CASE STUDY: CARBOHYDRATE SUPPLEMENTATION IMPROVES ULTRA-ENDURANCE PERFORMANCE IN A KETO-ADAPTED INDIVIDUAL

Matthew Carpenter, James Brouner, and Owen Spendiff

School of Life Sciences, Kingston University, Kingston upon Thames, United Kingdom

Case study
DOI 10.26582/k.56.1.16

Abstract:

Ketogenic dietary interventions cause a dramatic increase in fat oxidation, with a growing body of research indicating prolonged ketogenic diets do not impair exercise performance. However, there is neither strong evidence in support of such a strategy. Over prolonged endurance events, the need for carbohydrates becomes increasingly important to prevent glycogen depletion and hypoglycaemia. A case study methodology was used to examine the response of an ultra-endurance runner with experience of events ranging from 60 to 161km (age: 37; stature: 184cm; mass: 80.2±0.8kg; $\dot{V}O_{2\max}$ 56.5ml/kg/min; mean training volume 37km/week) to three identical 67km field tests following an 8-week ketogenic dietary intervention. Supplementation protocols comprised an acute carbohydrate feeding on the day of competition (74g carbohydrate [0.92g/kg pre-race], 310g [3.85g/kg] during race), in addition to a condition comprising an acute feed as well as a two day of carbohydrate feed (200g carbohydrate [2.5g/kg] in two day feed, 44g carbohydrate [0.54g/kg pre-race], 310g [3.85g/kg] during race), prior to the event and these were compared to baseline event where no carbohydrate was consumed, within race feeding restricted to low carbohydrate options. Compared to baseline (05:58:47 [hours:minutes:seconds]), the 67km time trial improved in both carbohydrate feeding conditions, with greater performance improvements after acute consumption compared to the two-day feed (05:36:59 vs. 05:42:01). Rate of fat oxidation during 0-15km and 40-45km of the acute condition time trial decreased compared to baseline (0.95±0.32g/min, 0.42±0.24g/min vs. 1.20±0.34g/min, 0.89±0.02g/min), and was greatest during the two-day feed condition (1.52±0.30g/min, 1.37±0.34g/min). Carbohydrate feeding impacted substrate metabolism and improved time to complete ultra marathon performance in a ketogenic athlete emphasising the importance of carbohydrates as a fuel for exercise performance. More research is required to determine the efficacy of this strategy within ketogenic athletic populations, as well as investigating optimal ketogenic dietary practices and carbohydrate supplementation protocols.

Keywords: *fat oxidation, RER, carbohydrate feeding, carbohydrate oxidation*

Introduction

Ketogenic diets are becoming an increasingly popular fuelling regime for recreational and elite athletes (Zinn, Wood, Williden, Chatterton, & Maunder, 2017). Despite a marked increase in the contribution of fat oxidation to substrate utilisation during endurance exercise in chronically keto-adapted athletes, there is little evidence to suggest this improves exercise performance. To date the research has shown mixed results, with most studies noting no change in performance (Helge, Wulff, & Kiens, 1998; McSwiney, et al., 2018; Phinney, Bistrian, Evans, Gervino, & Blackburn, 1983; Prins, et al., 2023; Prins, et al., 2019; Zajac, et al., 2014) and in some cases, performance impairments (Burke, et al., 2017; Helge, Richter, & Kiens, 1996). Performance impairments are likely a result of the ergolytic properties associated with prolonged carbohydrate restriction, for example, decreased glycogenolysis and a reduction in the active form of pyruvate dehydrogenase (PDHa) (Stellingwerff, et al., 2006), further to this, reductions in training capacity have been shown during the adaptation to a ketogenic diet (Heatherly, et al., 2018; McKay, et al., 2023), causing a training effect that may confound short-term studies (Lindseth, 2017). There is clear evidence that acute carbohydrate ingestion improves endurance performance, with particular benefits in prolonged (~60 minute) exercise (Stellingwerff & Cox, 2014). It is therefore plausible to suggest acute carbohydrate consumption will enhance the performance of keto-adapted athletes, especially during ultra-marathon events. This may be in part due to the ability of exogenous glucose to maintain blood glucose levels, with original studies that form the basis of our understanding of the importance of muscle glycogen concentrations also showing hypoglycaemia at the termination of exercise, in addition to low muscle glycogen concentrations (Noakes, 2022) with this review emphasising the importance of the maintenance of blood glucose through the homeostatic mechanisms of liver glycogen being a driver of the metabolic response to prolonged exercise.

However, the ability of the keto-adapted athlete to absorb and utilise carbohydrates is likely to be sub-optimal, with animal research showing that reducing carbohydrate intake decreases the SGLT1 protein content of the intestine leading to reduced carbohydrate absorption and oxidation during exercise (Dyer, et al., 2009; Higashida, et al., 2019; Jeukendrup, 2017; Shirazi-Beechey, et al., 1991). This is supported by human studies showing increased daily carbohydrate consumption increases exogenous glucose (Cox, et al., 2010). It is also unknown how different carbohydrate re-introduction strategies impact oxidation rates and, ultimately, exercise performance.

A synergistic outcome that combines high rates of carbohydrate oxidation with the retention of an enhanced capacity for fat oxidation provides a means of preventing glycogen depletion and hypoglycaemia, which would otherwise limit the performance in keto-adapted individuals in prolonged endurance performance (Cox, et al., 2010), as well as influencing performance through central nervous system-based mechanisms (Maunder, Kilding, & Plews, 2018; Stellingwerff & Cox, 2014). Whilst there is a growing body of research examining the impact of ketogenic diets on endurance performance, little work has been conducted in the context of ultra-endurance performance, despite the increased importance of fat oxidation in longer exercise formats (Frandsen, Vest, Larsen, Dela, & Helge, 2017) making it a more promising area of research in the context of ketogenic diets.

Research has shown the inevitability of ketosis in multi-stage ultra-marathon races regardless of high carbohydrate feeding (Cooper, et al., 2023), suggesting that keto-adaptation may be advantageous in individuals performing over this distance. However, at present, few studies have addressed the impact of carbohydrate feeding following prolonged exposure to a ketogenic diet. Previous case study-based research has found carbohydrates to improve some aspects of performance following keto-adaptation (Webster, Swart, Noakes, & Smith, 2018), with single-case research used as a means to rigorously study participants on an individual basis, with this being a valuable methodology to study unique populations (Barker, Mellalieu, McCarthy, Jones, & Moran, 2013) such as ultra-endurance athletes on a prolonged ketogenic diet. Therefore, the aim of this case study was to determine metabolic effects and performance outcomes of acute carbohydrate feeding strategies in a keto-adapted (defined as <5% calories from carbohydrates) sub-elite ultra-endurance athlete.

Methods

A trained male ultra-endurance runner (age: 37; stature: 184cm; mass: 80.2±0.8kg; $\dot{V}O_{2\max}$ 56.5ml/kg/min) was recruited to take part in this study. The participant has been competing in ultra-endurance events ranging between 60-161km for six years. The athlete followed his habitual training routine throughout the testing period, with an average of 39km per week during baseline, 33km per week during the acute carbohydrate phase, and 40km per week during the two-day carbohydrate feeding phase.

Informed consent was obtained, in addition to blood sampling consent. Ethical approval was granted by the University Ethics Board and all procedures and conduct met with the Declaration of Helsinki.

The study used a single case, ABC design. This design involved a baseline (condition A), followed by an acute carbohydrate feeding (condition B) and a two-day carbohydrate feeding (condition C).

The participant had been following a ketogenic diet for eight weeks prior to the first exercise test and tracked all food consumed for the entirety of the testing period using a mobile food logging application (MyFitnesspal, Inc) that uses a food composition database that is sourced by the App and users of the App (Tosi, et al., 2021), weighing food prior to inputting serving size. As well as this, urine ketones were monitored daily for the first fourteen days to check ketogenic status (Mission urinanalysis, San Diego, CA), with ketones achieved by day four. Food database tracking suggested 100% compliance, in addition to the urine ketone data, that showed ketosis in every test from day 4. Following the first 14 days of intervention, urine ketones were monitored every second day. The participant monitored his general diet, ensuring he adhered to a ketogenic diet; defined as <5% of total calories from carbohydrate. Body composition was evaluated to determine changes throughout the study using multi-frequency bioelectrical impedance analysis (Tanita Europe B.V. Amsterdam, Netherlands).

Body mass remained stable throughout the intervention when measured before each condition of testing, prior to interventions (mean body mass 80.2±0.8kg). Testing spanned over a 9-week period, which involved the participant completing a 67km ultra-marathon time trial (TT) under the three separate conditions. The first TT was performed in a fully ketogenic state, with no carbohydrate feeding before or during the time trail. The second TT entailed acute (on the day of the trial) carbo-

Table 1. Foods consumed on race day -2, race day -1 and on race day

Condition	**Baseline**	**Acute**	**2 Day Feed**
Race Day -2	Breakfast Egg, whole, cooked, fried, 2 large	Breakfast Sausage, 2 links Egg, fried, 2 large	Lunch Hand Cooked Sea Salt & Balsamic Vinegar Crisps (40g), 40 g
	Sausage - Sausage, 2 links		
	Lunch Cathedral City - Mature Cheese 50g, 60 g	Lunch Hamburger & Salad, 2 Plate	Roast Chicken & salad sandwich, 1 pack
	Peperami Hot - Meat Stick 22.5g, 45 g	Dinner	Dinner
	Dinner Extra Virgin Olive Oil 3 tablespoon (15g	Pork & Herb Chipolatas Seasoned With Rosemary & Thyme, 4 chipolatas	Chocolate Truffles, 2 chocolate
	Mature Cheese 50g, 30 g	Pimento Stuffed Olives With Manchego, 75 g	50% Milk Chocolate Slab, 17 g
	Roast Chicken Breast Fillet, 100 g	Mature Cheese 50g, 40 g	Butter, 3 tbls
	Passata, 99 g	Butter, 3 tbls	Wholemeal Rustic Roll, 1 roll
	Cougette, 30 g	Free Range Eggs (Medium), 232 g egg	Egg, whole, cooked, fried, 3 large
	Garlic, raw, 1 clove	Snacks	Bacon, 3 pieces
	Onion, Small Cooked	Salted Peanuts, 40 gram	Snacks
	Snacks		Mature Cheese 50g, 60 g
	Salted Peanuts 40 gram		Salted Peanuts, 40 gram
	Almond Milk – Unsweetened		Strawberries, 1 cup (144g)
	Seeds, flaxseed, 1 tbsp, whole		Fruit - Cherries - Dark Sweet No Sugar Added, 30 g
	Acai and blueberries, 15 g		Sea Salt & Balsamic Vinegar crisps, 33 g
	Coconut Oil, 1 tbsp		
Race Day -1	Breakfast	Breakfast	Breakfast
	Egg, fried, 2 large	Sausage - Sausage, 2 links	Rasins,
	Sausage - Sausage, 2 links	Egg, whole, cooked, fried, 2 large	Unsweetened Yoghurt, 80 g
	Dinner	Dinner Cypriot Halloumi Cheese, 100 g	Porridge - Oats, 90 g
	Almond Milk - Unsweetened flaxseed, 1 tbsp, whole	Lettuce, 1 cup shredded	Dinner
	Acai and blueberries, 15 g	Pimento Stuffed Olives With Manchego, 75 g	Vanilla Dairy Ice Cream
	Coconut Oil, 1 tbsp	Cucumbers, 20 g	Fresh - Strawberries, 1 cup (144g)
	Mature Cheese 50g, 40 g	Mayonnaise, 2 Tbsp (13g)	Butter, 2 tbls
	Seed Crackers, 20 g	Haimisha Cucumbers, 10 g	Baked Jacket, 100 g
	Butter, 3 tbls	Extra Virgin Olive Oil 3 tablespoon (15g)	Baked Jacket, 100 g
	Unsmoked Bacon, 200 gram	Tuna Chunks In Brine, 100 g	Mayonnaise, 50 g
	Snacks	Snacks	Extra Virgin Olive Oil 4 tablespoon (15g)
	Salted Peanuts, 40 gram	Mature Cheese 50g, 30 g	Mixed Leaf Salad, 84 g
		Salted Peanuts Original, 40 gram	Masala Chicken Breasts, 1 Pack
			Snacks Cheese Oatcakes, 6 biscuit
			Belgian Dark Chocolate Rice Thins, 2 Thin
Pre Race Meal	Coconut oil Flaxseed Almond milk Acai Blueberries	Chocolate Twist	Danish Bear Claw
During Race	Cheddar Cheese Salted Peanuts	Jaffa Cake Melon Crisps Tailwind Endurance Coca Cola	Jaffa Cake Melon Crisps Tailwind Endurance Coca Cola

Table 2. Food intake before and during ultra-endurance event

Condition	**Baseline**	**Acute**	**2 Day Feed**
2 Days Pre Race (Mean of 2 days ± SD)	**Calories (Kcal)** 2087 ± 511 **Carbohydrate (g)** 15 ± 5 **Fat (g)** 159 ± 44 **Protein (g)** 153 ± 87	**Calories (Kcal)** 2391 ± 331 **Carbohydrate (g)** 14 ± 0 **Fat (g)** 191 ± 12 **Protein (g)** 139 ± 48	**Calories (Kcal)** 2445 ± 130 **Carbohydrate (g)** 200 ± 82 **Fat (g)** 152 ± 2 **Protein (g)** 90 ± 12
Pre Race Meal	**Calories (Kcal)** 263 **Carbohydrate (g)** 3 **Fat (g)** 23 **Protein (g)** 20	**Calories (Kcal)** 548 **Carbohydrate (g)** 74 **Fat (g)** 22 **Protein (g)** 12	**Calories (Kcal)** 339 **Carbohydrate (g)** 44 **Fat (g)** 16 **Protein (g)** 5
During Race	**Calories (Kcal)** 371 **Carbohydrate (g)** 2 **Fat (g)** 30 **Protein (g)** 20	**Calories (Kcal)** 1398 **Carbohydrate (g)** 310 **Fat (g)** 14 **Protein (g)** 5	**Calories (Kcal)** 1398 **Carbohydrate (g)** 310 **Fat (g)** 14 **Protein (g)** 5
Total Food Consumption On Race Day	**Calories (Kcal)** 644 **Carbohydrate (g)** 5 **Fat (g)** 53 **Protein (g)** 40	**Calories (Kcal)** 1946 **Carbohydrate (g)** 384 **Fat (g)** 36 **Protein (g)** 17	**Calories (Kcal)** 1737 **Carbohydrate (g)** 354 **Fat (g)** 30 **Protein (g)** 10

hydrate consumption. This comprised a carbohydrate meal pre-TT, carbohydrate feeding during the TT and a post-TT carbohydrate meal. The final TT comprised a carbohydrate feed period beginning two days prior to the TT, as well as during it. Calories were controlled in the two days prior to the TT, and in-race nutrition strategies were identical in the two carbohydrate conditions.

Mean calorie intake throughout the testing period was 2150±511 kcal/day (range 210-2946 kcal/day). Mean daily macronutrient intake was: 15±5g (3% of total calories) carbohydrates, 175±44g fat (73% total calories), and 121±35g protein (23% total calories), with exact foods consumed around exercise testing outlined in Table 1, with the caloric and macronutrient breakdown of these foods detailed in Table 2, below.

The TT's were conducted using an identical route that the participant was familiar with, having run it previously. The route was a 12km trail that was completed in laps. Weather conditions were also similar across trials, with temperatures of 11°C, 11°C, and 15°C across the three tests respectively (Weather Underground, 2017) and all under dry conditions. Testing spanned over a 60-day period, in which three phases of testing were conducted. The acute phase was conducted 37 days following the end of the baseline phase, and the two-day phase began 13 days after the end of the acute phase.

Throughout the TT, heart rate (bpm) and distance (km) were measured continuously as well as time to completion using a running watch (Garmin Fenix 3, Garmin, Olath, Kanses). Oxygen kinetics and substrate oxidation were measured for the beginning 15km and for a 5km section between 40-45km using a Cosmed K5 (Cosmed Ltd, Via dei Piani di Monte, Sarello, PO Box 3, Pavonna di Albano, Rome, 00040 Italy). The unit was calibrated prior to each section, with the Cosmed K5 being put on the participant during a pre-scheduled food and drink station section.

Blood glucose (mmol) and lactate (mmol) were measured immediately prior, at 15km and then at subsequent 12km intervals throughout the TT, with the final measure immediately following the end of the TT. These were measured using finger-prick samples with the Biosen C-Line Sport (EKF diagnostic Sales GmbH, Ebendorfer Chaussee 3, Technologiepark Ostfalen, Germany).

Blood samples and the application of Cosmed K5 was performed simultaneously at feeding points to minimise the impact on time to completion, with all blood sampling completed prior to the participant finished consuming his relevant nutrition. Fat and carbohydrate oxidation were calculated using stochiometric equations outlined by Peronnet and Massicotte (1991).

Statistics

Data were analysed through visual analysis, with the data presented in tables and figures. Percentage change was used to determine changes in performance and physiological markers where appropriate.

Results

In the two days prior to ultra-endurance run, daily calorie intake at baseline was 2087±511 kcal/day comprising 15 ± 5g carbohydrate, 159±44g fat and 153±87g protein. During the acute condition, it was 2391±331 kcal/day, with 14±0g carbohydrate, 191±12g fat and 139±48g protein, and during the two-day load condition, it was 2445±130 kcal/day, with 200±82g carbohydrate, 152±2g fat and 90±12g protein.

On the morning of the ultra-endurance run, 263 kcal were consumed during the baseline condition, comprising 3g carbohydrate, 23g fat and 20g protein. In the acute condition, a meal comprising 548kcal, with 74g carbohydrate, 22g fat and 12g protein was consumed. In the two-day load condition, a 339 kcal meal was consumed with 44g carbohydrate, 16g fat and 5g protein. Body mass remained stable throughout the intervention when measured before each condition of testing, prior to the interventions (mean body mass 80.2±0.8kg).

67km TT (time trial) results

Time to completion (hours:minutes:seconds) was 6.1% faster during the acute condition (05:36:59) than baseline (05:58:47), with the two-day feed time (05:42:01) being 4.5% faster than baseline and 1.8% slower than under the acute condition.

Oxygen consumption and substrate oxidation, measured for the first 15km and a 5km section during the time trials, are shown alongside accompanying split times in Table 3.

Mean heart rate throughout the entirety of the TT was 148±8 bpm at baseline, 147±10 bpm during the acute condition, and 148±10 bpm in the two-day feed condition.

Lactate and glucose measures taken across the testing period are shown in Figures 1 and 2, below.

Discussion and conclusions

The main finding of this study revealed that a keto-adapted athlete's TT improved in both carbohydrate feeding conditions compared to baseline, with greater performance improvements evident after the acute consumption compared to the two-day feed (05:36:59 vs. 05:42:01). These findings, whilst only in the format of a case study, indicate that

Table 3. Pace and physiological markers during the first 15km and the 40-45km section of the TT across the three conditions

	First 15 km			Mid 5km section		
	Baseline	**Acute**	**2 Day Feed**	**Baseline**	**Acute**	**2 Day Feed**
Split time (Hours:minutes:seconds)	01:13:50	01:09:09	01:10:51	00:28:11	00:25:04	00:25:07
Oxygen Consumption (ml/kg/min)	42.3±6.6	46.7±4.0	47.1±4.9	35.3±3.1	37.7±2.6	45.4±4.4
RER	0.79±0.05	0.85±0.05	0.76±0.04	0.81±0.04	0.92±0.05	0.78±0.05
Carbohydrate Oxidation (g/min)	1.2±0.8	2.4 ± 1.0	1.02±0.7	1.37±0.57	2.95±0.66	1.24±0.85
Fat Oxidation (g/min)	1.2±0.3	0.95±0.3	1.52±0.3	0.89±0.02	0.42±0.24	1.37±0.34
Heart rate (bpm)	148±11	155±9	153±5	148±11	155±9	156±5

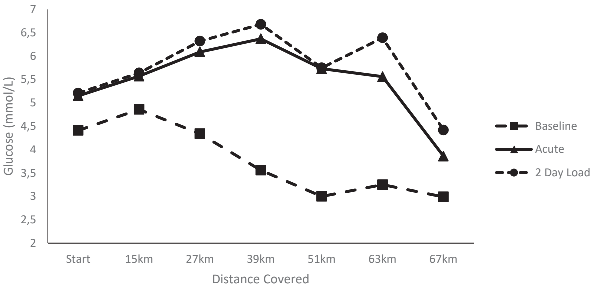

Figure 1. Glucose measurements throughout the duration of the time trial.

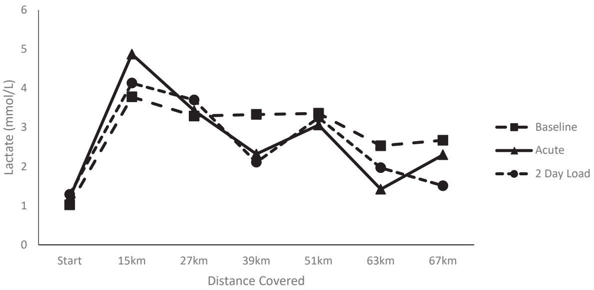

Figure 2. Lactate measurements throughout the duration of the time trial.

carbohydrates are ergogenic in keto-adapted individuals as they are in non-keto adapted individuals (Stellingwerff & Cox, 2014), despite poor glucose uptake following carbohydrate restriction (Shirazi-Beechey, et al., 1991; Stellingwerff & Cox, 2014), which may result in reduced efficacy of carbohydrate in this population. Performance improvements in longer duration activity are predominantly attributed to maintenance of glycogen stores and blood glucose, shown in Figure 2, that leads to augmented carbohydrate oxidation by the muscle (Stellingwerff & Cox, 2014; Stellingwerff, et al., 2006). This improved blood glucose maintenance prevents hypoglycaemia, which is thought to impair cognitive state (Warren & Frier, 2005) and perceived mental state (Glace, Murphy, & McHugh, 2002). This maintenance of blood glucose represents a key rationale explaining performance improvements, with hypoglycaemia occurring as a result of low hepatic glycogen content. Noakes (2022) outlined a scenario in which hypoglycaemia may in fact play a role in the homeostatic regulation of exercise, with hypoglycaemia being prevented through to ensure brain damage does not occur. This led Noakes to suggest that in endurance sports, increasing liver glycogen stores could maintain blood glucose and delay hypoglycaemia (Noakes, 2022), with the author also highlighting the fact that hypoglycaemia occurs earlier and to a greater extend on a low-carbohydrate diet, giving further rationale to this argument.

This also allows for greater uptake of glucose to skeletal muscle, alongside the reduced need for extreme rates of carbohydrate ingestion through fat adaptation. This is important in reducing the chance of gastro-intestinal (GI) distress (Stellingwerff & Cox, 2014). With up to 60-96% of ultra-marathon runners experiencing GI distress (Costa, et al., 2017), a ‘live and train keto, compete carb’ nutrition strategy may be a novel alternative to reduce the possibility of in race GI distress in some individuals. This method of fuelling may be a method of increasing fat metabolism and improving metabolic flexibility (Prins, et al., 2023). In addition, this study showed greater carbohydrate oxidation during the acute carbohydrate phase, which is a counter to the previous argument above. Thus, future work must explore the role of carbohydrate supplementation and changes in substrate oxidation in a larger cohort of keto-adapted individuals.

Table 3 shows fat oxidation was substantially lower during the acute condition compared to the ketogenic and two-day feeding conditions, especially compared to previously studied trained athletes (Volek, et al., 2016). In spite of this, rates of fat oxidation still exceeded those observed in non-keto adapted individuals (Venables, Achten, & Jeukendrup, 2005) and matched rates observed by well-trained keto-adapted athletes in the two-day feed condition despite carbohydrate ingestion. The two-day feeding condition showed elevated rates of fat oxidation at the beginning (1.52±0.30g/min) and in the middle section (1.24±0.85g/min) compared to both other conditions. This was despite increased oxygen consumption in the two-day load condition, demonstrating the ability to oxidise fat at an intensity (83% $\dot{V}O_{2\max}$ during first 15km) that would typically be predominantly carbohydrate dependant (Romijn, et al., 1993), this is consistent with recent findings showing the crossover point is shifted for fat-adapted athletes (Noakes, Prins, Volek, D’Agostino, & Koutnik, 2023). A further key finding from the TT was the participant’s ability to maintain a higher rate of oxygen consumption, and in accordance, to maintain a greater speed during carbohydrate supplementation conditions. Heart rate data further supports the ability to maintain higher intensities following carbohydrate ingestion, with a greater heart rate during the carbohydrate fed trials. Whilst lactate levels were not greatly different, they were observed to be greater throughout the second half of the TT during the ketogenic phase. This is unexpected, since through reductions in glycolysis, ketogenic interventions have previously shown reductions in exercising lactate (Zajac, et al., 2014). This may be a result of improved lactate clearance following a ketogenic intervention in all phases, as has been alluded to following four-week ketogenic interventions (Zajac, et al., 2014) in synergy with an increased rate of glycogen synthesis noted in this study. It is noted that the planned increase in pre-race muscle glycogen, presumably achieved by increased carbohydrate intake (~3 g/kg BM/d) in the two days prior to the third TT, did not appear to provide any benefit to performance above that achieved by the planned increase in exogenous CHO availability achieved through the intake of CHO (~4 g/kg) during the TT, although both strategies were associated with a faster TT than the chronic keto-adaptation alone. However, these findings are particular to an individual athlete and the circumstances of this case study, therefore a need this to be investigated in a larger cohort to determine optimal feeding strategies in keto-adapted individuals. It is also important to note that fat oxidation was greater during the two day feeding condition notwithstanding carbohydrate supplementation, supporting the previous research showing that fat oxidation can remain elevated after a period of keto-adaptation despite singular acute carbohydrate ingestion (Carey, et al., 2001; Lambert, et al., 2001). It is clear that fat oxidation was maintained at high rates and this enhanced ability to oxidise fat is particularly beneficial during ultra-endurance exercise (Frandsen, et al., 2017), thus a ketogenic dietary intervention may be useful for athletes looking to spare muscle glycogen over ultra-endurance activities. Future research should look to study this detail in more controlled settings to determine the level of the reduction in fat oxidation following carbohydrate supplementation.

We argue that interventions aimed at promoting the oxidation of endogenous fat stores are critical to the success of ultra-endurance. The evidence of this research revealed a keto-adapted athlete not only increased his fat oxidation as expected, but this persisted even after carbohydrate feeding, which is indicative of the adaptive physiological changes associated with the ketogenic diet working in synergy with acute carbohydrate feeding to monopolise metabolism pathways that can improve ultra-endurance performance. Therefore, this study provides evidence for the notion of training with low carbohydrate availability and competing with high carbohydrate availability to enhance exercise performance in keto-adapted athletes. Principally, the evidence outlined highlights the notion that this is predominantly due to the prevention of hypoglycaemia, suggesting that ketogenic athletes can benefit from carbohydrate ingestion in prolonged exercise in order to maintain normoglycaemia.

A limitation of this study is the lack of direct ketone measurement through venous or capillary blood, and more invasive measurement techniques such as muscle biopsies, and tracers to determine exogenous glucose oxidation would have allowed for further comparisons between differing carbohydrate conditions. Further to this, the reduced calorie intake during the baseline run may be a factor in performance reduction. Whilst calories were matched during both carbohydrate trials, considerably fewer calories were consumed throughout the ketogenic trial (Table 2). This is due to the participant struggling to tolerate high fat foods throughout the baseline run, limiting total calorie intake, which is an important consideration for ultra-endurance athletes. The use of a non-laboratory-based study is also a limitation, as the outside environment may confound results; however, this applied approach adds to the study's ecological validity and offers an insight into the impact of dietary manipulation in an applied setting. A further limitation is the use of a commercial app to monitor food intake which may limit the validity of food intake data since nutrition apps may cause incorrect estimations due to their food composition databased (Tosi, et al., 2021). It is important to note the differences in total calories consumed during the TT. In the ketogenic phase, the athlete consumed ~1,500 calories fewer than in both carbohydrate feeding phases, which may have impacted the time trial result.

Future research should seek to understand changes in physiology and performance following a 'live and train keto, compete carb' nutrition strategy in order to better understand optimal ways to fuel performance in ketogenic individuals. This will not only benefit individuals on ketogenic diets but better inform future research comparing ketogenic diets to standard diets, in which pre-exercise nutrition often differs between groups, with individuals on a ketogenic intervention not receiving pre-exercise carbohydrate, which may skew findings towards non-ketogenic dietary practises.

The aim of this single-case study was to assess the impact of a dietary intervention on a particular athlete from a cohort in which finding a homogenous group is challenging using a method in which practitioners may wish to replicate to optimise fuelling in keto-adapted athletes. The findings of this investigation clearly demonstrates that carbohydrate feeding enhanced time to completion in an ultramarathon in a keto-adapted individual. The synergy for oxidising carbohydrates whilst maintaining relatively high rates of fat oxidation following carbohydrate feeding is of significance to endurance athletes looking to enhance exercise performance in modalities that are impaired by limited glycogen stores. Researchers should look to study carbohydrate supplementation in larger cohorts of ketogenic athletes in order to determine the optimal use of carbohydrate in the keto-adapted athlete and better inform future ketogenic intervention studies.

References

Barker, J.B., Mellalieu, S.D., McCarthy, P.J., Jones, M.V., & Moran, A. (2013). A review of single-case research in sport psychology 1997–2012: Research trends and future directions. *Journal of Applied Sport Psychology*, *25*(1), 4-32. https://doi.org/10.1080/10413200.2012.709579

Burke, L.M., Hawley, J.A., Angus, D.J., Cox, G.R., Clark, S.A., Cummings, N.K., Desbrow, B., & Hargreaves, M. (2002). Adaptations to short-term high-fat diet persist during exercise despite high carbohydrate availability. *Medicine and Science in Sports and Exercise*, *34*(1), 83-91. https://doi.org/10.1113/JP273230

Burke, L.M., Angus, D.J., Cox, G.R., Cummings, N.K., Febbraio, M.A., Gawthorn, K., Hawley, J.A., Minehan, M., Martin, D.T., & Hargreaves, M. (2000). Effect of fat adaptation and carbohydrate restoration on metabolism and performance during prolonged cycling. *Journal of Applied Physiology*, *89*(6), 2413-2421. https://doi.org/10.1152/jappl.2000.89.6.2413

Carey, A.L., Staudacher, H.M., Cummings, N.K., Stepto, N.K., Nikolopoulos, V., Burke, L.M., & Hawley, J.A. (2001). Effects of fat adaptation and carbohydrate restoration on prolonged endurance exercise. *Journal of Applied Physiology*, *91*(1), 115-122. https://doi.org/10.1152/jappl.2001.91.1.115

Cooper, I.D., Kyriakidou, Y., Edwards, K., Petagine, L., Seyfried, T.N., Duraj, T., . . ., & Brookler, K. (2023). Ketosis suppression and ageing (KetoSAge): The effects of suppressing ketosis in long term keto-adapted non-athletic females. *International Journal of Molecular Sciences, 24*(21), 15621. https://doi.org/10.3390/ijms242115621

Costa, R.J., Miall, A., Khoo, A., Rauch, C., Snipe, R., Camões-Costa, V., & Gibson, P. (2017). Gut-training: The impact of two weeks repetitive gut-challenge during exercise on gastrointestinal status, glucose availability, fuel kinetics, and running performance. *Applied Physiology, Nutrition, and Metabolism, 42*(5), 547-557. https://doi.org/10.1139/apnm-2016-0453

Cox, G.R., Clark, S.A., Cox, A.J., Halson, S.L., Hargreaves, M., Hawley, J.A., & Burke, L.M. (2010). Daily training with high carbohydrate availability increases exogenous carbohydrate oxidation during endurance cycling. *Journal of Applied Physiology*, *109*(1), 126-134. https://doi.org/10.1152/japplphysiol.00950.2009

Dyer, J., Al-Rammahi, M., Waterfall, L., Salmon, K.S., Geor, R.J., Bouré, L., Edwards, G.B., Proudman, C.J., & Shirazi-Beechey, S.P. (2009). Adaptive response of equine intestinal Na+/glucose co-transporter (SGLT1) to an increase in dietary soluble carbohydrate. *Pflügers Archiv – European Journal of Physiology*, *458*(2), 419-430. https://doi.org/10.1007/s00424-008-0620-4

Frandsen, J., Vest, S.D., Larsen, S., Dela, F., & Helge, J.W. (2017). Maximal fat oxidation is related to performance in an Ironman triathlon. *International Journal of Sports Medicine*, *38*(13), 975-982. https://doi.org/10.1055/s-0043-117178

Glace, B., Murphy, C., & McHugh, M. (2002). Food and fluid intake and disturbances in gastrointestinal and mental function during an ultramarathon. *International Journal of Sport Nutrition and Exercise Metabolism*, *12*(4), 414-427. https://doi.org/10.1123/ijsnem.12.4.414

Heatherly, A.J., Killen, L.G., Smith, A.F., Waldman, H.S., Seltmann, C.L., Hollingsworth, A., & O'Neal, E.K. (2018). Effects of ad libitum low-carbohydrate high-fat dieting in middle-age male runners. *Medicine and Science in Sports and Exercise*, *50*(3), 570-579. https://doi.org/10.1249/mss.0000000000001477

Helge, J.W., Richter, E.A., & Kiens, B. (1996). Interaction of training and diet on metabolism and endurance during exercise in man. *The Journal of Physiology*, *492*(1), 293-306. https://doi.org/10.1113/jphysiol.1996.sp021309

Helge, J.W., Wulff, B., & Kiens, B. (1998). Impact of a fat-rich diet on endurance in man: Role of the dietary period. *Medicine and Science in Sports and Exercise*, *30*(3), 456-461. https://doi.org/10.1097/00005768-199803000-00018

Higashida, K., Terada, S., Li, X., Inoue, S., Iida, N., Kitai, S., & Nakai, N. (2019). Low-carbohydrate high-protein diet diminishes the insulin response to glucose load via suppression of SGLT-1 in mice. *Bioscience, Biotechnology, and Biochemistry*, *83*(2), 365-371. https://doi.org/10.1080/09168451.2018.1533803

Jeukendrup, A.E. (2017). Training the gut for athletes. *Sports Medicine, 47*(Suppl 1), 101-110. https://doi.org/10.1007/s40279-017-0690-6

Lambert, E.V., Goedecke, J.H., van Zyl, C., Murphy, K., Hawley, J.A., Dennis, S.C., & Noakes, T.D. (2001). High-fat diet versus habitual diet prior to carbohydrate loading: Effects on exercise metabolism and cycling performance. *International Journal of Sport Nutrition and Exercise Metabolism*, *11*(2), 209-225. https://doi.org/10.1123/ijsnem.11.2.209

Lindseth, I. (2017). Methodological issues question the validity of observed performance impairment of a low carbohydrate, high fat diet. *The Journal of Physiology*, *595*(9), 2989. https://doi.org/10.1113/JP273990

Maunder, E., Kilding, A.E., & Plews, D.J. (2018). Substrate metabolism during Ironman triathlon: Different horses on the same courses. *Sports Medicine*, *48*, 2219-2226. https://doi.org/10.1007/s40279-018-0938-9

McKay, A.K., Ross, M.L., Tee, N., Sharma, A.P., Leckey, J.J., & Burke, L.M. (2023). Adherence to a ketogenic low-carbohydrate, high-fat diet is associated with diminished training quality in elite racewalkers. *International Journal of Sports Physiology and Performance*, *18*(7), 686-694. https://doi.org/10.1123/ijspp.2022-0351

McSwiney, F.T., Wardrop, B., Hyde, P.N., Lafountain, R.A., Volek, J.S., & Doyle, L. (2018). Keto-adaptation enhances exercise performance and body composition responses to training in endurance athletes. *Metabolism, 81*, 25-34. https://doi.org/10.1016/j.metabol.2017.10.010

Noakes, T.D. (2022). What is the evidence that dietary macronutrient composition influences exercise performance? A narrative review. *Nutrients, 14*(4), 862. https://doi.org/10.3390/nu14040862

Noakes, T., Prins, P., Volek, J., D'Agostino, D., & Koutnik, A. (2023). Low carbohydrate high fat ketogenic diets on the exercise crossover point and glucose homeostasis. *Frontiers in Physiology, 14*, 1150265. https://doi.org/10.3389/fphys.2023.1150265

Peronnet, F., & Massicotte, D. (1991). Table of nonprotein respiratory quotient: An update. *Canadian Journal of Sport Science, 16*(1), 23-29.

Phinney, S.D., Bistrian, B.R., Wolfe, R.R., & Blackburn, G.L. (1983). The human metabolic response to chronic ketosis without caloric restriction: Physical and biochemical adaptation. *Metabolism*, *32*(8), 757-768. https://doi.org/10.1016/0026-0495(83)90105-1

Prins, P.J., Noakes, T.D., Buga, A., D'Agostino, D.P., Volek, J.S., Buxton, J.D., Heckman, K., Jones, D.W., Tobias, N.E., Grose, H.M., Jenkins, A.K., Jancay, K.T., & Koutnik, A.P. (2023). Low and high carbohydrate isocaloric diets on performance, fat oxidation, glucose and cardiometabolic health in middle age males. *Frontiers in Nutrition*, *10*, 1084021. https://doi.org/10.3389/fnut.2023.1084021

Prins, P.J., Noakes, T.D., Welton, G.L., Haley, S.J., Esbenshade, N.J., Atwell, A.D., Scott, K.E., Abraham, J., Raabe, A.S., Buxton, J.D., & Ault, D.L. (2019). High rates of fat oxidation induced by a low-carbohydrate, high-fat diet, do not impair 5-km running performance in competitive recreational athletes. *Journal of Sports Science and Medicine*, *18*(4), 738.

Romijn, J. A., Coyle, E., Sidossis, L., Gastaldelli, A., Horowitz, J., Endert, E., & Wolfe, R. (1993). Regulation of endogenous fat and carbohydrate metabolism in relation to exercise intensity and duration. *American Journal of Physiology—Endocrinology and Metabolism, 265*(3), E380-E391. https://doi.org/10.1152/ajpendo.1993.265.3.E380

Shirazi-Beechey, S.P., Hirayama, B.A., Wang, Y., Scott, D., Smith, M.W., & Wright, E.M. (1991). Ontogenic development of lamb intestinal sodium-glucose co-transporter is regulated by diet. *The Journal of Physiology*, *437*(1), 699-708. https://doi.org/10.1113/jphysiol.1991.sp018620

Stellingwerff, T., & Cox, G.R. (2014). Systematic review: Carbohydrate supplementation on exercise performance or capacity of varying durations. *Applied Physiology, Nutrition, and Metabolism*, *39*(9), 998-1011. https://doi.org/10.1139/apnm-2014-0027

Stellingwerff, T., Spriet, L.L., Watt, M.J., Kimber, N.E., Hargreaves, M., Hawley, J.A., & Burke, L.M. (2006). Decreased PDH activation and glycogenolysis during exercise following fat adaptation with carbohydrate restoration. *American Journal of Physiology—Endocrinology and Metabolism*, *290*(2), E380-E388. https://doi.org/10.1152/ajpendo.00268.2005

Tosi, M., Radice, D., Carioni, G., Vecchiati, T., Fiori, F., Parpinel, M., & Gnagnarella, P. (2021). Accuracy of applications to monitor food intake: Evaluation by comparison with 3-d food diary. *Nutrition*, *84*, 111018. https://doi.org/10.1016/j.nut.2020.111018

Venables, M.C., Achten, J., & Jeukendrup, A.E. (2005). Determinants of fat oxidation during exercise in healthy men and women: A cross-sectional study. *Journal of Applied Physiology*, *98*(1), 160-167. https://doi.org/10.1152/japplphysiol.00662.2003

Volek, J.S., Freidenreich, D.J., Saenz, C., Kunces, L.J., Creighton, B.C., Bartley, J.M., …, & Phinney, S.D. (2016). Metabolic characteristics of keto-adapted ultra-endurance runners. *Metabolism*, *65*(3), 100-110. https://doi.org/10.1016/j.metabol.2015.10.028

Warren, R.E., & Frier, B.M. (2005). Hypoglycaemia and cognitive function. *Diabetes, Obesity and Metabolism*, *7*(5), 493-503. https://doi.org/10.1111/j.1463-1326.2004.00421.x

Webster, C.C., Swart, J., Noakes, T.D., & Smith, J.A. (2018). A carbohydrate ingestion intervention in an elite athlete who follows a low-carbohydrate high-fat diet. *International Journal of Sports Physiology and Performance*, *13*(7), 957-960. https://doi.org/10.1123/ijspp.2017-0392

Zajac, A., Poprzecki, S., Maszczyk, A., Czuba, M., Michalczyk, M., & Zydek, G. (2014). The effects of a ketogenic diet on exercise metabolism and physical performance in off-road cyclists. *Nutrients*, *6*(7), 2493-2508. https://doi.org/10.3390/nu6072493

Zinn, C., Wood, M., Williden, M., Chatterton, S., & Maunder, E. (2017). Ketogenic diet benefits body composition and well-being but not performance in a pilot case study of New Zealand endurance athletes. *Journal of the International Society of Sports Nutrition*, *14*(1), 22. https://doi.org/10.1186/s12970-017-0180-0

Submitted: July 27, 2023
Accepted: May 31, 2024

Correspondence to:
Matthew Carpenter
Kingston University
Kingston upon Thames, KT1 2EE, United Kingdom
E-mail: k1408169@kingston.ac.uk

Acknowledgements

The authors declare that the results of the study are presented clearly, honestly and without falsification, fabrication or inappropriate data manipulation.

Competing interests

The authors declare that they have no competing interests.