Carbohydrate ingestion during recovery from prolonged exercise

JAMES A. BETTS¹, CLYDE WILLIAMS²
*Corresponding author
1. Sport & Exercise Science, School for Health, University of Bath, U.K.
2. School of Sport & Exercise Sciences, Loughborough University, U.K.

INTRODUCTION

Given the large quantities of endogenous carbohydrate that are metabolised during prolonged exercise (1-3), a crucial component of recovery clearly involves the replenishment of these finite energy reserves. The early work by Bergstrom et al. (1967) identified a strong positive correlation (r=0.92) between the pre-exercise glycogen content of the quadriceps femoris and subsequent exercise time to exhaustion on a cycle ergometer (2). Despite this clear central role for muscle glycogen in metabolism during exercise, liver glycogen is also known to be an important source of endogenous carbohydrate. Recent evidence using ¹³C MRS to quantify both muscle and liver glycogen concentrations has indicated that the restoration of exercise capacity following an initial bout of prolonged exercise may be dictated to a large extent by the overall rate of carbohydrate storage during recovery (4). This latter study among others also demonstrates that the ingestion of carbohydrate as opposed to a placebo in the hours following prolonged exercise can accelerate muscle glycogen storage during a short-term recovery (4-6). However, the specific rate of muscle glycogen resynthesis during recovery can vary greatly depending on the relative timing, type and quantity of carbohydrate that is ingested.

TIMING OF CARBOHYDRATE INGESTED

There are 3 major considerations in terms of supplement timing during recovery: how soon after the initial exercise session should supplementation begin; how frequently during the recovery period should supplements be ingested; and how soon before a subsequent exercise session should supplementation cease? In answer to the first of these considerations, exercise induced insulin sensitivity is known to be greatest in the early hours of recovery such that the capacity to increase muscle glucose uptake via carbohydrate ingestion can become gradually diminished over time (7-9). Indeed, it has been reported that delaying the ingestion of carbohydrate following exercise by just 2 hours can result in almost a 50 percent reduction in the rate of muscle glycogen resynthesis during recovery (10). Contrary to this finding, Parkin et al. (1997) reported no detrimental effect of a 2 hour delay in carbohydrate provision on the resynthesis of muscle glycogen when assessed over 8 hours of recovery (11). It may therefore be that the rate of muscle glycogen resynthesis can be accelerated in the first few hours after exercise through immediate carbohydrate feeding but slows thereafter, primarily due to the limit which muscle glycogen imposes on its own synthesis (12). This pattern of resynthesis is illustrated in Figure 1 and would suggest that the prompt ingestion of carbohydrate following exercise is of increased importance when recovery time is more restricted, although the precise benefit of immediate feeding due to insulin sensitivity may in turn be mediated by training status (13). Of course, irrespective of the development of insulin resistance later in recovery, it would seem prudent to begin carbohydrate feeding as early as possible in recovery simply to maximise the time available for ingested carbohydrate to be incorporated into endogenous reserves.

In relation to the issue regarding how frequently carbohydrate should be ingested during recovery, studies by Blom et al. (1987) and Ivy et al. (1988) have both provided carbohydrate at 2 hour intervals over 4-5 hour recovery periods and subsequently observed muscle glycogen resynthesis rates in the region of 22-25 mmol glucosyl units kg dry mass⁻¹ h⁻¹. Notably, these rates of muscle glycogen resynthesis were achieved with relatively modest rates of carbohydrate ingestion (i.e. 0.35-0.75 g CHO kg body mass⁻¹ h⁻¹) yet doubling the amount of carbohydrate ingested in each study did not increase the rate of muscle glycogen storage any further (14, 15). It has been suggested that providing carbohydrate at 2 hour intervals during recovery may not sustain elevations in systemic insulin sufficiently between feedings, thus resulting in sub-optimal stimulation of both the uptake of glucose into muscle and its subsequent conversion into glycogen (16). This suggestion is supported, albeit indirectly, by a variety of studies in which the ingestion of carbohydrate at 15-30 minutes intervals over 3-5 hour recovery periods has resulted in rates of muscle glycogen resynthesis ranging from 30-45 mmol glucosyl units kg dry mass⁻¹ h⁻¹ (17-20). However, applied evidence has shown that more frequent feeding during recovery might also increase the reliance upon carbohydrate oxidation during subsequent exercise, although this effect was not found to be detrimental in terms of exercise capacity (21). The final consideration regarding carbohydrate timing during a short-term recovery in particular is whether a given feeding schedule should be terminated in the hour immediately preceding a subsequent exercise bout in order to prevent any potential metabolic

ABSTRACT

The intensive physical training programmes followed by many athletes often involve repeated bouts of physical exertion with relatively limited time available for recovery between exercise sessions. These individuals therefore strive to maximise their rate of recovery following exercise and the ingestion of carbohydrate is now widely recognised as an appropriate nutritional strategy to achieve this aim. This review considers several key issues relating to carbohydrate ingestion during recovery from prolonged exercise, with specific emphasis on the most effective methods of replenishing depleted fuel sources and ultimately restoring the capacity for physical exercise.
disturbances during that activity. Indeed, it has been clearly demonstrated that ingestion of carbohydrate 45 minutes prior to exercise can increase the rate of muscle glycogen degradation during that activity by \(\approx 17\) percent as a consequence of hypoglycaemia due to the combined influences of dietary induced hyperinsulinaemia and exercise induced glucose uptake (22). However, while there is some evidence that such metabolic disturbances can be detrimental in terms of exercise capacity (23), it is generally believed that this effect is a transient response (i.e. "rebound" hypoglycaemia) and would not therefore contribute to eventual fatigue (24, 25). This belief is upheld with specific reference to recovery by the study by Tsintzas et al. (2003) in which ingesting moderate (\(\approx 0.5\) g CHO/kg body mass\(^{-1}\)h\(^{-1}\)) as opposed to low (\(\approx 0.2\) g CHO/kg body mass\(^{-1}\)h\(^{-1}\)) amounts of carbohydrate at frequent intervals during recovery was found to significantly increase the rate of glycogen storage prior to subsequent exercise without negatively affecting the rate of glycogen degradation during the ensuing activity (26). Nonetheless, even if carbohydrate ingestion late in recovery does not influence subsequent metabolism, from a practical perspective it seems reasonable to suggest that feeding should cease at least 15-30 minutes before exercise to minimise any risk of gastrointestinal discomfort.

**TYPE OF CARBOHYDRATE INGESTED**

There are a number of considerations regarding the type or form of carbohydrate that should be ingested during recovery. Given the central role of insulin in the promotion of carbohydrate storage, it has been suggested that high glycaemic index (GI) carbohydrates may represent the most effective nutritional strategy for recovery (27). A study by Kiens et al. (1990) has confirmed that the almost doubled insulin response when ingesting high as opposed to low GI carbohydrates following exercise can result in a higher muscle glycogen concentration 6 hours later. However, similar to the issue of delayed carbohydrate feeding discussed above, the apparent benefit of ingesting high GI carbohydrates over the first 6 hours of recovery was not apparent 14 h later (28), although other authors have found differences in glycogen availability to persist for up to 24 hours into recovery (29). It is worth noting, however, that there may be additional benefits associated with the ingestion of lower GI carbohydrates during recovery. Specifically, while fructose has a lower GI than glucose and consequently results in relatively slow storage of muscle glycogen (15), ingesting a mixture of glucose and fructose may provide the optimal balance of carbohydrate for the combined resynthesis of both muscle and liver glycogen during recovery (4, 15). A recent study by Wu & Williams (2006) also indicates that the ingestion of low GI carbohydrates may impart benefits in terms of physical performance via increased oxidation of lipid during exercise following feeding (30).

Another interesting question regarding different types of supplement is whether the carbohydrates ingested during recovery should be in solid or liquid form. Initial comparisons between carbohydrate-rich liquids and mixed macronutrient meals suggest that muscle glycogen storage can be equally stimulated with either method of ingestion (31, 32). However, even if solid and liquid supplements can be assumed to stimulate muscle glycogen resynthesis with equal effect, the latter can achieve this aim while simultaneously encouraging rehydration and would therefore be preferable in most situations. Whether or not the specific osmolality of a given fluid also mediates the rate of muscle glycogen resynthesis following exercise remains debatable and therefore requires further investigation (19, 35).

**QUANTITY OF CARBOHYDRATE INGESTED**

It has been well established that carbohydrate ingestion of any substantial magnitude during recovery will stimulate muscle glycogen resynthesis more effectively than when no carbohydrate at all is ingested (4-6). What is less clear is the precise effect of a graded increase in carbohydrate intake on recovery, particularly with regard to the factors which may limit the rate of muscle glycogen resynthesis when very large quantities of carbohydrate are ingested. Overall, it is likely that the difficulty in ascertaining the smallest quantity of carbohydrate necessary to maximise the rate of muscle glycogen storage is at least partially due to the confounding influence of various other factors such as those discussed above regarding the timing and type of carbohydrate ingested. It was initially proposed by Blom et al. (1987) that the ingestion of just 0.35 g CHO/kg body mass\(^{-1}\)h\(^{-1}\) might be sufficient to maximise the rate of muscle glycogen synthesis following exhaustive cycling. This opinion was based on these authors’ findings that increasing the rate of carbohydrate ingestion from \(\approx 0.18-0.35\) g CHO/kg body mass\(^{-1}\)h\(^{-1}\) resulted in a linear increase in muscle glycogen synthesis during recovery (\(r=0.99\) but with no further acceleration of glycogen storage when carbohydrate intake was increased to 0.7 g CHO/kg body mass\(^{-1}\)h\(^{-1}\) (15). In fact, even when carbohydrate ingestion rate has been further raised from 0.75-1.5 g CHO/kg body mass\(^{-1}\)h\(^{-1}\), the rate of muscle glycogenesis has remained unaffected (14). However, it is likely that the plateau in muscle glycogen storage rates in both the above studies was due to the relative infrequency of feedings during recovery (i.e. 2 hour intervals) rather than a genuine attainment of the maximal possible rate of muscle glycogen resynthesis. In support of this contention, when the majority of available published data regarding carbohydrate ingestion and muscle glycogen resynthesis during short-term recovery is examined collectively (Figure 2), it is apparent that ingestion of \(\approx 1\) g CHO/kg body mass\(^{-1}\)h\(^{-1}\) can elevate the rate of muscle glycogen resynthesis above that previously proposed to be maximal following lower carbohydrate ingestion rates. All the studies included in Figure 2 involved supplementation with carbohydrate in isolation over recovery periods ranging from 2-6 hours in duration and a general positive correlation is apparent between the 2 variables \((r=0.65; P<0.01)\). The specific methodologies employed across this range of studies varied greatly with respect to a number of factors that are known to impact upon muscle glycogen resynthesis (e.g. the degree of muscle damage and glycogen depletion induced prior to recovery; (36, 37)). In particular, the muscle glycogen concentrations at the start of recovery ranged from \(\approx 16-260\) mmol glucosyl units kg dry mass\(^{-1}\) across these studies (26, 38). Given the effective autoregulation of muscle glycogen concentration (12), it is highly likely that the large variation in terms of glycogenesis at any given rate of carbohydrate ingestion is mainly the result of these differences between studies in terms of glycogen availability at the beginning of recovery. Of primary importance, however, is that the general dose-response relationship

![Figure 2. Rates of muscle glycogen resynthesis during 2-6 h recovery periods across 26 separate studies involving varied carbohydrate ingestion rates during recovery (based on data reported in references 4-6, 10, 14, 15, 17-20, 26, 31, 36, 38, 39, 40-50).](image-url)
between carbohydrate intake and glycogen resynthesis appears to be limited at a maximal rate of ~45 mmol glycosyl units kg dry mass\(^{-1}\)h\(^{-1}\), a rate which can be accomplished by ingesting \(\sim 1.2\) g CHO·kg body mass\(^{-1}\)h\(^{-1}\) (20).

The relationship illustrated in Figure 2, together with the proposed association between pre-exercise muscle glycogen availability and exercise capacity (2), may well account for the enhanced recovery of endurance running capacity when 0.5 g CHO·kg body mass\(^{-1}\)h\(^{-1}\) is ingested during a 4 h recovery in comparison with ingestion of a placebo (51). However, given these same correlations, it is puzzling to find that some studies have not reported further enhancements of exercise capacity when carbohydrate dose is increased upwards of 0.5 g CHO·kg body mass\(^{-1}\)h\(^{-1}\) (52, 53), particularly in view of subsequent findings confirming that the rate of muscle glycogen resynthesis would have been accelerated by such an increase in carbohydrate intake (26). Nonetheless, our most recent evidence has now demonstrated that increasing the rate of carbohydrate ingestion during recovery from 0.8-1.1 g CHO·kg body mass\(^{-1}\)h\(^{-1}\) is reflected by a concomitant improvement in exercise capacity following recovery (54).

**SUMMARY**

Carbohydrate ingestion during recovery from prolonged exercise plays a crucial role in replenishing depleted carbohydrate reserves and therefore in promoting the rapid restoration of exercise capacity. Based upon current evidence, the optimal method of carbohydrate supplementation for recovery involves ingesting \(\sim 1\) g/kg body mass\(^{-1}\)h\(^{-1}\) of a high glycaemic index carbohydrate, beginning immediately after exercise and then at frequent intervals for the remainder of recovery (i.e., \(\leq 30\) minute intervals). These recommendations are likely to be quantitatively more important when the time available for recovery is less than 8 hours; if a repeated performance is not required until the next day then personal preferences can be taken into account more readily without any major detriment to the recovery process.

**REFERENCES AND NOTES**

44. Roy BD, Tarnopolsky MA. Influence of differing macronutrient
43. Zawadzki KM, Yaspelkis BB, 3rd, Ivy JL. Carbohydrate-protein
41. McCoy M, Proietto J, Hargreaves M. Skeletal muscle GLUT-4
37. Asp S, Watkinson A, Oakes ND, Kraegen EW. Prior eccentric
35. Rowlands DS, Wallis GA, Shaw C, Jentjens RLPG, Jeukendrup
64. Roy BD, Tarnopolsky MA. Influence of differing macronutrient
industry hi-tech
unhappy with profits coming from the venture, which were
between the two companies, Podravka revealed it was
their position in the Polish retail market. Podravka brought the
An agreement between Podravka and Rieber & Søn has
AN ABRUPT END
Omega-3 research studies and provides links to the abstracts.
visitors with important Omega-3 information such as
marketers and retailers about the organization, its mission,
website, www.goedomega3.com. The website was created to
DHA Omega-3 (GOED Omega-3) launched their new
On Friday, February 9, the Global Organization of EPA and
www.nikkenfoods.com [...]
In the future, we would like to research and develop new
inc, lays the foundation for continued growth in North America
USA, Inc, explains: “The establishment of Nikken Foods USA,
Japan, director and chairman of the Board of Nikken Foods
acquisition
NIKKEN FOODS
www.kyowa.co.jp
been used as an ingredient in the medical nutrition industry,
but dietary supplement manufacturers are increasingly finding uses for
www.lycored.com
SPRAY-DRIYING AND ENCAPSULATION SPECIALIST
Friesland Foods Keflivt is expanding its food ingredients spray-
drying capacity in Southeast Asia. The investment in new
multi-purpose equipment enables Friesland Foods Keflivt to
implement its Asian growth and added-value strategy by
producing its current and future product portfolio itself. The
investment amounts to 21 million euros, creating some 90
new jobs in Salatiga, Central Java, Indonesia. Friesland Foods
Keflivt also opened a new sales office for the Southeast Asia region in Salatiga in January 2007. Friesland Foods
Keflivt requires a regional production facility in Asia due to
the rapidly growing sales of creamers and higher added value specialty ingredients such as nutritional oil powders for
instant drinks, soups and sauces, bakery supplies, infant formulas and enhanced nutrition products for the Asian
market. Innovation for the portfolio and cost effectiveness are very important to being successful as a co-innovator in the
food industry in the rapidly growing Southeast Asian market. Friesland Foods Keflivt has doubled its production
sales office will provide technical services and full customer
sales office to serve its customers in the dietary
VITIVA OPENS NEW OFFICE IN FRANCE
Vitiva has announced the opening of a new sales office in
Cannes, France, to serve its customers in the dietary
supplement food and beverage markets. In response to the
growing demand for Vitiva’s high-value products, the new sales office will provide technical services and full customer
VITIVA NEWS NEWS
www.kievit.com
Friesland Foods Kievit opened a new regional sales office in Salatiga, Central Java, Indonesia on 1 January 2007. Maintain contacts with customers and
calancing sales and marketing activities in the region itself enables the company to respond more quickly to specific
questions from customers. In addition, Friesland Foods Keflivt is better able to gather regional market information, allowing
it to immediately exploit market developments. Friesland Foods Keflivt is an operating company of Royal Friesland Foods.
www.kievit.com
GOED OMEGA-3 LAUNCHES NEW WEBSITE
On Friday, February 9, the Global Organization of EPA and
DHA Omege-3 (GOED Omege-3) launched their new
www.goedomega3.com. The website was created to inform members, science media, health professionals, trade
merchants and retailers about the organization, its mission, and its muscular benefits. The website also provides
visitors with important Omega-3 information such as downloadable versions of the Voluntary Monograph and the Omega-3 Newsletter. Additionally, the site describes key
Omega-3 research studies and provides links to the abstracts.
AN ABRUPT END
An agreement between Podravka and Reiber & Sàh has been bought to an abrupt end as the company’s reassess
their position in the Polish retail market. Podravka brought the agreement to an end on 1 January this year after being
unsatisfactory by its results. The two companies saw the agreement as a means of reducing operating costs involved in
operating in the country. Despite reducing operating costs between the two companies, Podravka revealed it was
unhappy with profits coming from the venture, which were falling to increase its competitiveness in the country.
www.lycored.com

LYCORED NAMES SOCHIM AS ITS AGENT IN ITALY
TARGETS THE ITALIAN DIETARY SUPPLEMENT MARKET
Lycored Ltd., Israel, announced today the appointment of Sochim International SpA, Italy, as its strategic partner for the sale of the Lycored product line into the Italian dietary supplement market. “Sochim has a strong commitment to serving its customers well and making effective sourcing, marketing, and support,” says Udi Alroy, Marketing Director at Lycored. “They have built an excellent reputation spanning many decades and are active in the dietary supplements industry. After extensive discussions with Dr. Barbara Pacifici, Scientific Director at Sochim, we are convinced that Sochim does not just “sell” ingredients, but offers value-added solutions; an ideal asset to Lycored’s loyal customer base in Europe.” Sochim will market Lycored’s extensive line of high-value, natural
carotenoids, including Lyc-O-Mato® tomato lycopene complex, beta-carotene and the Lyco-O-Linen line. The patented lutein line was the open to get the opportunity to provide data for a loaded with Lycopodium, a good looking, and Lycogold, which is very competitive in terms of innovation and brings substantial benefits needed by a market in rapid evolution. “The LycoRed natural carotenoids line fits perfectly into our portfolio and adds value to our catalog”, explains Dr. Barbara Pacifici, Scientific Director at Sochim. “The Italian market is very competitive, looking for innovation and embracing scientific concepts. In this respect, Lycored’s branded ingredients respond perfectly to this market demand. We welcome the opportunity to offer these excellent products to our customers and we are very enthusiastic about working closely with the LycoRed team”. Lycored creates innovative products through a combination of new and innovative products and close relationship with their customers. Lycored’s nutrition solutions simplify the development and production process of cutting-edge food, beverage and nutritional supplement products. Partnership and support through all the stages of product development allows the customer to benefit from Lycored’s expertise and experience.
www.lycored.com

PHOSPHORUS AND YOUNG FEMALES
Calcium and phosphorus, essential nutrients known to
affect one of the most important regulators of bone metabolism, parathyroid hormone (PTH). The high phosphorus intake of Western diets is considered detrimental to bone due to increased PTH secretion. There have been few controlled dose-response studies on the effects of high phosphorus intake. In this study, the short-term effects of four phosphorus-dosing doses provided in a cross-over design were looked at. Fourteen healthy women, ages 20-28 were randomized to four controlled study days. Each study subject served as his own control. The supplement doses of phosphorus were 0 (control), 250, 750, and 1500mg per day in 3 equally divided

ACTICOA™
Scientific research into the nutritional benefits of cocoa continues to unlock the secrets of this remarkable fruit. The
positive effects of cocoa polyphenols on health and well-being have been known for some time now and the list of proven properties of these powerful antioxidants continues to grow. A recent study conducted by the independent ETAP Research Center in France is breaking entirely new ground in establishing links between the consumption of polyphenols and longevity. Its findings point to the possibility that cocoa polyphenols not only improve the quality of life, especially when getting older, but may well play a part in prolonging it as well. The study concluded that the lifespan of rats consuming Barry Callebaut’s ACTICOA™ cocoa polyphenol powder was 30 percent longer than that of rats subjected to the same stress levels without being given cocoa polyphenols. A group of rats subjected to severe stress and a high intake of polyphenols lived 30% longer than control rats.

NEW HEALTHY SNACK BARS
According to a recent report by the Office of Dietary Supplements (ODS) of the National Academy of Sciences, evidence
demonstrating the effectiveness of plant sterols and stanols in lowering plasma lipids is among the top 25 most significant scientific advances in dietary supplement research of the past year. Plant sterols are the active ingredient in new
CardiPRO™ nutrient bars from LaBelle, Inc. ODS cited a study published in Journal of Cardiology in which 2 grams per day
would bring cholesterol levels in the bloodstream significantly lowered LDL “bad” cholesterol, an effect that was
further enhanced when the “phytosterols” were offered in addition to statin drug therapy. Plant sterols and related stanols have chemical structures similar to cholesterol, but are actually heart healthy. By increasing the dietary intake of plant
sterols, the liver becomes a “cholesterol blaster” and cannot release cholesterol during meals, as well as increase cholesterol
excretion, resulting in lower blood cholesterol levels. www.cds.od.nih.gov; www.labellenic.com

AGRANA BUSINESS
Acquisitions within Agrana’s fruit segment have continued to drive the company’s own growth and success throughout the year. The first quarter of 2007/08 will lead to a
higher-than-expected improvement in revenues for the reporting year. www.agrana.com

SOFT GEL TECHNOLOGIES, INC.® APPOINTS SOCHIM INTERNATIONAL S.P.A. AS THEIR AGENT FOR ITALY
Soft Gel Technologies, Inc (SGT) has appointed Sochim International S.p.A., of Milan, Italy to represent their portfolio of dietary supplement products in Europe.
www.sochim.com

A new report released by the European Commission of permitted levels of these metals in our diet. Metals and other elements can be present in the soil, air, or water and can contaminate food and beverages, from contamination during manufacture/processing and storage, or by direct addition, but excessive amounts of any metal could be potentially dangerous.

www.food.gov.uk