

## **Fat Metabolism and the Athlete**

### **Can the Ingestion of Medium Chain Triglycerides Enhance Performance by Producing A Glycogen Sparing Effect in Endurance Athletes?**

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#### **Introduction**

It is widely accepted that elite athletes are a product of genetics and quality training. To become or remain competitive at the top of their respective sports elite athletes must seize upon every legal advantage which might be available to them. A major contribution to success may be achieved by nutritional manipulation of an athlete's diet as it is only by consuming the correct fuel mix that an athlete can produce the energy needed to perform at the highest level. Energy production for body movement is an essential factor in maintaining peak performance with each discipline having specific requirements. For example: explosive sports require rapid energy production over a short timescale whereas endurance events demand economy allowing the athlete to sustain the highest work rate possible over an extended period.

Although carbohydrate (CHO) is considered the fuel of choice for athletic energy, fatty acids have certain advantages that potentially make them just as important. For example, fat contains over twice the amount of energy as an equal weight of CHO. Furthermore, as it is stored without water, it is comparatively light, and stored in abundance compared with the limited supply of CHO. Unfortunately, fat metabolism is relatively slow and there appears to be many potential rate-limiting steps prior to oxidation and subsequent energy release.

Strategies aimed at improving athletic performance has prompted research into nutritional practices that could, in theory, enhance fatty acid metabolism and lead to a sparing effect on CHO potentially improving exercise endurance. Nutritional interventions such as the ingestion of caffeine, L-carnitine, consumption of medium chain triglycerides (MCT), fat ingestion, fat infusions, and high fat, low carbohydrate dietary regimes have all been proposed as possible ergogenic aids (Hawley 1998).

Whilst a wealth of research has been undertaken into CHO metabolism, comparatively little is known about the processes of fatty acid regulation and utilisation. The intention here is to briefly review the potential of fat as an energy source, consider some of the key regulatory factors and review some of the postulated limiting steps in fat metabolism. It is suggested that one of the main limits to long chain fatty acid metabolism is its inability to cross the inner mitochondrial membrane without a transport mechanism. However, it appears that medium chain fatty acids can pass into the mitochondria independently and thus may be an alternative substrate for rapid oxidation. The key aim of this dissertation is to critically review current research investigating the effectiveness of exogenous MCT ingestion on athletic performance and its glycogen sparing effect.

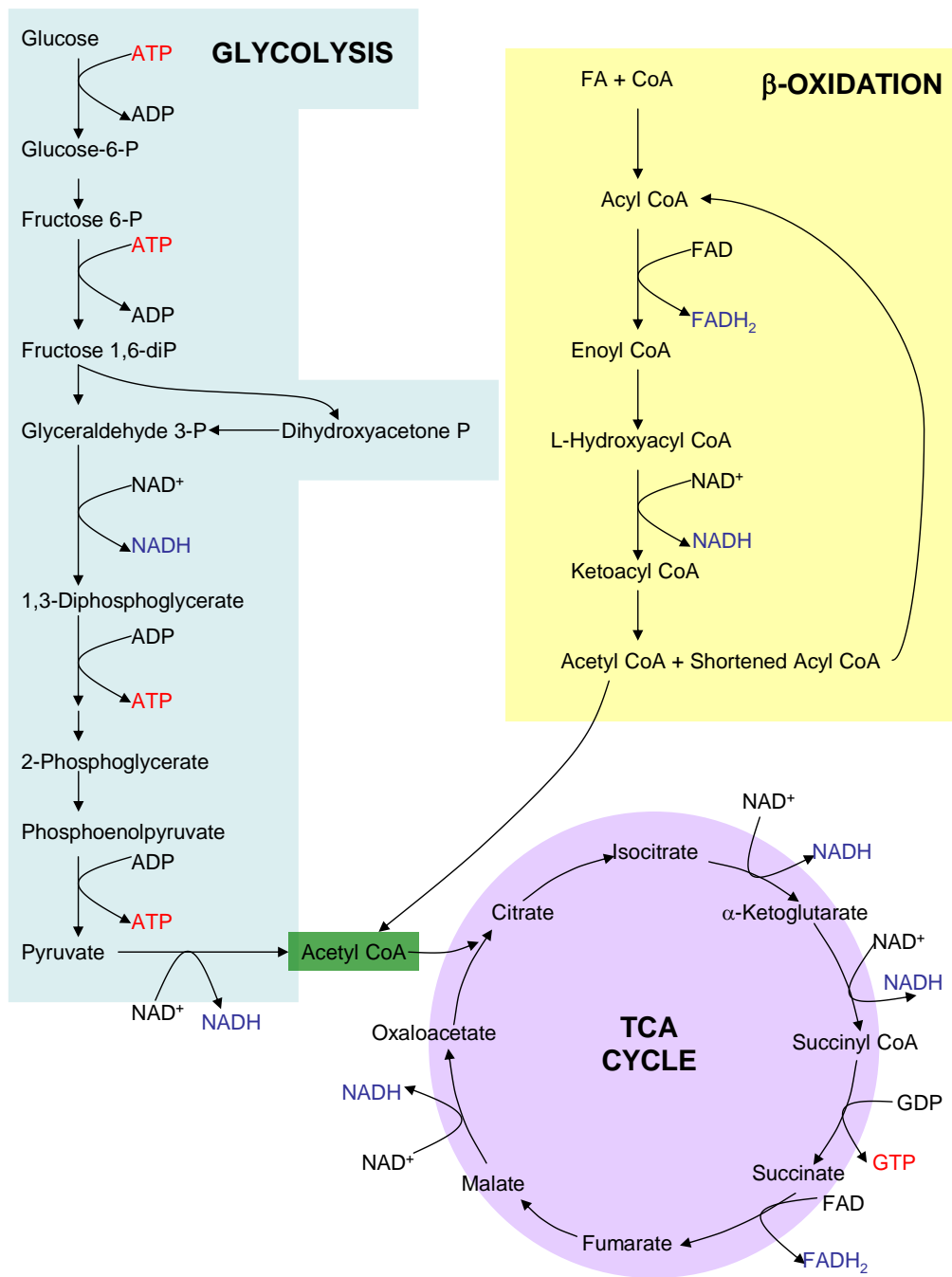
### **Fat as an Energy Source**

The macronutrients CHO, fat and protein provide energy to maintain body functions. It is generally believed that the major role of protein is to provide amino acids for synthesising tissue and that its role as an energy substrate is of lesser consequence under normal dietary conditions. However, recent research has suggested that protein may play a more important role as an energy substrate than was previously understood (Wagenmakers 1998).

Nevertheless, CHO and fat, in the form of triglycerides, provide the predominant fuels for muscle contraction in humans. The major sources of CHO within the body are found in the blood, as glucose, and in the liver and muscle as glycogen. Williams (2002) suggests that an average untrained male may have around 5g of glucose in the blood, 75-100g of glycogen in the liver and 300-400g of glycogen within the muscle tissue representing a total of ~1200-1600 Kcal. Compared to the 80,000-100,000 Kcal of energy which might be stored as fat, it can be seen that CHO provides a very limited energy source which will become rapidly depleted during exercise lasting more than a couple of hours (Williams 2002). It is therefore paramount that the body has the ability to absorb, transport and oxidise fat if the metabolic demands of endurance exercise are to be met.

Ultimately, the metabolic fate of CHO, fat and protein is to drive oxidative phosphorylation of adenosine diphosphate (ADP) to resynthesise adenosine triphosphate (ATP) *via* the electron transport chain. Energy release from the macronutrients can be outlined in three stages:

1. Digestion, absorption and assimilation for cellular metabolism
2. Degradation to acetyl-coenzyme A (CoA) within the cytosol
3. Phosphorylation of ADP within the mitochondria



**Figure 1: Outline of Glycolysis and  $\beta$ -oxidation and subsequent entry of Acetyl-CoA into the TCA cycle**

P = phosphate, diP = diphosphate

CHO (or glycogen in the muscle) and fat follow different pathways prior to entering the tricarboxylic (TCA) cycle; however, both pathways result in the degradation of the respective molecules to acetyl-CoA (figure 1). At key stages the cofactors nicotinamide adenine dinucleotide (NAD) and flavin adenine dinucleotide (FAD) accept electrons for transfer to the electron transport chain with the concomitant synthesis of ATP. Glucose first undergoes glycolysis yielding a total of 6 ATP in the process. A further 32 ATP are formed by the degradation of 2 pyruvate molecules to acetyl CoA and further degradation through the TCA cycle. As 2 ATP are initially used to phosphorylate the substrate a total yield of 36 ATP molecules are generated per unit of glucose. Fatty acids, liberated from triglycerides, consist of long-chain hydrocarbon groups ranging from C4 to C36 with C12 to C20 being the most prevalent in the human diet. Chains of less than C6 are called short chain fatty acids and chains of C8-C10 are classed as medium chain fatty acids. Fatty acids must undergo  $\beta$ -oxidation, systematically cleaving the fatty acid chain into 2-carbon acyl fragments, prior to entering the TCA cycle. A single C18 fatty acid chain will yield 147 ATP. It is clear that fatty acids provide a greater number of ATP per molecule than glucose; however, to produce the equivalent amount of ATP glucose requires just 6 molecules of oxygen while a C18 fatty acid would require 26 molecules of oxygen. Furthermore, at maximal rates, ATP production by glucose is faster than that produced by fatty acids. Studies have shown that maximal high energy phosphate formation from fatty acids is  $\sim 0.4 \text{ mol}\cdot\text{min}^{-1}$  while aerobic or anaerobic production from glycogen can be as much as  $\sim 1.0 - 2.4 \text{ mol}\cdot\text{min}^{-1}$  (Jeukendrup *et al* 1998c)

Under steady state conditions glycolysis results in the formation of pyruvate. However, during times of high metabolic demand the formation of NADH exceeds the rate of its entry into the respiratory chain and therefore the regeneration of  $\text{NAD}^+$  is inhibited. As a

consequence the non-oxidised hydrogens combine with pyruvate to form lactate liberating  $\text{NAD}^+$  for further glycolysis. Essentially, the formation of lactate 'buys time' and shifts part of the metabolic burden from the muscle to the liver (Stryer 1988). Elevated plasma lactate levels produced during high intensity exercise, and to a lesser extent, during long-duration lower intensity exercise, have been associated with low levels of free fatty acids (Ranallo and Rhodes 1998). It is suggested that lactate may have an antilipolytic effect. Carbohydrate, therefore, has a role to play in anaerobic energy production whereas fatty acid degradation is directly related to oxygen availability. During anaerobic conditions NADH and FADH resulting from  $\beta$ -oxidation can not enter the respiratory chain and the resulting build-up of these products inhibits further  $\beta$ -oxidation. Nevertheless, fat remains important as an energy source, particularly for endurance athletes which essentially utilises aerobic energy pathways. Importantly, fat contains over twice the amount of  $\text{Kcal}\cdot\text{g}^{-1}$  than CHO (fat 9 Kcal versus CHO 4 Kcal); furthermore, fats are hydrophobic and thus are generally stored without water. Conversely, each gram of glycogen is stored along with approximately 2.7g of water; therefore, relative to weight, fat is a highly concentrated energy store.

The majority of fat is stored in the adipose tissue as triglycerides (3 fatty acids esterified to glycerol). Smaller amounts are stored intramuscularly whilst further tiny amounts are found circulating in the plasma. It is suggested that there are difficulties in determining the amount of muscle triglycerides due to problems in distinguishing between lipid droplets within muscle fibres and adipose sites between fibres. However, it is well established that intramuscular triglycerides contribute to energy production during performance of moderate intensity exercise (Ranallo and Rhodes 1998). In general an average 80kg male might typically store 12000g of fat in adipose sites, 300g of intramuscular triglycerides and 4.5g as plasma triglycerides and plasma free fatty acids (McArdle *et al* 1999). The mechanisms

involved in transporting fatty acids from sites of storage to places of utilisation are believed to be generally understood. However, Ranallo and Rhodes (1998) suggest that regulation appears to be 'multifactoral' and may include: nutritional status, hormonal effects, exercise intensity and duration and individual training status. They conclude that further research is required to better understand the role that fat plays as an energy substrate for endurance sports.

### **Hormonal Regulation**

Hormonal regulation plays an important role in determining the substrate mix for energy metabolism. The onset of exercise initiates an initial drop in the levels of plasma free fatty acids which is brought about by free fatty acid uptake in the working muscles and the time delay for their release and transport from the adipocytes. The rate of lipolysis is controlled by the actions of several hormones including the catecholamines epinephrine, norepinephrine as well as insulin, glucagon and growth hormone. Insulin and glucagon are thought to be key regulators of energy metabolism. Insulin, which is secreted by the  $\beta$ -cells of the pancreas, stimulates the storage of fuels and protein synthesis; it is believed to be a strong inhibitor of lipolysis. Glucagon, a product of the  $\alpha$ -cells of the pancreas, responds to low plasma glucose concentrations by stimulating glycogenolysis and inhibiting glycogen synthesis (Stryer 1988).

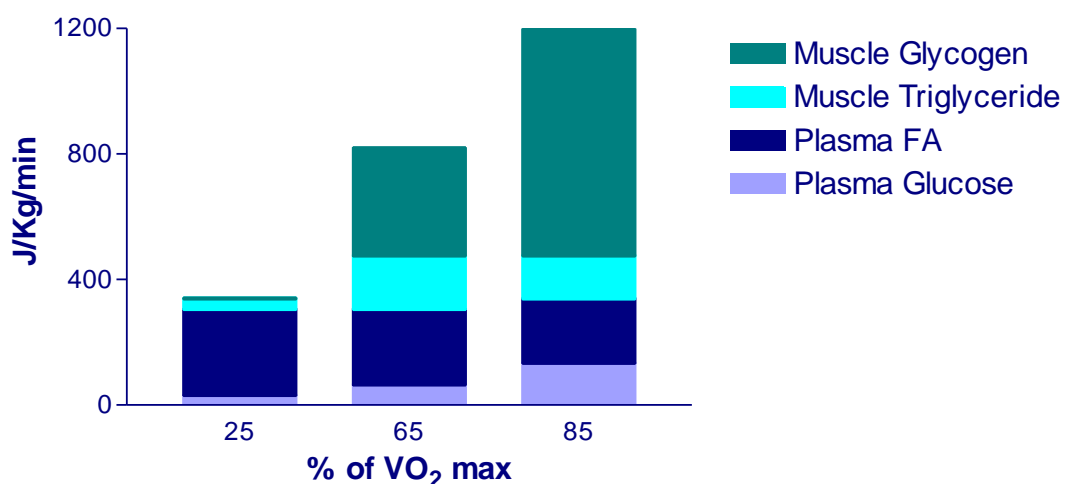
The catecholamines are secreted by the adrenal medulla and sympathetic nervous system when plasma glucose concentrations are low. Epinephrine's role in energy metabolism is the stimulation of glycogenolysis by the liver and muscles and lipolysis within adipose tissue and muscle. Norepinephrine powerfully stimulates lipolysis in adipose tissue. Jeukendrup *et al* (1998) suggest that growth hormone, which is stimulated by exercise, has a 'facilitating

effect' on the catecholamines as it optimises the energy substrate mix by decreasing glucose uptake by the tissues and elevating the mobilisation of fatty acids (Jeukendrup *et al* 1998a).

Studies have shown that with exercise intensities ranging from 25-65%  $\text{VO}_2$  max lipolysis increased with associated elevations in epinephrine concentrations (Romijn *et al* 1993; Mora-Rodriguez and Coyle 2000). However, intensities ranging from 65-85%  $\text{VO}_2$  revealed a plateau in lipolysis even though epinephrine concentrations continued to rise. Mora-Rodriguez and Coyle (2000) designed a study which involved the graded infusion of epinephrine, at increasing doses, intravenously into seven moderately trained subjects, to assess the affects of plasma epinephrine on fat metabolism during exercise. The subjects cycled at 25%  $\text{VO}_2$  max for 60 minutes. After the initial 15 minutes the cyclists received varying rates of epinephrine by infusion: low, medium, high and none (control). A further control was carried out at 45%  $\text{VO}_2$  max without infusion to establish exercise induced epinephrine concentrations and rate of lipolysis. Whilst all of the results of this study are not discussed here; an interesting finding revealed that the low infusion at 25%  $\text{VO}_2$  produced the same epinephrine concentrations as the 45%  $\text{VO}_2$  control. However, the level of fatty acid oxidation was significantly higher in the low infusion trial. This appears to confirm that exercise intensity attenuates epinephrine's stimulatory effect on lipolysis. The reasons for this are unclear but reduced blood flow to the adipose tissue during exercise is postulated as a possible cause of reduced lipolysis. It appears that although exercise intensity and duration seem to directly affect lipolysis the role of the catecholamines and other hormonal regulators are not fully understood and further research is needed.

## Limiting Factors

It is well understood that a mixture of CHO and triglycerides are used for fuel both at rest and during exercise and that their respective contributions are dependent on intensity, duration and upon the diet prior to exercise. Romijn *et al* (1993) used stable isotope tracers and indirect calorimetry to investigate the regulation of endogenous fat and glucose. They studied five trained subjects during exercise at 25, 65 and 85%  $\text{VO}_2$  max. Figure 2 shows that at low exercise intensities virtually all energy is supplied from fat. However, at exercise intensities above  $\sim 80\%$   $\text{VO}_2$  max CHO becomes the predominant fuel. Unfortunately, depletion of the limited CHO stores appears to elicit fatigue and associated deterioration of performance in the athlete. It would be extremely advantageous, under these conditions, if the comparatively plentiful supply of fatty acids could be drawn upon to sustain oxidation. Unfortunately, fatty acid oxidation appears to be limited by processes that are not fully understood.



**Figure 2: Substrate utilization at different exercise intensities (25%, 65% and 85%  $\text{VO}_2$  max). Adapted from Romijn *et al* 1993**

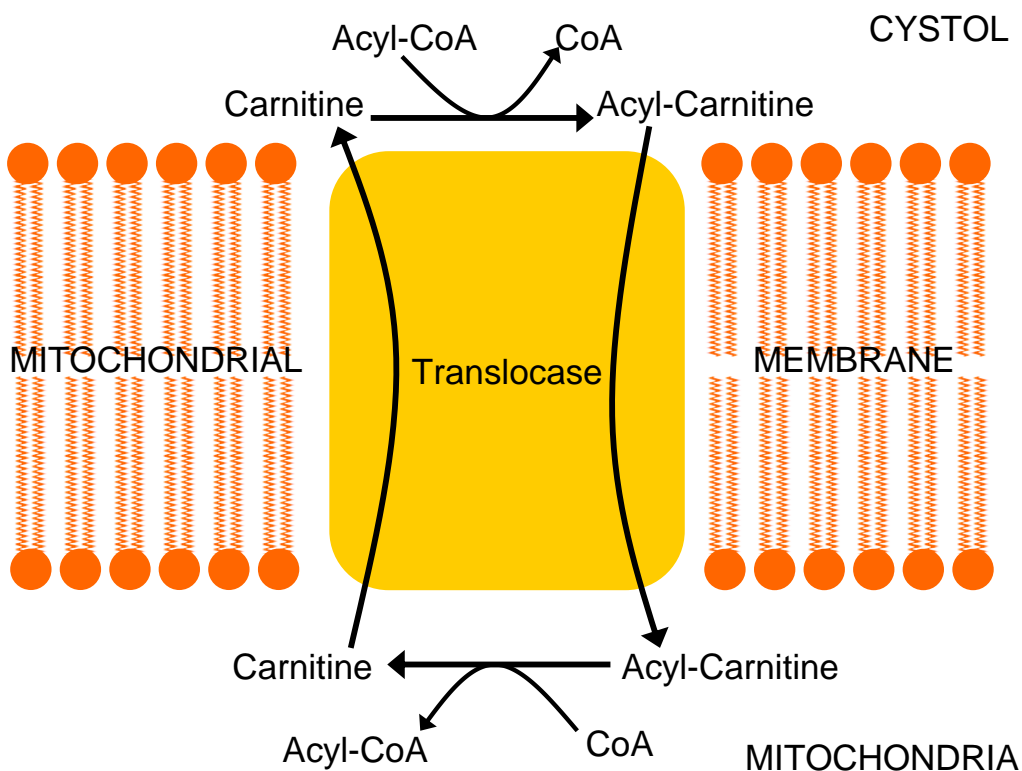
The metabolic pathways subsequent to acetyl-CoA formation are the same for both CHO and fatty acids, therefore any rate limiting steps must occur prior to the TCA cycle (Jeukendrup *et al* 1998c). Processes such as  $\beta$ -oxidation, fatty acid activation, carnitine mediated transport across the mitochondrial membrane, or fatty acid transport from the blood to the intracellular site of activation are key potential rate limiting steps (summarised in table 1).

The transport of fatty acids across the inner mitochondrial membrane is of particular interest here as LCT entry into the mitochondria appears to be directly inhibited and may be a key rate-limiting step in fat metabolism (Sidossis *et al* 1997). Subsequent to delivery of fatty acids to the cytoplasm of the muscle there are two possible fates: they may be esterified and used to replenish intracellular storage or they may be activated to acyl-CoA for transport to the site of oxidation within the mitochondria. However, acyl-CoA is unable to traverse the inner mitochondrial membrane so a transport mechanism is required for translocation (figure 3). Carnitine plays an essential role: the acyl-CoA ester is first converted to acyl-carnitine by the enzyme carnitine acyl transferase (CAT I) enabling transfer from the cytosol to the mitochondrial matrix. Upon delivery to the inner membrane reconversion to acyl-CoA by the enzyme CAT II completes the process. The transport step appears to rely upon a 1:1 exchange ratio with a molecule of free carnitine transferred in the opposite direction. This has led to postulated theoretical ergogenic effects of supplementation with exogenous carnitine (Brass and Hiatt 1998).

**Table 1 Processes that potentially limit fat oxidation**

<b>Potential Limiting Steps</b>	
Mobilisation from adipose tissue	The quantity of fat stored within most tissues, including muscle, is very limited. Therefore, they are reliant on being supplied with fatty acids from the diet or adipose tissue. Mobilisation of fatty acids from adipose tissue is limited by the rate of lipolysis, rate of reesterification within adipocyte and the rate of transportation from adipose tissue to the blood.
Transport to the muscle	Fatty acids are transported in the blood bound to albumin. Although albumin has at least three binding sites there is a decreasing affinity as each site is taken up by fatty acids. Transportation is limited by the fatty acid/albumin ratio. Increased plasma concentrations of non protein-bound fatty acids leads to reesterification. However, during exercise increasing blood flow may partially offset the decreased transport capacity.
Uptake by the muscle cell	Fatty acids must translocate through a series of structures before reaching the site of oxidation ( <i>luminal membrane, cytoplasmic compartment and albuminal membrane of the endothelial cell, interstitial space, sarcolemma and cytoplasm</i> ). It has long been believed that uptake of fatty acids by the muscle is a passive process. However, evidence is now building which suggests that ‘carrier proteins’ have a role to play. It is possible that the transport process is saturated above certain fatty acid concentrations. This could be interpreted as a limiting step across the cell membrane.
Mobilisation from IMTG pools	Intra-muscular triglyceride (IMTG) stores are found close to the mitochondria. Very little is known about their regulation or utilisation. The amount of IMTG stored appears to depend on muscle fibre type and physical exercise. Type I fibres appear to contain the most IMTG and athletes seem to have an increased capacity for storage and oxidation. Lipoprotein lipase and the $\beta$ -adrenergic receptors are believed to be involved in regulation.
Transport into mitochondria	The inner mitochondrial membrane is impermeable to fatty acids, (particularly long chain triglyceride (LCT) which are dependant on active transportation by carnitine to reach the site of oxidation
Oxidation within the mitochondria	$\beta$ -oxidation within the mitochondria is a process where the fatty acid chain undergoes successive cleavage by two carbons until complete oxidation. The number of carbons and the amount of saturation have been shown to affect the rate of oxidation.

(Jeukendrup *et al* 1998c)



**Figure 3: Active transport of fatty acids into mitochondria.**

**Adapted from Stryer 1988.**

It is widely believed that short and medium chain fatty acids can cross the inner mitochondrial membrane independently of the carnitine transport system. This and other potential qualities has opened up a line of research investigating the use of MCT as an alternative energy substrate free of some of the rate limiting processes undertaken by long chain fatty acids.

### **Fat Absorption and Metabolism**

Compared to protein and CHO the digestion of fat is slower and involves a complex pathway to produce free fatty acids for use as an energy source. Digestion is initiated by lingual lipase in the mouth and gastric lipase in the stomach. The resultant chyme leaves the stomach and

passes to the small intestine where bile acts to emulsify the lipid globules which assist pancreatic lipase in breaking down the lipids. Cholecystokinin is released into the duodenum which regulates gastrointestinal functions such as stomach motility and secretion, gallbladder function, bile flow and enzyme secretion.

Due to a lower molecular weight, MCT require less pancreatic lipase and bile, which enables rapid and more complete hydrolysis when compared to LCT. Hopman *et al* (1984) found that in contrast to LCT ingestion, levels of pancreatic secretions remain unaltered, and gallbladder contractions and cholecystokinin levels are unaffected by MCT ingestion. Furthermore, gastric emptying of LCT is strongly inhibited when large amounts of fats are ingested (Hopman *et al* 1984). In this state gastric inhibitory peptide and secretin are released, reducing stomach motility causing retention of chyme in the stomach. However, when combined with CHO, MCT undergo very rapid emptying (Beckers *et al* 1992). Following absorption into the intestinal mucosa long chain fatty acids reform into triglycerides and combine with phospholipids, protein and cholesterol to form chylomicrons and are transported to the liver *via* the lymphatic system. Conversely, MCT, due to their shorter chain length, are not incorporated into chylomicrons but are able to bypass the lymphatic system and enter the portal system bound to albumin for direct transport to the liver. Subsequently, MCT can be detected in the circulation within minutes whereas LCT will take 3-4 hours (Hawley *et al* 1998).

Studies have shown that oxidation of MCT produces significantly elevated levels of ketone bodies compared to LCT. Bach *et al* (1996) state that a single oral dose of 45-100g MCT increases plasma ketone body concentrations up to  $700\mu\text{mol}\cdot\text{L}^{-1}$  within 1-2 hours which is four times higher than that observed from an equivalent dose of LCT (Bach *et al* 1996). As

MCT are so readily oxidised the rapid formation of acetyl-CoA by  $\beta$ -oxidation exceeds its entry into the TCA cycle. Therefore, the surplus acetyl-CoA is redirected into the ketogenesis pathway resulting in the formation of ketone bodies: acetoacetate and  $\beta$ -hydroxybutyrate. The liver is incapable of metabolising ketone bodies; however, skeletal muscle readily oxidises acetoacetate *via* the TCA cycle. It has been theorised that ketone bodies produced as a result of oxidation of MCT could provide an alternative substrate for exercising muscles thus sparing muscle glycogen (Berning 1996).

In contrast to LCT, which are found abundantly in animal and vegetable fat, MCT generally are not naturally occurring. They are a derivative of coconut and palm kernel oil and contain saturated fatty acids of C6-12 carbons. MCT are semi-synthetic and made by the hydrolysis of coconut oil and subsequent fractionation of the fatty acids, which are esterified with glycerol to form triglycerides. Their melting points are low and thus are liquid at room temperature. MCT possess distinct metabolic properties when compared with LCT: they are rapidly emptied from the stomach, absorption is more rapid and efficient, are independent of the carnitine transport system and are oxidised rapidly. Indeed, studies have shown that 54-85% of MCT are oxidised following administration during endurance exercise (Massicotte *et al* 1992; Jeukendrup *et al* 1995; Jeukendrup *et al* 1996b).

For over thirty years MCT have been proposed for medical conditions where digestion, absorption or transport of LCT is impaired. Furthermore, due to the fact that fatty acids delivered by MCT are poorly stored and abundantly oxidised, they have been prescribed by clinical nutritionists as a means of reducing body weight in obese patients. The Food and Drug Agency describe MCT as 'generally regarded as safe' with recommended daily allowances for healthy adults ranging from 30-100g. However, undesirable symptoms such

as nausea, vomiting, bloating, emesis, gastrointestinal discomfort, abdominal cramps and osmotic diarrhoea are often reported (Bach *et al* 1996). These symptoms can be reduced by progressive incorporation into the diet and tolerance often improves over time (Bach *et al* 1996).

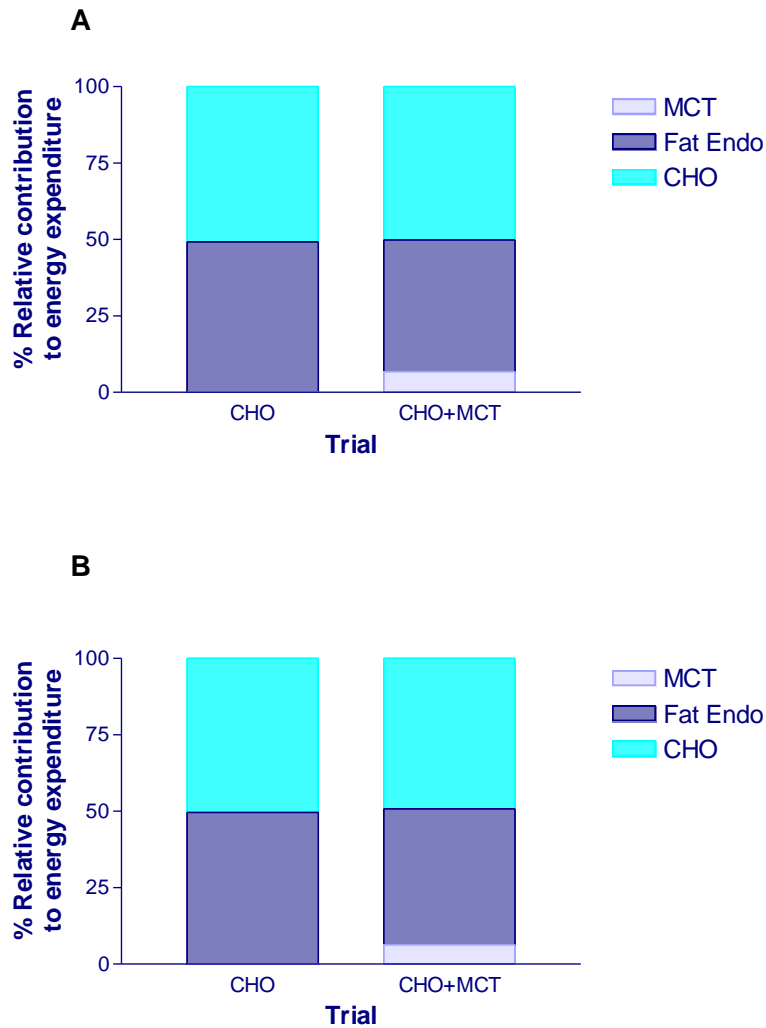
### **Medium Chain Triglycerides and the Quest for a Glycogen Sparing Effect**

Over the last decade or so a number of studies have set out to attempt to establish whether the ingestion of MCT can indeed produce a glycogen sparing effect. Whilst the general aims of these studies have been similar, the methods have differed which has made it difficult to draw many definitive conclusions from the data. One effect appears fairly clear in that virtually all studies reported gastro intestinal distress amongst their subjects of some kind or another (discussed later). Table 2 summarises the key studies reviewed here.

Following a preliminary study (Beckers *et al* 1992) which suggested enhanced delivery of energy by a combination of MCT with CHO, Jeukendrup *et al* (1995) set out to compare the metabolic responses produced by the ingestion of exogenous CHO, CHO plus MCT and MCT alone (Jeukendrup *et al* 1995). Eight male athletes of similar stature and fitness agreed to take part in the study. All subjects took part in a pre trial to establish individual work maximum for later use in the experimental trials. Four trials were undertaken separated by 7 days. Prior to the tests and following a standard breakfast subjects ingested a drink ( $4\text{ml}\cdot\text{Kg}^{-1}$  at the start plus  $2\text{ml}\cdot\text{Kg}^{-1}$  every 20 minutes throughout the trial) of either 15% CHO solution, an equicaloric CHO + MCT suspension (energy 70% CHO 30% MCT), or pure MCT in water. The fourth trial aimed to establish whether any differences between the CHO + MCT and CHO trial were due to MCT or different amounts of CHO. Therefore, a high CHO + MCT drink

(214g CHO + 29g MCT) was also included. The trials involved a 180 minute cycle at 57%  $\text{VO}_2$  max during which blood samples and expiratory gasses were collected at regular intervals for analysis of glucose, lactate,  $\beta$ -hydroxybutyrate, free fatty acids and glycerol concentrations. Exogenous MCT and CHO oxidation was measured by adding a trioctanoate tracer to the MCT oil.

The key finding of this study was that MCT coingested with CHO rapidly increased the oxidation rate of MCT compared to ingestion of MCT only. Indeed, during the second hour of the CHO + MCT trial 71-76% of the MCT ingested was oxidised compared to only 33% in the MCT trial. The authors suggest this could be due to an effect on processes of either gastric emptying, intestinal absorption, extraction and release of free fatty acids by the liver or free fatty acid uptake and oxidation by muscle. However, of these possibilities increased gastric emptying and intestinal absorption are more likely because of a sharp rise in plasma free fatty acids and  $\beta$ -hydroxybutyrate levels in the CHO + MCT trial but not in the MCT only trial. The contribution of MCT to energy expenditure was small: 6.8% (CHO + MCT) and 3.2% (MCT) in the second hour and 6.4% (CHO + MCT) and 6.4% (MCT) during the final hour. This was apparently due to the small amount of MCT ingested. However, increasing the dose of MCT was not considered feasible due to gastrointestinal distress. It is suggested that a maximal tolerance exists of ~30g in 3 hours. Concentrations of  $\beta$ -hydroxybutyrate remained stable in the CHO trial whereas levels in the CHO + MCT, and particularly the MCT trial, rose sharply. This study appears to support the hypothesis that oral ingestion of MCT may serve as an energy source during sub maximal exercise particularly when co ingested with CHO. However, the results do not appear to suggest an endogenous glycogen sparing effect. Furthermore, although the authors do not acknowledge it, the data may demonstrate endogenous fat sparing (figure 4).



**Figure 4:** Relative contributions of CHO, endogenous fat (fat endo) and MCT to energy expenditure during 60-120 minutes (A) and 120-180 minutes (B) time periods for CHO and CHO + MCT trials. Adapted from Jeukendrup *et al* (1995)

Evidence of endogenous fat sparing as a result of MCT ingestion was also reported in an earlier study by Massicotte *et al* (1992). These researchers carried out an experiment to compare any effects of exogenous MCT or glucose ingestion on endocrine and metabolic responses to prolonged exercise using six young healthy males aged between 20 and 26. They undertook five separate two hour bouts of exercise at approximately 65%  $\text{VO}_2$  max on a cycle ergometer. The experiments, separated by at least seven days, involved ingesting

either 1 litre of water (control), 25g (219 Kcal) MCT or 57g (220 Kcal) glucose. The MCT and glucose were labelled with a [<sup>13</sup>C] trioctanoate tracer. The MCT was ingested one hour before exercise to allow for absorption whereas the glucose was consumed in eight equal volumes every 15 minutes (0-105 min).

The results, based on the isotopic composition of expired CO<sub>2</sub>, showed that ingestion of MCT prior to exercise, or glucose during exercise, prevented the small but significant fall in blood glucose levels which were observed in the control. It is suggested that the maintenance of blood glucose concentrations suppresses the effects of hormonal responses to prolonged exercise, causing a significant decrease in endogenous fat oxidation. Conversely, there was no effect on the rate of endogenous carbohydrate oxidation. Indeed, the researchers concluded that any increase in the availability of free fatty acid is offset by a reduction of endogenous fat utilisation with no sparing of endogenous carbohydrate.

A later study (VanZyl *et al* 1996), based on calculations between the rate of total CHO oxidation and that of plasma glucose oxidation, reported reduced oxidation of muscle glycogen during endurance cycling following ingestion of MCT. The study was designed to investigate the metabolic effects of ingesting a large quantity (86g over 3 hours) of MCT and MCT combined with CHO during endurance exercise. Subjects were six male endurance trained cyclists of similar age, height and body mass. Each subject completed successive experimental trials, in random order, separated by 10 days. Trials consisted of a two-hour cycle on an ergometer at 60% VO<sub>2</sub> max immediately followed by a 40Km time trial. Between trials the subjects followed their normal training and eating regimes. On the day of the test subjects consumed a standard ~85g CHO breakfast 2-3 hours prior to testing. Throughout the test subjects ingested a drink (400ml after a 5 minute warm up and 100ml

every 10 minutes thereafter until exercise cessation, total 2 litres) of either, 10% CHO solution, a 4.3% MCT emulsion, or a 10% CHO and 4.3% MCT mixture. All drinks contained a sugar free glucose tracer to enable the rate of plasma glucose oxidation to be determined from the plasma glucose and VCO<sub>2</sub> disintegrations. Gas exchange measurements, analysis of blood metabolite and hormone concentrations, and calculations of total CHO and fat oxidation were also conducted. Their results demonstrated a reduced cycling speed with MCT ingestion alone compared with that of CHO. However, the MCT and CHO solution produced a 2.5% improvement on the 40Km time trial. It was proposed that the improvement in performance was a result of decreased muscle glycogen oxidation during the submaximal two-hour cycle. It is suggested that this is evidence of a glycogen sparing effect.

Thus far only one study (van Zyl 1996) has reported any beneficial effect of ingesting MCT on exercise performance. The authors attribute the differences in their study with that of others (notably Jeukendrup *et al* 1995) to the ‘almost threefold greater amount of MCT ingested.’ Despite this comparatively large dose they do not report any effects of gastrointestinal distress. The study was also notable by its omission of a suitable control, such as water, preventing a comparison of the physiological results with baseline data obtained without CHO or MCT ingestion.

Based on their earlier work (Jeukendrup *et al* 1995; Jeukendrup *et al* 1996a; Jeukendrup *et al* 1996b) and intrigued by the results from a previous study (van Zyl *et al* 1996), Jeukendrup *et al* (1998b) devised a study to examine the effects of ingesting a large quantity of MCT, either alone, or in combination with carbohydrate. Previous work (Costill *et al* 1977; Dyck *et al* 1993; Vukovich *et al* 1993) had suggested that inducing high plasma fatty acid concentrations by either a high fat meal or intravenous infusion of triglycerides combined with heparin

produced a glycogen sparing during exercise compared to controls. Clearly intravenous infusion is not a practical or even a legal strategy for the athlete. However, the results from the previous study appear to suggest that large amounts of MCT ingestion may provide the breakthrough in the quest for a glycogen sparing effect (van Zyl *et al* 1996). Jeukendrup *et al* (1998b), in keeping with van Zyl *et al* (1996), on separate occasions administered to their subjects (seven endurance trained male cyclists), drinks containing either 10% CHO (170g), 10% CHO with 5% MCT (170/85g) or a 5% MCT (85g) or (in contrast with van Zyl *et al* 1996) a control consisting of flavoured water. Isotope-ratio mass spectrometry was used to monitor [<sup>13</sup>C] enriched carbohydrate ingested by the athletes.

Prior to the study baseline VO<sub>2</sub> max and maximal work rate for each subject was determined. On test days standardised procedures were followed which included lunch, collecting resting blood and expired breath gasses and a warm up. The initial exercise involved a two-hour cycle at 60% VO<sub>2</sub> max. During the first minute subjects were given 8ml·Kg<sup>-1</sup> of one of the test drinks and received a further 2ml·Kg<sup>-1</sup> every 15 minutes thereafter. Following this the subjects undertook a 15 minute simulated time trial at 75% of their individual maximal workload. Blood samples were taken at 30 minutes and expiratory gasses every 15 minutes, for analysis of glucose, lactate, β-hydroxybutyrate, fatty acids and glycerol concentrations. Indirect calorimetry was used to determine total energy expenditure, oxidation rates of total fats, CHO and exogenous glucose. The results of this study revealed that the time taken to perform the preset work set in the four trials were consistent in all but the MCT only experiment which was significantly slower (at least 2.5 minutes). Average work rate measured in the time trials was 17-18% lower after ingestion of MCT only and the mean heart rate was also significantly lower. Data revealed lower mean heart rate, plasma lactate and β-hydroxybutyrate concentrations in the MCT trial compared to the others. This was attributed

to the fact that the cyclists reported an inability to 'push as hard' due to gastrointestinal cramping following MCT ingestion. (Jeukendrup *et al* 1998b)

Goedecke *et al* (1999) embarked on a study, which aimed to investigate the effects of various amounts of MCT plus CHO on gastric symptoms, fuel metabolism and exercise performance. Nine endurance trained cyclists took part in three consecutive trials, separated by seven days, involving a 2 hour cycle on an ergometer at 55%  $W_{peak}$  immediately followed by a 40Km cycle time trial. On test days, standardised meals were supplied after which (two hours prior to the test), 400ml of the U-[ $^{14}C$ ] labelled test solution for that day was ingested. These were either 10% glucose, 10% glucose plus 2.1% MCT (LO-MCT) or 10% glucose plus 4.3% MCT (HI-MCT). The MCT emulsion contained 80% C6-10 MCT and 20% LCT. A further 400ml of the test solution was consumed after resting blood samples were obtained, and thereafter, 100ml was ingested every 10 minutes until the trial was complete. Blood samples were collected every 20 minutes for analysis of plasma insulin concentrations, plasma free fatty acids, glycerol and  $\beta$ -hydroxybutyrate concentrations. CHO and fat oxidation was calculated by using non-protein respiratory exchange ratio. Gastrointestinal distress was recorded at 30 minute intervals during the trial and for the subsequent 48 hours. Symptoms were classified upper (*excessive belching, feeling bloated, stomach cramps, nausea or vomiting*) and lower (*excessive flatulence, frequent urges to defecate, diarrhoea*) and were further graded from 0-5 where a score of  $<3$  being consider as mild and  $\geq 3$  being severe. The results showed that both the HI and LO-MCT trials produced significantly higher plasma fatty acid concentrations than the glucose only trial. Plasma glycerol levels were comparable in all three trials and rose steadily throughout. Contrastingly, and related to the amount of MCT ingested,  $\beta$ -hydroxybutyrate concentrations increased significantly and were highest in the HI-MCT trial. There were no significant differences in CHO or fat oxidation in any of the

trials. CHO oxidation decreased over time while fat oxidation increased from  $\sim 0.24$ - $0.5 \text{g}\cdot\text{min}^{-1}$ .

The cyclists most commonly reported excessive belching, stomach cramps, bloatedness and nausea. However, the most serious gastrointestinal symptom was vomiting which was reported by one of the subjects. There were no reports of any diarrhoea during the trial; although, one of the cyclists reported severe diarrhoea and stomach cramps during the post 48 hour period (Goedecke *et al* 1999). In this study MCT ingestion did not improve average cycling speeds in the 40 Km time trial. The authors compare their results with that of van Zyl *et al* (1996) and Jeukendrup *et al* (1998b). They point out that  $\beta$ -hydroxybutyrate concentrations in their study were similar to that of Jeukendrup *et al* (1998b) but about half of that of van Zyl *et al* (1996). This was attributed to the fact that the pre-exercise meal contained  $\sim 140\text{g}$  of CHO compared to only  $\sim 85\text{g}$  in the van Zyl *et al* (1996) study. They suggest that high plasma insulin concentrations attenuate hepatic ketogenesis thereby elevating glucose utilisation in the liver. This resulted, it was proposed, in greater availability of glycerol 3-phosphate, which promoted esterification of fatty acids and therefore limited excess production of acetyl-CoA thereby reducing the production of ketone bodies.

It is further postulated that the ingestion of  $\sim 140\text{g}$  of CHO 2 hours prior to exercise eliminated the glycogen sparing effect of MCT ingestion. This is in contrast with the findings of van Zyl *et al* (1996) who, as previously discussed, reported CHO sparing and a subsequent improved time trial performance following 2 hours of preliminary exercise. Goedecke *et al* (1999) suggest that the elevated insulin levels in their study ( $\sim 13$ - $24 \text{mU}\cdot\text{L}^{-1}$ ) increased glucose uptake by the muscle and attenuated fat oxidation. They believe that reduced fat oxidation negates the possibility of the glycogen sparing effect previously observed by van Zyl *et al*

(1996). Goedecke *et al* (1999) assert that the failure of their experiment to reproduce the results obtained by van Zyl *et al* (1996) research team was due to elevated plasma insulin concentrations rather than gastrointestinal distress as proposed by Jeukendrup *et al* (1998b).

Angus *et al* (2000) are critical of some previous studies that have employed methods where the time taken to exhaustion at a given power output was used as a measure of exercise performance. This they suggest does not reflect a true 'competitive performance' as a normal race takes place over a set distance and is won by the competitor who completes it in the fastest time. Subsequently, they designed a study which, like that of van Zyl *et al* (1996) and Jeukendrup *et al* (1998b), compared the effects of CHO or CHO plus MCT ingestion but which better replicated the competitive environment. Their subjects were required to complete a 100km (2.5 – 3 hours) time trial rather than a simulated time trial following a period of steady state exercise. In this trial the subjects could choose their own power output which was dependant on pedal frequency; they were encouraged to complete the distance as quickly as possible. The eight male endurance trained cyclists/triathletes ingested 250ml prior and 250ml every 15 minutes until completion of the trial, either a 6% CHO solution, a 6% CHO plus 4.3% MCT solution or a sweet placebo. The MCT consisted of 71% C8 and 23% C10 carbon chains.

Not surprisingly, and in support of a wealth of previous data from other studies, the results showed that CHO ingestion reduced the time to complete the time trial compared to the placebo. Indeed, for the first 135 minutes, regardless of trial, the subjects were able to maintain similar power outputs. However, in the later part of the time trial power output fell significantly in the placebo group. CHO oxidation rates in all trials were  $\sim 3.5 - 4\text{g}\cdot\text{min}^{-1}$  for

the first 90 minutes but subsequently fell in the placebo trial compared to that of the CHO and the CHO+MCT. Fat oxidation increased over time in all trials.

Whilst the CHO in the non-placebo supplements enabled the athletes to maintain their power outputs and subsequently complete the time trial in a faster time, there appeared to be no benefit of adding MCT. There were no differences in respiratory exchange ratio, total fat oxidation or plasma free fatty acid concentrations.

During the trials the athletes worked at about 75%  $\text{VO}_2$  max which produced an 83% contribution by CHO to total energy expenditure. This intensity, the authors suggest, could have been 'too severe' for the absorption and oxidation of MCT. It would appear that in conditions where CHO is available MCT may not be utilised at higher exercise intensities. It was also suggested that lipolysis was blunted by the effect of insulin. In this study the subjects received a pre-trial breakfast, similar to that consumed prior to a real event, which was high in CHO. Gastrointestinal distress was reported in the MCT containing trial. Four of the eight subjects complained of negative side effects; two of which suffered vomiting and/or diarrhoea (Angus *et al* 2000).

In another recent investigation (Horowitz *et al* 2000) it is suggested that previous studies have not investigated MCT metabolism under conditions of restricted endogenous fat mobilisation. In order to investigate whether a 'tolerable' dose of MCT could produce a glycogen sparing effect during intense exercise they elected to use an MCT plus CHO combination as CHO ingestion has been shown to impair endogenous fat oxidation (Horowitz *et al* 1997). Furthermore, it has been shown previously (Jeukendrup *et al* 1998) that MCT oxidation is more rapid when coingested with CHO as compared to MCT alone. It is, therefore, proposed

that combining pre-exercise CHO ingestion with high exercise intensity, which is also known to suppress plasma free fatty acid levels, would provide 'optimal conditions' under which MCT ingestion might be shown to reduce muscle glycogen oxidation. Furthermore, they argue that under high exercise intensity, most energy is supplied by muscle glycogen; thus any energy derived from MCT would be reflected by reduced oxidation from muscle glycogen. Their second objective was to investigate whether coingested MCT and CHO might increase plasma glucose availability and uptake during exercise.

Seven, physically well matched, trained cyclists took part in the study. On two occasions they were asked to cycle on an ergometer for 30 minutes at 84%  $\text{VO}_2\text{max}$ . Following an overnight fast (12 hours) at one hour prior to exercise they ingested either a CHO meal (0.72g sucrose/Kg body weight) or MCT plus CHO meal (0.36g tricaprin/ Kg body weight ~50g plus 0.72 sucrose/Kg body weight). Data were obtained by muscle biopsies from the vastus lateralis at 30 minutes prior and immediately after the tests. Blood was taken at regular intervals after ingestion of the meals and throughout the exercise. Spirometry was used to measure  $\text{O}_2$  uptake and  $\text{CO}_2$  production.

Results revealed no differences in average power output between the tests. Responses for average energy expenditure,  $\text{VO}_2$ , respiratory exchange ratio, heart rate and perceived exertion were also closely correlated. Muscle glycogen concentrations in the vastus lateralis were similar throughout both trials. The addition of MCT to a CHO meal did not reduce muscle glycogen utilisation; however, it did significantly alter blood glucose kinetics by increasing plasma glucose availability. Results also suggested that MCT ingestion increased gastric emptying and intestinal absorption of the coingested CHO. The subsequent increase in the rate of appearance of glucose in the blood did not however alter exogenous CHO

oxidation. It is suggested that further glucose uptake may have been prevented by the high rates of glycogenolysis. It is interesting to recall that Goedecke *et al* (1999) suggested that the high CHO breakfast in their study that could have attenuated fat oxidation and negated a glycogen sparing effect. However, the subjects in the Horowitz *et al* (2000) study consumed their test meal following an overnight fast and still no glycogen sparing effect was evident.

In a more recent study (Oopik *et al* 2001) the effect of MCT consumption on both energy metabolism and endurance exercise was assessed. Seven male endurance trained runners aged  $19.4 \pm 1.7$  years of similar weight and height, and having a  $\text{VO}_2$  of  $67.5 \pm 4.8 \text{ ml}\cdot\text{min}^{-1}\cdot\text{kg}^{-1}$  took part in two series of experiments separated by one month. Only dietary manipulations differed for the seven days prior to endurance performance testing. Endurance capacity, tested on a treadmill, was carried out on four occasions before and after MCT supplementation or placebo (cooking oil) consumption for seven days. During the MCT trial subjects ingested an average of 34g of MCT per day in two equal portions (total 238g over seven days). The subjects were instructed to keep a food diary for the period when they were ingesting the MCT or placebo for analysis. A measurement of  $\text{VO}_2$  max for each subject was determined by a progressive exercise test carried out on a treadmill at the start of the study and the data used to set the exercise intensity during the endurance tests. Endurance performance was measured by running time to exhaustion at an average of about 80% of individual  $\text{VO}_2$  max. Subjects determined when exhaustion had been achieved although verbal encouragement to continue was given. Pre and post test blood samples were taken for the measurement of haemoglobin and packed cell volume and the values used to determine changes in cell volume. Concentrations of  $\beta$ -hydroxybutyric acid, glycerol and glucose were also measured. Further capillary blood was taken from the finger tip before the test and at 15 minute intervals during the exercise.

The results revealed that on average the runners reached exhaustion after 65 minutes in both trials before dietary intervention and following the ingestion of the placebo. However, after seven days of MCT ingestion exhaustion was reached after 58 minutes. Concentrations of  $\beta$ -hydroxybutyrate were significantly higher during the exercise tests following MCT ingestion. It has been proposed that ketone bodies may provide an alternative fuel source for exercising muscles (Berning 1996). However, although ketone bodies were clearly available and in excess of that measured in the placebo trial, they did not appear to improve endurance capacity. Interestingly, as with Jeukendrup *et al* (1998b) but in contrast with van Zyl *et al* (1996) this research found a detrimental effect on performance following MCT ingestion caused by gastrointestinal problems.

It is intriguing that van Zyl *et al* (1996) did not report any gastrointestinal problems amongst their subjects considering the large dose of MCT administered, which starkly contrast with the findings of Jeukendrup *et al* (1998b), Goedecke *et al* (1999), Angus *et al* (2000) and Oopik *et al* (2001). Indeed, Jeukendrup *et al* (1998b) suggested that it may have been gastrointestinal distress, following MCT ingestion, that prevented their subjects from performing well in their time trial. Further, Oopik *et al* (2001) found five out of seven of their subjects reported abdominal cramping and diarrhoea during MCT supplementation. It should be remembered that the Oopik *et al* (2001) study only used 34g MCT per day as compared with approximately 85g per day in the aforementioned studies. This suggested that even fairly low doses of MCT can cause negative side effects in some athletes. However, Oopik *et al* (2001) did report that two of their runners were unaffected by gastrointestinal distress and therefore suggest that tolerance may be highly individualised. This appears in agreement with Goedecke *et al* (1999) who claim that the results of their study did not show significantly greater incidence of gastrointestinal distress following MCT ingestion compared with that of

CHO; however, they do concede that two of their subjects suffered severe gastrointestinal distress. This, they argue, suggested that some individuals may be less tolerant of MCT ingestion and should experiment with ingestion before using the strategy in competition. They conclude that the potential benefits of MCT plus CHO ingestion need not be negated by gastrointestinal distress. Indeed, all of the studies are extremely limited in the size of cohort which ranged from a minimum of six to a maximum of nine subjects (all male). With the exception of the Oopik *et al* (2001) study which commenced MCT ingestion for a seven day period prior to the trial, administration of MCT occurred either just prior to (two hours or less), and/or during the trials. In contrast, MCT administered to patients with medical conditions have avoided or minimised gastrointestinal problems by gradual introduction into the diet.

One of the main aims of the study by Goedecke *et al* (1999) was to examine the effect of MCT on gastric symptoms. On this issue, it is interesting to note, and indeed question, why the MCT test solution included 20% LCT. Indeed, the mix of test solutions is inconsistent amongst many of the studies and may provide an explanation as to the differing reports of gastrointestinal distress. Previously, van Zyl *et al* (1996) used short-chain (four hexose) glucose polymers in their CHO drinks and a combination of C8 and C10 fatty acids in their MCT drinks; whereas Jeukendrup *et al* (1998b) employed glucose and 99% pure C8 fatty acids.

Notwithstanding the limitations of current research there appears little evidence to support a glycogen sparing effect by exogenous ingestion of MCT. The limited data that suggests that there may be a link (van Zyl *et al* 1996) is based on inferred rather than direct evidence and further studies have failed to repeat the findings. It appears equivocal that MCT is rapidly

metabolised, particularly when co ingested with CHO. Elevations in plasma ketone bodies have been consistently reported in all studies and in themselves have been proposed as a glycogen sparing substrate. However, at best, data suggests that rather than a glycogen sparing effect, exogenous MCT ingestion produces endogenous fat sparing. Clearly the overriding consequence of ingesting MCT appears to be gastrointestinal distress which has been proposed to lead too a decrease in performance in many subjects. Whilst there is a need for further research current data does not support exogenous MCT ingestion for endurance athletes as a means of sparing glycogen and improving performance.

**Table 2 Summary of studies showing MCT dose, gastrointestinal effects and trial results. Control data omitted**

<b>Author Date</b>	<b>Test Protocol</b>	<b>Dosing Regime</b>	<b>GI Distress</b>	<b>Results</b>
van Zyl <i>et al</i> 1996	2 hour cycle on an ergometer at 60% VO <sub>2</sub> max followed by a 40Km simulated time trial	<b>MCT only</b> 17g MCT after 5min warm up and 11x 4.3g every 10min (47.3g) <b>Total MCT = 65g</b> <b>CHO plus MCT</b> 40g CHO+65g MCT as above <b>Total MCT = 65g</b>	None reported  None reported	No glycogen sparing  Glycogen sparing during 2 hour cycle at 60% VO <sub>2</sub> resulted in improved subsequent 40Km time trial performance
Jeukendrup <i>et al</i> 1998	2 hour cycle on an ergometer at 60% VO <sub>2</sub> max followed by a 15 minute simulated time trial	<b>MCT only</b> 0.4g/Kg (~28g) MCT ingested after 1min warm up and 0.1g/Kg (~7g) every 15min throughout the test <b>Total MCT = 85g</b> <b>CHO plus MCT</b> 170g CHO plus 85g MCT as above <b>Total MCT = 85g</b>	GI cramps Vomiting & diarrhoea (after the trial)  GI cramps	Decreased performance  No significant effect on CHO or fat oxidation. No positive effect on performance.
Goedeche <i>et al</i> 1999	2 hour cycle on an ergometer at 55% W <sub>peak</sub> followed by a 40Km simulated time trial	<b>LO-MCT plus CHO</b> 7g MCT+40g CHO 2h prior to test, 7g + 40g CHO at start of test and 11x 1.7g+10g CHO every 10min throughout test (19g MCT) <b>Total MCT = 33g</b> <b>HI-MCT plus CHO</b> 13.7g MCT+40g CHO 2h prior to test, 13.7g +40g CHO at start of test and 11x 3.4g + 10g CHO every 10min throughout test (38g MCT) <b>Total MCT = 65g</b>	Excessive belching, bloated feeling  Stomach cramps, nausea Severe diarrhoea post 48 hrs.	No improvement in performance
Horowitz <i>et al</i> 2000	30 minute cycle on an ergometer at 84% VO <sub>2</sub> max	<b>MCT plus CHO</b> after an over night fast, single dose of 36g MCT plus 25g CHO ingested 1 hour before test <b>Total MCT = 36g</b>	None reported	No effect on muscle glycogen use during exercise
Angus <i>et al</i> 2000	Simulated 100Km cycle time trial (2.5–3 hours) on an ergometer	<b>CHO plus MCT</b> 15g CHO + 10.75g MCT at the start of the trial and every 15min until completion of the trial (average 160 minutes = 11 doses) <b>Total MCT = 118g</b>	Stomach fullness, belching, loose stools, vomiting and diarrhoea	No glycogen sparing effect or evidence of improved performance
Oopik <i>et al</i> 2001	Running time to exhaustion at 80% VO <sub>2</sub> max on a treadmill	<b>34g MCT</b> ingested daily for 7 days prior to test. Administered in 2 equal doses each day <b>Total MCT over 7 days = 238g</b>	Abdominal cramping and diarrhoea (some severe)	Decreased endurance performance

## References

- Angus, D. J., Hargreaves, M., Dancy, J. and Febbraio, M. A. (2000). Effect of carbohydrate or carbohydrate plus medium-chain triglyceride ingestion on cycling time trial performance. *Journal of Applied Physiology* **88**(1): 113-119.
- Bach, A. C., Ingenbleek, Y. and Frey, A. (1996). Usefulness of dietary medium-chain triglycerides in body weight control: Fact or fancy? *Journal of Lipid Research* **37**(4): 708-726.
- Beckers, E. J., Jeukendrup, A. E., Brouns, F., Wagenmakers, A. J. M. and Saris, W. H. M. (1992). Gastric-emptying of carbohydrate - medium chain triglyceride suspensions at rest. *International Journal of Sports Medicine* **13**(8): 581-584.
- Berning, J. R. (1996). The role of medium-chain triglycerides in exercise. *International Journal of Sport Nutrition* **6**(2): 121-133.
- Brass, E. P. and Hiatt, W. R. (1998). The role of carnitine and carnitine supplementation during exercise in man and in individuals with special needs. *American College of Nutrition* **17**(3): 207-215.
- Costill, D. L., Coyle, E. F., Dalsky, G., Evans, W., Fink, W. J. and Hoopes, D. (1977). Effects of insulin on muscle glycogen usage during exercise. *Journal of Applied Physiology* **43**: 695-699.
- Dyck, D. J., Putman, C. T., Heigenhauser, G. J. F., Hultman, E. and Spriet, L. L. (1993). Regulation of fat-carbohydrate interaction in skeletal-muscle during intense aerobic cycling. *American Journal of Physiology* **265**(6): E852-E859.
- Goedecke, J. H., Elmer-English, R., Dennis, S. C., Schloss, I., Noakes, T. D. and Lambert, E. V. (1999). Effects of medium-chain triacylglycerol ingested with carbohydrate on metabolism and exercise performance. *International Journal of Sport Nutrition* **9**(1): 35-47.
- Hawley, J. A. (1998). Fat burning during exercise - can ergogenics change the balance? *Physician and Sportsmedicine* **26**(9): 56-+.
- Hawley, J. A., Brouns, F. and Jeukendrup, A. (1998). Strategies to enhance fat utilisation during exercise. *Sports Medicine* **25**(4): 241-257.
- Hopman, W. P. M., Jansen, J., Rosenbusch, G. and Lamers, C. (1984). Effect of equimolar amounts of long-chain triglycerides and medium-chain triglycerides on plasma cholecystokinin and gallbladder contraction. *American Journal of Clinical Nutrition* **39**(3): 356-359.
- Horowitz, J. F., MoraRodriguez, R., Byerley, L. O. and Coyle, E. F. (1997). Lipolytic suppression following carbohydrate ingestion limits fat oxidation during exercise. *American Journal of Physiology-Endocrinology and Metabolism* **36**(4): E768-E775.
- Horowitz, J. F., Mora-Rodriguez, R., Byerley, L. O. and Coyle, E. F. (2000). Preexercise medium-chain triglyceride ingestion does not alter muscle glycogen use during exercise. *Journal of Applied Physiology* **88**(1): 219-225.
- Jeukendrup, A. E., Saris, W. H. M., Brouns, F., Halliday, D. and Wagenmakers, A. J. M. (1996a). Effects of carbohydrate (cho) and fat supplementation on cho metabolism during prolonged exercise. *Metabolism-Clinical and Experimental* **45**(7): 915-921.
- Jeukendrup, A. E., Saris, W. H. M., Schrauwen, P., Brouns, F. and Wagenmakers, A. J. M. (1995). Metabolic availability of medium-chain triglycerides coingested with carbohydrates during prolonged exercise. *Journal of Applied Physiology* **79**(3): 756-762.
- Jeukendrup, A. E., Saris, W. H. M., VanDiesen, R., Brouns, F. and Wagenmakers, A. J. M. (1996b). Effect of endogenous carbohydrate availability on oral medium- chain

- triglyceride oxidation during prolonged exercise. *Journal of Applied Physiology* **80**(3): 949-954.
- Jeukendrup, A. E., Saris, W. H. M. and Wagenmakers, A. J. M. (1998a). Fat metabolism during exercise: A review - part ii: Regulation of metabolism and the effects of training. *International Journal of Sports Medicine* **19**(5): 293-302.
- Jeukendrup, A. E., Thielen, J., Wagenmakers, A. J. M., Brouns, F. and Saris, W. H. M. (1998b). Effect of medium-chain triacylglycerol and carbohydrate ingestion during exercise on substrate utilization and subsequent cycling performance. *American Journal of Clinical Nutrition* **67**(3): 397-404.
- Jeukendrup, J. E., Saris, W. H. M. and Wagenmakers, A. J. M. (1998c). Fat metabolism during exercise: A review part i: Fatty acid mobilization and muscle metabolism. *International Journal of Sports Medicine* **19**(4): 231-244.
- Massicotte, D., Peronnet, F., Brisson, G. R. and Hillairemarcel, C. (1992). Oxidation of exogenous medium-chain free fatty-acids during prolonged exercise - comparison with glucose. *Journal of Applied Physiology* **73**(4): 1334-1339.
- McArdle, K., Katch, F. and Katch, V. (1999). *Sports and exercise nutrition*, Lippincott Williams and Wilkins.
- Mora-Rodriguez, R. and Coyle, E. F. (2000). Effects of plasma epinephrine on fat metabolism during exercise: Interactions with exercise intensity. *American Journal of Physiology-Endocrinology and Metabolism* **278**(4): E669-E676.
- Oopik, V., Timpmann, S., Medijainen, L. and Lemberg, H. (2001). Effects of daily medium-chain triglyceride ingestion on energy metabolism and endurance performance capacity in well-trained runners. *Nutrition Research* **21**(8): 1125-1135.
- Ranallo, R. F. and Rhodes, E. C. (1998). Lipid metabolism during exercise. *Sports Medicine* **26**(1): 29-42.
- Romijn, J. A., Klein, S., Coyle, E. F., Sidossis, L. S. and Wolfe, R. R. (1993). Strenuous endurance training increases lipolysis and triglyceride-fatty acid cycling at rest. *Journal of Applied Physiology* **75**(1): 108-113.
- Sidossis, L. S., Gastaldelli, A., Klein, S. and Wolfe, R. R. (1997). Regulation of plasma fatty acid oxidation during low- and high- intensity exercise. *American Journal of Physiology-Endocrinology and Metabolism* **35**(6): E1065-E1070.
- Stryer, L. (1988). *Biochemistry*. New York, W.H. Freeman and Company.
- VanZyl, C. G., Lambert, E. V., Hawley, J. A., Noakes, T. D. and Dennis, S. C. (1996). Effects of medium-chain triglyceride ingestion on fuel metabolism and cycling performance. *Journal of Applied Physiology* **80**(6): 2217-2225.
- Vukovich, M. D., Costill, D. L., Hickey, M. S., Trappe, S. W., Cole, K. J. and Fink, W. J. (1993). Effect of fat emulsion infusion and fat feeding on muscle glycogen utilization during cycle exercise. *Journal of Applied Physiology* **75**(4): 1513-1518.
- Wagenmakers, A. J. M. (1998). Muscle amino acid metabolism at rest and during exercise: Role in human physiology and metabolism. *Exercise and Sports Science Reviews* **26**: 287.
- Williams, M. H. (2002). *Nutrition for health, fitness and sport*, McGraw-Hill.