental run to exhaustion Double-blind design	6% CHO-E solution 8 mL/kg BM 15 min before exercise	8% longer time to exhaustion	CHO was not ingested during exercise
Foskett et al.[33]	6 active games players	Modified LIST: Part A for 90 min, and then continuously to exhaustion Double-blind design	6.4% CHO-E solution 8 mL/kg BM prior to exercise 3 mL/kg BM every 15 min during exercise	21% longer time to exhaustion Sprint performance unchanged Similar physiological function between trials	Low subject number
Abbey and Rankin[34]	10 trained games players	5 × 15 min intermittent exercise: 2 × 55 m jogging at 55% $\dot{V}O_{2max}$ 2 × 55 m running at 120% $\dot{V}O_{2max}$ 2 × 55 m walking 4 × 55 m sprinting Agility and shooting tests performed during exercise	6% CHO-E solution 8.8 mL/kg BM 30 min prior to exercise and at half-time	No difference in time to exhaustion No difference in sprint performance	CHO intake regimen may not have enabled performance improvement CHO availability may not have been a limiting factor in CHO or PLA trial Blinding procedures used were not stated
Ali and Williams[35]	17 trained games players	Extended LIST (part A only, 90 min duration) following glycogen-depleting exercise Passing test performed before, every 15 min during and after exercise	6.4% CHO-E solution 8 mL/kg BM prior to exercise 3 mL/kg BM every 15 min during exercise	No difference in sprint performance Similar physiological function between trials	Exercise capacity was not assessed Blinding procedures used were not stated
Roberts et al.[36]	8 trained games players	BURST test	9% CHO-E solution 1 h before exercise and 21, 46, and 77 min during exercise Volume ingested: 1.2 g/kg BM/h	No difference in sprint performance Similar physiological function between trials	Protocol design based on activity profile data of Rugby Union forwards only Blinding procedures used were not stated

a All studies were PLA controlled.

BCAA = branched-chain amino acids; **BM** = body mass; **BURST** = Bath University Rugby Shuttle Test; **CHO-E** = carbohydrate-electrolyte; **F** = females; **LIST** = Loughborough Intermittent Shuttle Test; **PLA** = placebo; $\dot{V}O_{2max}$ = maximal oxygen uptake.

and metabolic alterations that infer greater performance and/or capacity.[25,31] Improvements in intermittent exercise capacity with carbohydrate ingestion during part B of the non-modified LIST range between 32% and 52%, with effect sizes ranging from d = 0.44–2.69.[23,24,26,30] The validity of this performance measure should be considered, as team games athletes are rarely required to continue running to exhaustion during training or competition. However, the intermittent run to exhaustion should perhaps not be viewed as an exhaustive exercise test *per se*, but rather as an assessment of the ability to maintain high-intensity exercise, which is a recognized marker of performance and fatigue during field-based team games.[37] Despite this, the fixed workloads of most team games protocols (e.g. part A of the LIST protocol) do not permit the subject to alter their work rate; therefore, the influence of carbohydrate on self-governed work rate during team games exercise cannot be quantified. Future protocols, such as that proposed by Ali et al.[42] should address this. The influence of carbohydrate supplementation on sprint performance during team games exercise is contentious, with only three studies showing any form of improvement[27-29] (see section 4.2).

Abbey and Rankin[34] found no effect of carbohydrate supplementation on exercise performance or capacity during a team games protocol. However, the different protocol and tests of sprint performance and exercise capacity from those discussed above, along with less frequent carbohydrate ingestion, may help to explain this. Morris et al.[18] found no performance or capacity benefits with carbohydrate ingestion during a slightly modified LIST in 30°C heat. Lack of performance enhancement was attributed to carbohydrate availability not being a limiting factor in the unacclimatized subjects. As the authors must have recognized this prior to the study, it raises the question of why they failed to account for it by, for example, acclimatizing the subjects. The rate of rise in rectal temperature was greatest in the carbohydrate and placebo trials compared with the flavoured water trial. The authors suggested this was indicative of greater thermal strain due to impaired fluid delivery with ingestion of the carbohydrate-electrolyte solution. However, this is confused when it is noted that mean rectal temperature at the end of the protocol was not significantly different between the three trials. Furthermore, impaired fluid delivery with carbohydrate ingestion is dependent on multiple factors that were not measured in this study (section 5.1), and this does not explain the similar rate of rise in rectal temperature in the placebo trial. An order effect was reported for the total distance run (19% increase in trial 3 compared with trial 1), despite a randomized and counterbalanced approach to trial ordering. This may reflect a learning and/or, possibly, an acclimatization effect across the three trials. Finally, only four of the nine subjects completed the full protocol in the flavoured water trial, three in the placebo trial and only one in the carbohydrate trial. This invalidates any statistical tests carried out on the data. As a result of these issues, the findings of this study should be interpreted with extreme caution.

3.3 Mental Function and Skill Performance

All studies in this section are summarized in table III. Carbohydrate intake during team games exercise has been associated with significantly better maintenance of whole-body motor skills and mood state,[27,28] and reduced perception of exertion,[29] fatigue[27] and force production[28] in the latter stages of exercise. Carbohydrate intake does not appear to influence cognitive function during team games exercise.[27,28] Roberts et al.[36] found no influence of carbohydrate on the same motor skills test used by Welsh et al.[27] and Winnick et al.[28] and attributed this to the different protocol used in their study. The lack of influence of carbohydrate on agility in the study of Abbey and Rankin[34] may have been due to carbohydrate not being a limiting factor in the exercise protocol.

Findings on the influence of carbohydrate on mental function during exercise may be influenced by the assessment procedure used, with Backhouse et al.[46] suggesting the Profile of Mood States test may not be sensitive enough to detect treatment effects on psychological responses to exercise. Using the Felt Arousal Scale, a subjective measure of perceived arousal, the authors demonstrated a significantly better maintenance of perceived arousal

Table III. Summary of team game-specific laboratory and field studies on the effects of carbohydrate (CHO) supplementation immediately before and during team games exercise on mental function and skill performance in adults[a]

Study	No. of subjects and training level	Protocol	Supplementation	Significant findings	Limitations
Zeederberg et al.[43]	22 trained games players	90 min outdoor competitive soccer game Tackling, heading, dribbling, shooting, passing and ball control performance recorded throughout game	6.9% CHO-E solution 5 mL/kg BM 15 min prior to match and at half-time	No significant effect on tackling, heading, dribbling, shooting, passing or ball control ability	Confounding factors associated with soccer performance in the field Blinding procedures used were not stated
Northcott et al.[44]	10 active games players	90 min circuit designed to replicate soccer, 15 min interval Passing and shooting tests undertaken every 15 min during protocol	8% CHO-E solution 8 mL/kg BM 15 min prior to exercise and at half-time	Significantly better maintenance of passing and shooting performance in last 15 min of exercise	No validity or reliability data regarding the exercise protocol, shooting or passing tests Blinding procedures used were not stated
Ostojic and Mazic[45]	22 trained games players	90 min outdoor soccer match, 15 min interval. Treatment (n = 11) and PLA (n = 11) group Dribbling, precision, coordination and power tests undertaken after the match	7% CHO-E solution 5 mL/kg BM immediately prior to match 2 mL/kg BM every 15 min during match	Significant improvement in dribbling performance and precision scores No difference in coordination or power	Confounding factors associated with soccer performance in the field Blinding procedures used were not stated Skill measures only taken after soccer match
Welsh et al.[27]	10 (5 F) trained games players	Modified LIST: 4 × modified part A, with a 20 min recovery between the second and third set Modified part A: 3 × 20 m walking 2 vertical jumps at 80% maximum height 1 × 20 m sprint 3 × 20 m run at 120% $\dot{V}O_{2max}$ 2 vertical jumps at 80% maximum height 3 × 20 m jogging at 55% $\dot{V}O_{2max}$ Double-blind design Motor skill (hopscotch), jumping, cognitive (SCWT) and mood (POMS) tests undertaken before, during and after protocol	18% and 6% CHO-E solution 5 mL/kg BM prior to exercise 3 mL/kg BM every 15 min (6% only) 5 mL/kg BM at half-time (18% only)	Significantly better maintenance of motor skill in last 15 min Significantly lower sensation of fatigue at exhaustion No difference in cognitive function	No validity or reliability testing of modified LIST protocol

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Table III. Contd

Study	No. of subjects and training level	Protocol	Supplementation	Significant findings	Limitations
Winnick et al.[28]	20 (10 F) active games players	Modified LIST: 4×15 min modified part A, 5 min interval after set 1 and 3, 20 min interval after set 2 Modified part A, see Welsh et al.[27] Double-blind design Motor skill (hopscotch), jumping, force sensation (perception of force at wrist extensors), cognitive (SCWT) and mood (external POMS) tests undertaken before, during and after protocol	6% CHO-E solution 5 mL/kg BM prior to exercise and at beginning of 20 min interval 3 mL/kg BM beginning of each 5 min interval, 10 min into 20 min interval and immediately after fourth set	Significantly better motor skills during final 30 min Significantly improved mood during final 15 min Significantly reduced force sensation No influence on cognitive function	No validity or reliability testing of modified LIST protocol
Ali et al.[29]	16 trained games players	Extended LIST (part A only, 90 min duration) following glycogen-depleting exercise LSST and LSPT undertaken before and after exercise	6.4% CHO-E solution 5 mL/kg BM prior to exercise 2 mL/kg BM every 15 min during exercise	Significant reduction in RPE during final 15 min of exercise Significantly better maintenance of shooting performance No difference in passing performance	Blinding procedures used were not stated
Backhouse et al.[46]	17 trained games players	Extended LIST (part A only, 90 min duration) Measures of pleasure-displeasure (scale) and perceived arousal (felt arousal sale) recorded throughout exercise	6.4% CHO-E solution 8 mL/kg BM prior to exercise 3 mL/kg BM every 15 min during exercise	Significantly greater perceived activation in last 30 min Trend for attenuation of RPE in last 30 min of exercise	Blinding procedures used were not stated No performance measures were made
Abbey and Rankin[34]	10 trained games players	5×15 min intermittent exercise: 2×55 m jogging at 55% $\dot{V}O_{2max}$ 2×55 m running at 120% $\dot{V}O_{2max}$ 2×55 m walking 4×55 m sprinting Agility and shooting tests performed during exercise	6% CHO-E solution 8.8 mL/kg BM 30 min prior to exercise and at half-time	No significant difference in agility No significant difference in passing performance	CHO intake regimen may not have enabled performance improvement CHO availability may not have been a limiting factor in CHO or PLA trial Blinding procedures used were not stated
Ali and Williams[35]	17 trained games players	Extended LIST (part A only, 90 min duration) following glycogen-depleting exercise LSPT performed before, every 15 min during and after exercise	6.4% CHO-E solution 8 mL/kg BM prior to exercise 3 mL/kg BM every 15 min during exercise	No difference in passing performance	Blinding procedures used were not stated

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Table III. Contd

Study	No. of subjects and training level	Protocol	Supplementation	Significant findings	Limitations
Currell et al.[47]	11 trained games players	10 × 6 min exercise: 10 sec walk, 10 sec jog, 10 sec cruise, 10 sec jog, 10 sec cruise, 15 sec walk, 5 sec sprint, 15 sec jog, 5 sec sprint Exercise pattern repeated four times per 6 min exercise block Tests of agility, dribbling, kicking and heading performed during exercise	7.5% CHO-E solution 6 mL/kg BM 30 min prior to exercise 4 mL/kg BM at half-time 1 mL/kg BM every 12 min during exercise	Significant improvement in dribbling, agility and shooting performance No significant difference in heading performance	Blinding procedures used were not stated
Roberts et al.[36]	8 trained games players	BURST test Motor skill (hopscotch) test performed before, during and after exercise	9% CHO-E solution 1 h before exercise and 21, 46 and 77 min during exercise Volume ingested: 1.2 g/kg BM/h	No different in motor skills throughout protocol	Protocol design based on activity profile data of Rugby Union forwards only Blinding procedures used were not stated

a All studies were PLA controlled.

BM = body mass; **BURST** = Bath University Rugby Shuttle Test; **CHO-E** = carbohydrate electrolyte; **F** = females; **LIST** = Loughborough Intermittent Shuttle Test; **LSPT** = Loughborough Soccer Passing Test; **LSST** = Loughborough Soccer Shooting Test; **PLA** = placebo; **POMS** = Profile of Mood States; **RPE** = rating of perceived exertion; **SCWT** = Stroop Colour Word Test; $\dot{V}O_{2max}$ = maximal oxygen uptake.

during the final 30 minutes of the LIST with carbohydrate ingestion, along with a non-significant attenuation in the rating of perceived exertion (RPE). Exercise performance and capacity were not assessed, making it impossible to observe whether increased arousal influenced these measures.

Zeederberg et al.[43] found no effect of a carbohydrate-electrolyte solution on aspects of skill performance in two teams during two outdoor soccer matches. The ability to successfully complete these actions was determined according to set criteria defined by the authors. For example, passing performance was governed by the criterion ‘‘a player kicks the ball to a team-mate without interception by the opposition or over the sideline for a defensive clearance.’’ This does not account for the possibility that the player miskicked the ball (e.g. in attempting a shot on goal and the ball happened to reach a team-mate). It also does not quantify the quality of the pass, which may have been successful due to poor positioning of the opposition players rather than passing accuracy. Hypoglycaemia may inhibit performance of skills requiring sensory-visual information, small and precise postural changes and tactical thinking and inter-player cooperation,[29,43] providing a rationale for carbohydrate ingestion to improve skill performance. However, the absence of post-match hypoglycaemia in either trial in the Zeederberg et al.[43] study suggests carbohydrate availability was not an issue, possibly negating the requirement for carbohydrate ingestion. The conflicting results reported by Ostojic and Mazic[45] (table III) may be due to differences in the tests administered or the degree of test familiarization the subjects were given. Additionally, Ostojic and Mazic[45] conducted their tests after a soccer match, and therefore presented no evidence that carbohydrate ingestion modulated skill aspects during soccer. As both studies were conducted in the field, the extraneous factors that can affect field-based soccer performance (section 3.2) could have also influenced the measures of skill in both studies.[29]

Northcott et al.[44] found a significantly better maintenance of passing and shooting performance with carbohydrate ingestion. However, no information was provided on the validity or reliability of the shooting and passing tests, or the exercise protocol. Distance covered increased significantly during the first and second 45-minute periods of the protocol in the carbohydrate trial. This may have been independent of the solution consumed, possibly representing a protocol reliability issue.

The recent development and validation of specific laboratory tests of soccer shooting accuracy and passing performance[48] has enabled a more objective quantification of the influence of carbohydrate supplementation on these variables. Carbohydrate ingestion before and during team games exercise has been demonstrated to significantly improve or maintain shooting accuracy in glycogen depleted[29] and non-glycogen depleted[47] subjects, with no significant influence on passing performance.[29,34,35] However, the observation that the performance of a dribbling test is significantly better maintained during the last 30 minutes of the LIST when a non-carbohydrate fluid is consumed compared with no fluid ingestion,[49] suggests that the relative influence of fluid and carbohydrate intake on skill performance in team games should be quantified. This will determine whether one is more important than the other with regard to skill performance, and whether an additive effect is evident when fluid and carbohydrate are co-ingested.

3.4 Physiological and Metabolic Responses

Ingestion of carbohydrate-electrolyte solutions does not appear to directly influence $\dot{V}O_2$, HR, core temperature (T_{core}), plasma volume (PV) or fluid loss during team games exercise.[11,13-15,22-25,27-29,31,35,36,43,45,46,50] Some authors have reported a significantly lower HR throughout exercise with carbohydrate ingestion,[24,26] attributed to a trend for better maintenance of PV. However, other work has reported non-significantly greater PV losses with carbohydrate supplementation without a significant alteration in HR response.[23] Yaspelkis et al.[14] reported a significantly higher HR at exhaustion with carbohydrate supplementation, which may reflect an increased ability to continue exercise due to carbohydrate-mediated central and/or peripheral alterations (section 4.1). The significantly higher $\dot{V}O_2$ with carbohydrate supplementation reported by Ali et al.[29] and Coggan and Coyle[12] could relate to an augmented work rate (section 4.2). Ostojic and Mazic[45] found a significantly lower BM loss after a soccer match, attributed to larger sweat and urine losses in the placebo trial. However, sweat rate and urine loss were not measured in the study. Furthermore, the limitations associated with using BM loss as a measure of hydration status should be considered.[51] Extraneous factors associated with conducting the study in the field, such as possible differences in exercise intensity both within and between teams, as well as differences in the timing of BM measurement between players before, during and after the match, may also have contributed to the different BM losses, independent of carbohydrate intake.

Carbohydrate ingestion alters the metabolic response to team games exercise, with a significant increase in blood glucose concentration found either periodically,[11,12,14,15,23,26,29,31,33,35,36,46,50,52] or throughout exercise.[13,24,45] Studies that have not recorded increased blood glucose concentration may have been hampered by infrequent blood sampling opportunities[22,43] or a small sample size.[25] Significant increases in blood insulin concentration may also occur with carbohydrate supplementation,[12,14,31,33] but this is not consistently observed.

Significantly greater carbohydrate oxidation rates are recorded with carbohydrate ingestion,[12,14,29,31,35] along with a strong trend for attenuated blood free fatty acid (FFA) levels[12,14,24,26,31,33,35] and fat oxidation rates,[31,35] although this is not consistent.[23,25,29,36,45] Nassis et al.[15] found no increase in carbohydrate oxidation rates with carbohydrate intake, but this may be due to protocol issues (section 3.1). RER appears to be significantly higher during prolonged intermittent exercise when carbohydrate is ingested.[12-14] Ali et al.[29] did not find a between-trials difference in RER during the LIST, despite a higher rate of carbohydrate oxidation in the carbohydrate trial. This highlights the issues associated with using RER to quantify metabolic responses to intermittent exercise (section 3.1).

The blood lactate response to prolonged intermittent exercise is largely unaffected by carbohydrate ingestion,[11-13,23,24,26,27,29,33,35,36,45] except at exhaustion, where it has been reported to be significantly higher.[14,15] This may reflect the ability to continue exercising to a higher intensity, as previously discussed in this section and section 4.1. However, if this is the case, blood lactate concentration is not a reliable marker of this phenomenon, as numerous studies have described enhanced intermittent exercise capacity without a significant increase in blood lactate concentration. It is also worth noting that blood lactate concentration only reflects activities undertaken a few minutes prior to sampling, and the balance between lactate movement into and out of the blood.[53,54]

3.5 Summary

Early research was almost unanimous in supporting the consumption of carbohydrate-electrolyte solutions during prolonged intermittent exercise for maintaining and/or improving exercise performance and capacity. However, the studies presented significant methodological concerns that limit their applicability to actual team games. A key concern is the failure to use protocols that accurately replicate the physiological demands of team games.

Contemporary research constructed methodologies and protocols more representative of the activities and physiological demands of team games and was almost unequivocal in its support for the efficacy of carbohydrate supplementation in improving intermittent exercise capacity. Most research shows no benefit of carbohydrate supplementation on sprint performance. The minority of research showing no influence of carbohydrate supplementation on intermittent exercise capacity displays methodological issues that could significantly impact the findings. Therefore, this work should be interpreted with caution.

Carbohydrate supplementation may elicit alterations in effort perception and mood state, which could facilitate improvements in exercise performance or capacity late in the exercise bout. The presence and extent of any such influence of carbohydrate will likely depend on factors including pre-exercise muscle glycogen status, the intensity and duration of the exercise bout and the amount and timing of carbohydrate ingestion. More work is required using appropriate evaluative tools to confirm the presence of such an effect, as well as its influence on exercise performance and/or capacity. Carbohydrate supplementation may facilitate a better maintenance of shooting accuracy during team games, with negligible support for improvements in passing, dribbling, tackling or heading. Again, these studies may be influenced by such factors as pre-exercise glycogen concentration; the existing skill level of subjects; the validity and reliability of and ability to compare between the various skill tests employed; the extent of test familiarization; and the type, intensity and duration of exercise. Further work using consistent, well controlled protocols and a uniform battery of standardized tests will enable greater understanding of the influence of carbohydrate on skill performance.

Carbohydrate ingestion does not directly alter the physiological response to prolonged intermittent exercise. Any alterations that may occur are likely due to carbohydrate-mediated augmentations in work rate. The general metabolic response to prolonged intermittent exercise with carbohydrate supplementation is an increase in blood glucose concentration and significantly greater carbohydrate oxidation rates, along with attenuated blood FFA levels and fat oxidation rates.

4. Mechanisms of Enhancement with Carbohydrate Supplementation during Prolonged Intermittent, High-Intensity Exercise

4.1 Intermittent Exercise Capacity

It appears that carbohydrate supplementation extends intermittent exercise capacity via reduced muscle glycogen utilization in the first ~75 minutes of exercise.[23,24,26] Nicholas et al.[25] seemed to confirm this by showing a combined 22% reduction in type I and II muscle fibre glycogen utilization with carbohydrate ingestion during 90 minutes of the LIST. This was attributed to factors including exogenous carbohydrate oxidation sparing endogenous stores, greater activity of the pyruvate dehydrogenase complex due to hyperinsulinaemia and lower blood lactate concentration and glycogen resynthesis in type II fibres due to elevated blood glucose and insulin levels. Other studies support the hypotheses of carbohydrate-mediated muscle glycogen sparing and/or glycogen resynthesis during team games exercise due primarily to observations of increased blood glucose and/or blood insulin concentrations during exercise.[14,18,23,24,26] However, only Yaspelkis et al.[14] measured muscle glycogen concentration, finding a 25% greater concentration at the end of exercise in type I muscle fibres in the carbohydrate trial. This suggests sparing of muscle glycogen rather than its synthesis during exercise, which is suggested to occur in type II muscle fibres.[25] Supporting evidence for greater pyruvate dehydrogenase activity with carbohydrate supplementation is lacking. However, work into the mechanisms of carbohydrate efficacy should continue when it is considered that only a small amount of exogenous carbohydrate appears to be oxidized, or made available for oxidation, in the first hour of exercise regardless of whether carbohydrate exerts an ergogenic effect[55] or not.[56]

The potential influence of carbohydrate on perceptual responses to exercise may enable enhanced intermittent exercise capacity (see section 3.3).[29,46,57] While this hypothesis requires more work, as the relationship between carbohydrate ingestion, RPE and performance during team games exercise has not been clearly established, it does appear that carbohydrate may modify the perception of effort during team games.

The significantly lower HR reported by some authors[24,26] during team games exercise when carbohydrate is ingested (section 3.4) infers reduced stress on the cardiovascular system and an ability to exercise at a higher intensity for a given HR, and may possibly contribute to improved intermittent exercise capacity. However, the common observation that carbohydrate exerts no influence on PV or HR during team games exercise suggests that altered HR response is not a plausible or consistent ergogenic mechanism of carbohydrate supplementation. Furthermore, Ali et al.[29] found a trend for a higher HR with carbohydrate ingestion during the LIST; however, this may have been due to the faster sprint times reported in the carbohydrate trial (section 4.2).

4.2 Sprint Performance

Improved sprint performance during team games exercise following ingestion of a carbohydrate-electrolyte solution has been attributed to maintenance of blood glucose levels,[27,29] which may enable greater muscle and cerebral metabolism,[29] thereby maintaining central nervous system (CNS) function and allowing better maintenance of power output or muscle glycogen sparing.[28] These hypotheses are debatable, as blood glucose concentration did not reach hypoglycaemic levels in the carbohydrate or placebo trial in the studies of Ali et al.[29] or Welsh et al.,[27] and muscle glycogen levels were not measured by Winnick et al.[28] It should be stated that the subjects in the Ali et al.[29] study began exercise with depleted glycogen stores. This may explain the improved sprint performance with carbohydrate supplementation in this study, as short-duration, maximal-intensity exercise can be attenuated if muscle glycogen levels fall below a critical threshold (~200 mmol/kg dry weight).[58,59] Therefore, ingestion of carbohydrate may have provided a sufficient supply of glucose to the muscle to enable greater sprint performance in the glycogen-depleted state compared with placebo. However, the extent of glycogen depletion was not quantified; therefore, this hypothesis is speculative. Furthermore, Foskett et al.[33] and Ali and Williams[35] reported a significant attenuation of sprint performance during the LIST protocol in the carbohydrate and placebo trials when subjects began exercise in a glycogen-depleted state. However, the extent of glycogen depletion was not reported. It also does not explain the improved sprint performance documented by Welsh et al.[27] or Winnick et al.,[28] as subjects in these studies were not glycogen depleted prior to exercise.

When glycogen availability is not compromised, phosphocreatine concentration and its rate of resynthesis rather than carbohydrate availability is more related to short-duration sprint performance,[60] perhaps helping to explain the lack of effect of carbohydrate on sprint performance in most studies. However, it should be considered that, while phosphocreatine availability is the determining factor when short sprints are interspersed with adequate passive recovery, during team games, subjects are required to jog, run and walk between each sprint. In this situation, phosphocreatine resynthesis may not be complete enough to contribute fully to each sprint, particularly in the later stages of the protocol. If this were the case, other substrates, notably carbohydrate and fat, would become more prevalent fuels during the sprints.[61] Therefore, carbohydrate supplementation may be important for maintaining sprint performance during the later stages of team games exercise. This may be particularly pertinent when pre-exercise muscle glycogen stores are not optimal,[29] but may also help to explain the findings of Welsh et al.[27] and Winnick et al.[28] who found a significant improvement in sprint performance in the late stages of exercise only. It may also help to explain the non-significant between-trials difference in sprint performance observed in most studies. However, this requires further investigation.

4.3 Mental Function and Skill Performance

Studies confirming improved mood, force output and effort perception with carbohydrate supplementation during team games exercise have implicated carbohydrate-mediated alterations in brain chemistry, particularly attenuated serotonin production,[62,63] as a potential mechanism.[27,28,46] However, none of the studies collected data that could directly confirm this, instead inferring increased brain glucose uptake based on significantly elevated blood glucose concentrations in the carbohydrate trial.[64] Cerebral glucose uptake begins to decline when blood glucose concentration falls below ~3.6 mmol/L,[65] which did not happen in the placebo trial in the studies of Backhouse et al.[46] or Welsh et al.[27] and, in the Winnick et al.[28] study, blood glucose levels were not measured. It is therefore difficult to accept this explanation. Furthermore, the concept of CNS fatigue remains unclear and difficult to experimentally isolate and confirm, particularly from a mechanistic perspective.[66] It is also extremely difficult to differentiate central from peripheral effects when carbohydrate is ingested during exercise.[67] Work needs to be conducted that is sensitive enough to resolve the nature of the influence of carbohydrate on mental function during team games exercise, yet using tests that are externally valid to team games performance.

The significantly improved, or better maintained, performance of certain skills reported by some authors has also been largely attributed to carbohydrate-mediated alterations in CNS function that enable better motor control and hence skill performance.[27-29,47] However, the issues with this are discussed above. Ali et al.[29] suggested an augmentation of neuromuscular function with carbohydrate supplementation that may also enable greater motor control, but this was not supported with data. Maintenance of blood glucose concentration, sparing of muscle glycogen and therefore, possibly, attenuation of muscle fatigue and, perhaps, better performance of the anaerobic component of the skill test have also been postulated.[27-29,44,45] However, no muscle glycogen measurements were taken,[27,29] and some studies did not measure blood glucose concentration.[28,44,45] Furthermore, hypoglycaemia did not occur in any of the other studies,[27,29] and Ali and Williams[35] failed to show a significant improvement in passing performance with carbohydrate supplementation despite very similar between-trial blood glucose responses to their 2007 study. However, the possible effects of low blood glucose concentration on skill performance have not been elucidated.[29] Further work must attempt to quantify the mechanisms responsible for improvements in skill performance during team games exercise when carbohydrate is ingested.

5. Modulators of Carbohydrate Efficacy

Research supporting the use of carbohydrate-electrolyte solutions during team games exercise generally focuses on supplementation of an approximate 6% carbohydrate-electrolyte solution of similar composition. The current research output does not provide a sufficient thesis on factors that modulate the efficacy of carbohydrate supplementation during team games exercise. Potential modulators may be different from those during prolonged steady-state exercise due to the constantly changing exercise intensity and frequency, duration and intensity of rest intervals, the potential for team games exercise to slow the rate of GE[68] and restricted access to carbohydrate-electrolyte solutions during many team games. Work must be undertaken to further understanding in this area, and ultimately lead to the formulation of clear guidelines for the optimal ingestion of carbohydrate during team games exercise. Some of these important modulators are discussed in sections 5.1–5.7.

5.1 Fluid Volume and Solution Composition

If carbohydrate-electrolyte solutions are consumed during exercise, then fluid and carbohydrate intake are interdependent and should not be considered in isolation. Therefore, the following discussion on fluid volume, carbohydrate concentration, carbohydrate composition and solution osmolality is presented as one topic.

5.1.1 Fluid Volume

Mild dehydration increases T_{core}, RPE and BM loss, and impairs skill performance during team games exercise.[49,69,70] Team games athletes should maintain adequate hydration status in order to maximize performance. This can be achieved by replacing the same amount of fluid that is lost during exercise and is a recommended practice for team games athletes.[10,71-75] Failure to ingest an appropriate volume of fluid during exercise may prevent the athlete from maximizing their performance even when ingesting carbohydrate. More specific fluid ingestion recommendations are difficult due to the numerous factors that can influence fluid requirements, such as BM, exercise intensity, individual sweat rates and environmental conditions. Section 5.2 further discusses fluid intake strategies for team games.

5.1.2 Carbohydrate Concentration

Only three studies have employed different carbohydrate concentrations during prolonged intermittent exercise.[11,13,27] Unfortunately, the use of different carbohydrate compositions,[11] relatively small increases in carbohydrate ingestion between solutions[13] and different carbohydrate concentrations within the same trial,[27] limit the usefulness of the results. Ingesting too little carbohydrate may not meet energy requirements during exercise (section 3.1). However, consuming too much carbohydrate can attenuate GE rate, cause gastrointestinal distress and impair intestinal fluid absorption (section 5.1.4).[68,76,77] A 5–7% carbohydrate-electrolyte solution is currently recommended for team games,[10] along with the recommendation of Jeukendrup and Jentjens[19] for an optimal carbohydrate intake of ~1.0–1.1 g/min. However, neither of these recommendations have been thoroughly tested using externally valid team games protocols.

5.1.3 Carbohydrate Composition

Carbohydrate oxidation rate depends on multiple factors, one of which is the composition of ingested carbohydrate.[19] This suggests that different carbohydrate compositions may have different efficacies during exercise. Ingestion of multiple transportable carbohydrates, typically glucose and fructose in a ratio of ~2 : 1, appears beneficial during prolonged steady-state exercise for increasing GE rate,[78] intestinal carbohydrate and water absorption (section 5.1.4)[78,79] and exogenous carbohydrate oxidation rates,[79-82] although the latter is not universally found.[83] In the only study to manipulate carbohydrate composition during prolonged intermittent exercise,[11] it was not possible to discern between effects due to changes in carbohydrate concentration and composition (section 5.1.2). Therefore, the effect of alterations in carbohydrate composition during team games exercise should receive close attention in future work.

Recently, the first study investigating the effect of a carbohydrate gel during team games exercise reported a 45% improvement in intermittent exercise capacity compared with a placebo solution,[30] analogous to the effect of carbohydrate solutions (section 3.2). This is supported by evidence of a similar time-course of carbohydrate oxidation and peak carbohydrate oxidation rate between carbohydrate gels and drinks of the same composition.[84] This represents a step forward for the research base by investigating carbohydrate delivery in essentially a different medium. Although initial findings are positive, more research is required.

5.1.4 Solution Osmolality

Following ingestion of isocaloric carbohydrate solutions of differing composition and osmolality, less than 5% of the variance in GE rate is due to differences in osmolality.[85] Similar findings have been replicated numerous times at rest and during exercise.[86-90] Solution osmolality often increases in proportion to caloric content, indicating that the inhibition of GE originally attributed to osmolality[91,92] may have been confused with the influence of increased caloric density.[93] Significant negative correlations between carbohydrate content and GE rate with ingestion of iso-osmotic carbohydrate solutions, and positive correlations between solution caloric content and the half-time of GE, have been reported.[94,95] Calbet and MacLean[95] confirmed that caloric content explained 92% of the variance in GE rate. This, along with the observation of a similar GE rate when solutions with the same carbohydrate concentrations but significantly different osmolalities are consumed,[94,96] suggests that carbohydrate content and caloric density are more important than solution osmolality in modulating GE rate.

Rapid fluid and carbohydrate delivery to the systemic circulation is crucial for exercise performance. The osmolality of a carbohydrate-electrolyte solution appears inversely related to the rate of water absorption in the small intestine,[97-101] with conflicting findings[86,96,102-105] attributed to the activity and number of intestinal solute transporters, alterations in osmolality over the length of the small intestine, and solution composition.[10,106,107] Increasing the carbohydrate concentration of a carbohydrate-electrolyte solution can increase osmolality, and therefore attenuate the rate of intestinal water absorption,[108] when carbohydrate concentration reaches ~8%.[103] This should be considered when manipulating the concentration of carbohydrate-electrolyte solutions (section 5.1.2), as increasing carbohydrate concentration may allow increased absorption of carbohydrate, but could attenuate GE rate and intestinal water absorption, and result in sub-optimal hydration status.

Carbohydrate type can also influence solution osmolality and, therefore, intestinal water absorption[10] when carbohydrate concentration is >6%.[103] Incorporating multiple transportable carbohydrates into a solution can offset the effect of high osmolality on intestinal water absorption[109] by activating a greater number of intestinal solute transport mechanisms. This could enable a high volume of carbohydrate delivery while maintaining adequate intestinal water absorption. For a more detailed discussion on this topic, the reader is referred to the review of Shi and Passe.[110]

5.1.5 Recommendations

Future work must study the effects of altering fluid volume, carbohydrate concentration, composition and solution osmolality, independently and in an integrated fashion. This will enable discovery of the optimal composition of a carbohydrate-electrolyte solution for maximizing intestinal fluid and carbohydrate absorption during team games exercise.

5.2 Fluid and Carbohydrate Ingestion Pattern

Fluid may take ~40–60 minutes from the time of ingestion to be transported around the systemic circulation and become physiologically useful.[111,112] This, coupled with the potential attenuation of GE due to the intensity of team games exercise[68,76] and the addition of carbohydrate to a solution,[90,113] and the insufficient opportunities to ingest fluid at regular intervals during team games,[31] casts doubt on the efficacy of consuming consistent amounts of fluid and carbohydrate throughout team games exercise. Coyle[111] suggests that it may be beneficial to drink larger volumes early in exercise, ingest fluid throughout exercise to ensure gastric volume is high after 40 minutes, and then ingest little fluid thereafter to minimize gastric volume towards the end of exercise, and thereby minimize the volume of fluid present that cannot aid, and may inhibit, performance by adding weight and perhaps causing gastrointestinal discomfort. It would be interesting to compare the ‘standard’ intake regimen employed in most team games research (see table II) with one that provides greater volumes of fluid in the early stages of exercise and then progressively less as exercise continues.

Clarke et al.[31] investigated the effect of consuming a carbohydrate-electrolyte solution in a team games-specific fashion (a large bolus prior to and at 45 minutes during exercise) compared with more frequent ingestion during a team games exercise protocol. Exercise performance and capacity were not assessed but the overall metabolic response to exercise – quantified by measurement of blood glucose, insulin, non-esterified fatty acids, glycerol and adrenaline concentrations – was similar between trials. This suggests that ingestion of carbohydrate-electrolyte solutions before a game and at half-time is a practical alternative for fluid and carbohydrate provision.[31] However, this is not supported by the study of Abbey and Rankin.[34] More work is required in this area.

5.3 Glycaemic Index of Pre-Exercise Meals

This review will not discuss the glycaemic index in detail, and the interested reader is referred to the recent review by O'Reilly et al.[114] Manipulating the glycaemic index of a meal consumed several hours before team games exercise does not significantly affect sprint performance or intermittent exercise capacity,[115,116] despite increased fat oxidation rates with a low-glycaemic index meal.[116] Lack of effect may be due to the requirement for high-intensity efforts throughout team games protocols, which would be dependent on phosphocreatine and carbohydrate metabolism.[60,61]

Ingesting a carbohydrate-electrolyte solution before and during steady-state endurance exercise negates the proposed benefits of a pre-exercise low-glycaemic index meal[117,118] by minimizing potential differences in metabolic response or substrate oxidation between low- and high-glycaemic index meals.[117,118] Chryssanthopoulos and Williams[119] reported a significant improvement in steady-state running capacity when ingestion of a pre-exercise carbohydrate meal was combined with carbohydrate ingestion during exercise. However, a low- to high-glycaemic index meal comparison was not made. No research has investigated the interaction between pre-exercise meals of differing glycaemic index and ingestion of a carbohydrate-electrolyte solution before and during team games exercise. This should be carried out in order to quantify the optimal pre- and during exercise nutritional strategy for team games athletes.[114]

5.4 Fluid Temperature

Provision of cold fluid (4–5°C) encourages greater fluid ingestion during exercise in mild and high ambient temperatures,[120,121] and may also enable significantly greater steady-state endurance cycling performance[122] and capacity[121,123] in the heat compared with ingestion of warm fluid (16–38°C). Cold fluid may act as a heat sink, attenuating the rise in body heat storage and, possibly, T_{core}.[123] However, endurance capacity has been improved with cold fluid ingestion without significant changes in T_{core}.[121,122] Cold fluid intake may significantly reduce skin temperature[122,124] and attenuate skin blood flow and sweat rate[125] during exercise in temperate and hot environments. This may represent a redistribution of cardiac output from the skin to the exercising muscles and may enable improved endurance performance/capacity.[122] However, this requires further investigation as skin temperature, blood flow and exercise performance/capacity have not yet been measured in the same study. The influence of cold fluid ingestion on steady-state cycling capacity in moderate environmental conditions appears negligible.[123,126]

The studies discussed above were conducted using similar exercise protocols (steady-state recumbent or upright cycling for ~50–120 minutes at 50–66% $\dot{V}O_{2max}$). No work has used prolonged running as a modality; furthermore, no prolonged intermittent cycling or running protocols have been employed. Variable intensity cycling in high ambient temperatures may significantly increase heat storage, the rate of rise in T_{core}, whole-body sweat rate and dehydration, and significantly reduce forearm blood flow compared with steady-state cycling.[127] This, along with the current recommendation for a fluid temperature of 15–21°C[73] and the acknowledgement that preferred fluid temperature varies greatly between individuals,[73] provides a rationale for investigating the effects of fluid temperature during team games exercise. This should be conducted using fluid with and without carbohydrate, to observe whether alterations in the temperature of a carbohydrate-electrolyte solution provide an additional effect over and above that of carbohydrate or fluid alone.

5.5 Carbohydrate Mouthwash

Insufficient opportunities exist for regular fluid ingestion during field-based team games, and any opportunities that do arise may be brief and not afford the athlete the time to ingest the optimal volume of fluid or carbohydrate. Furthermore, evidence of an attenuated GE rate and, possibly, increased gastrointestinal discomfort with ingestion of carbohydrate-electrolyte solutions during team games exercise,[77] along with the recent suggestion by Edwards and Noakes[128] that the degree of sweat loss and associated dehydration commonly encountered during soccer is not crucial to performance, suggests that a carbohydrate-based ergogenic aid that can be rapidly utilized and has no tolerance issues may be useful for team games players.

In recent years, the use of carbohydrate mouthwashes has been shown to enhance running and cycling performance lasting ~30–60 minutes.[129-132] Other work has failed to show a benefit of carbohydrate mouthwashes,[133,134] possibly due to study differences in solution blinding, the influence of dehydration and endogenous muscle glycogen availability. The apparent mechanisms for enhancement with carbohydrate mouthwashes revolve around modification of central drive and motivation and/or activation of reward and motor control centres in the brain rather than a metabolic cause.[129,131] These alterations may elicit a more favourable perception of effort during exercise.[129,130] For more information on the enhancement mechanisms of carbohydrate mouthwashes, see Chambers et al.[131]

All previous studies of carbohydrate mouthwashes used steady-state protocols. The potential of carbohydrate mouthwashes during team games exercise is strong, particularly in allowing easier and more rapid supplementation than carbohydrate-electrolyte solutions and limiting possible gastrointestinal distress associated with fluid and carbohydrate ingestion.[133] Research needs to quantify this potential benefit, particularly regarding whether a carbohydrate mouthwash is sufficient to enhance team games performance in the presence of significant muscle glycogen depletion.

5.6 Ambient Temperature

The effect of carbohydrate supplementation during prolonged exercise in the heat is equivocal. If exercise is terminated due to attainment of a critical T_{core} – a concept that, while having some empirical support,[135,136] is not universally accepted[137-139] – carbohydrate is not beneficial to performance.[140] However, if subjects do not terminate exercise due to hyperthermia, ingestion of a 6% sucrose/glucose solution has been shown to improve prolonged cycling performance in the heat.[140] During prolonged exercise in a cool environment, a 7% carbohydrate solution is also able to improve exercise capacity.[141] However, these findings apply to prolonged steady-state exercise. Only two studies have investigated carbohydrate supplementation during prolonged intermittent exercise in the heat.[11,18] The major limitations of these studies (see sections 3.1 and 3.2) prevent confident interpretation and application of the findings. Therefore, there is a large scope for focused and well conducted research into the effect of carbohydrate supplementation during team games exercise in different ambient temperatures.

5.7 Populations

No research into carbohydrate supplementation during team games exercise has focused exclusively on adult female subjects. Females generally oxidize less carbohydrate and more fat during exercise than do males,[142,143] with less muscle glycogen utilization recorded during steady-state running[144] but not cycling.[145] It would be interesting to observe whether carbohydrate supplementation during team games exercise enabled any performance and/or capacity improvements in females and, if so, whether mechanisms behind these improvements were different from those behind improvements in male subjects.

A large number of children and adolescents actively participate in organized team games.[146,147] However, the research base investigating the physiological responses of this population to this form of exercise, as well as investigating fatigue mechanisms and avenues of performance enhancement is sparse. This is likely due to the many problems faced when conducting research in young people such as recruitment and retention, gaining parental consent, child assent and ethical approval to undertake all necessary experimental procedures,[148,149] ensuring subjects understand and fulfil all procedural requirements of a study and adequately controlling for the influence of biological maturation, which is often hampered by ethical and consensual restrictions.[150]

Adolescents appear to exhibit a maturation-dependent exercising metabolic response involving greater fat and lower carbohydrate oxidation than adults;[151] however, the large number of potentially confounding factors involved in the study of developmental changes in energy metabolism make a firm consensus extremely difficult.[152,153] They also appear able to oxidize significantly more exogenous carbohydrate during moderate-intensity steady-state cycling than adults.[154] Additionally, a significant improvement in steady-state exercise cycling capacity with carbohydrate supplementation has been observed in 10- to 14-year-old males.[155] This provides a rationale for the study of carbohydrate supplementation during team games exercise in these subjects.

We recently demonstrated, for the first time, that ingestion of a 6% carbohydrate-electrolyte solution immediately before and during a modified LIST protocol significantly improved the intermittent exercise capacity of trained 12- to 14-year-old team games players by 24% compared with a placebo.[156] Neither sprint performance nor physiological responses to exercise were affected by carbohydrate supplementation, except at exhaustion, where subjects elicited a significantly higher peak HR in the carbohydrate trial, but with no significant difference in RPE compared with the placebo trial. This was attributed to carbohydrate supplementation enabling participants to continue working to a higher intensity via better maintenance of muscle metabolism (section 4.1), or the influence of carbohydrate on perceptual responses to exercise (section 3.3). Further work is required to confirm these mechanisms in this population. These positive findings provide a platform from which to investigate other factors associated with carbohydrate supplementation during team games exercise in adolescents, such as those discussed in sections 5.1–5.6, in order to widen and strengthen the research base in this area.

6. Conclusions

Most early research investigating carbohydrate supplementation during prolonged intermittent exercise was subject to methodological limitations that restricted both its scientific rigour and its applicability to actual sporting activity. The development of team game-specific exercise protocols enabled a more focused investigative approach to this topic. The findings of this review into carbohydrate supplementation immediately prior to and during team games exercise are as follows:

1. Carbohydrate supplementation significantly improves intermittent exercise capacity in adults. Possible mechanisms include muscle glycogen sparing or resynthesis during low-intensity periods and altered effort perception during exercise. More research into the mechanisms of carbohydrate efficacy is required.
2. Initial findings suggest that carbohydrate supplementation significantly improves intermittent exercise capacity in adolescent team games players. Enhancement mechanisms may be, at least partially, centrally mediated. Future work should investigate this further.
3. Carbohydrate supplementation has a negligible effect on sprint performance in adults and adolescent team games players. Carbohydrate efficacy may depend on endogenous muscle glycogen availability.
4. Carbohydrate supplementation may elicit alterations in effort perception and mood state that could improve performance in the later stages

of team games exercise and may enable better maintenance of shooting accuracy during team games, with negligible support for improvements in passing, dribbling, tackling or heading. Improvements with carbohydrate intake are attributed to improved cerebral glucose uptake, greater CNS function and motor control. More work is required in these areas.

5. Carbohydrate ingestion does not directly alter physiological responses to prolonged intermittent exercise, with any alterations likely due to an augmented work rate via carbohydrate supplementation. Carbohydrate supplementation usually increases blood glucose and insulin concentrations either periodically or throughout exercise, increases carbohydrate oxidation rates and RER, and attenuates blood FFA levels and fat oxidation rates.

6. It has been suggested that a 5–7% carbohydrate-electrolyte solution containing multiple transportable carbohydrates and sodium, and with an osmolality of 250–370 mOsm/kg may be optimal before and during team games exercise. However, very little subsequent work has attempted to empirically test these recommendations, as well as other potential modulators of carbohydrate efficacy, during team games exercise.

7. Several key areas need to be addressed by future research. These include manipulations in ingested fluid volume, carbohydrate concentration, carbohydrate composition and solution osmolality, both independently and in an integrated fashion; the influence of the glycaemic index of pre-exercise meals with and without carbohydrate supplementation; alterations to fluid and carbohydrate ingestion patterns and fluid temperature; the influence of carbohydrate mouthwash supplementation; carbohydrate supplementation in different ambient temperatures; and the investigation of all of these areas in different populations.

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