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Review

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The Effects of Medium-Chain Triglyceride Oil Supplementation on Endurance Performance and Substrate Utilization in Healthy Populations: A Systematic Review

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Background: The use of medium-chain triglyceride (MCT) oil has increased due to its potential for therapeutic and ergogenic properties. Although recent evidence has suggested that MCT oil supplementation may lead to an improvement in endurance and substrate utilization, contradicting studies have reported the ergogenic benefits of MCT oil toward exercise performance.

Methods: An extensive systematic review was conducted to assess the role of MCT oil as an ergogenic aid in exercise performance. Moreover, this study examined any alterations in substrate utilization and various physiological components while using MCT oil. The databases searched in this review were PubMed, Embase, CINAHL, and the Cochrane Library.

Results: Most studies reported that MCT oil did not improve exercise performance and had no effect on respiratory exchange ratio, glucose concentration, fat and carbohydrate oxidation, and lactate concentration. Although ketones were increased when supplementing with MCTs, most studies demonstrated that the body could not utilize the MCT oil-induced ketones as its primary energy source during an acute bout of endurance exercise. Thirty grams of MCTs seems to be the safe maximal dosage to minimize adverse reactions during or after exercise.

Conclusion: MCT oil showed very little to no ergogenic effects on exercise performance and substrate utilization in healthy populations. Future research is needed to examine the effects of long-term intake of MCT oil alongside various diets, perhaps a ketogenic diet, on exercise performance within different sports/exercises in a variety of populations.

Key words: Low carbohydrate diet, Ergogenic substances, Caprylic acid, Capric acid, Ketogenic diet

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INTRODUCTION

Current trends in the supplementation and fitness industries have led to the use of ergogenic aids to increase exercise performance, substrate utilization, and the mechanisms behind these factors. Medium-chain triglyceride (MCT) oil has been reported as a therapeutic aid for Alzheimer disease, epilepsy, and malabsorption.[1-5] Moreover, MCT oil has been considered to improve endurance exercise performance by providing a quick source of energy because MCTs can quickly undergo beta-oxidation.[3,6-8] However, while some studies have shown that MCT oil may improve physiological functions related to endurance exercise, others showed no evidence that supports its use.[9-15] Investigation is needed into whether MCT oil can aid in sparing glycogen stores or increase the rate of fat oxidation in tangent with an individual's aerobic output.

MCTs are saturated fatty acids found in animal and plant sources

and contain 8–12 carbons. MCT oil is extracted from coconut oil or palm kernel oil and processed by manufacturers for public use as a supplement. When consumed, MCTs are hydrolyzed in the intestines and transported directly to the liver via the hepatic portal venous system.[12,16,17] Unlike long-chain triglycerides (LCTs), MCTs can easily pass through the mitochondrial membrane without carnitine palmitoyl transferase or a shuttle system.[18-21] However, MCTs rapidly cross the mitochondrial membrane and enter metabolic pathways to be beta-oxidized, producing a larger amount of acetyl-CoA than carbohydrates (CHOs).[18-21] The liver mitochondria convert additional acetyl-CoA into ketone bodies beta-hydroxybutyrate (BOHB), acetoacetate (AcAc), and acetate (Ac) or oxalacetate.

MCTs are a better immediate energy source than LCTs due to their rapid absorption and beta-oxidation. Only a very small percentage of MCTs (less than 2%) contribute to fat storage, and most MCTs are converted to energy for immediate use in the body.[22] Thus, MCT oil may provide individuals with a quick and readily available energy source during exercise. Researchers have explored whether MCT oil aids in sparing glycogen stores by providing the body with an alternative energy source, improving endurance exercise performance. One study showed that trained cyclists had significantly faster cycling speeds and times for a 40-km time trial (TT) when supplementing MCTs combined with CHOs.[15] The cyclists cycled for 2 hours at 60% of maximal oxygen consumption (VO_2max) and subsequently performed a 40-km TT at a self-selected racing pace (> 60% of VO_2max). In contrast, another study with the same exercise protocol showed that trained cyclists receiving MCTs and CHOs together had significantly slower times for a 40-km TT (> 60% of VO_2max) compared with the group taking CHOs alone.[23] Similarly, another study had cyclists consume MCTs alone while cycling at 63% of VO_2max for 2 hours followed by a maximal exercise effort for a 15-minute TT. The study reported a significant decrease in the 15-minute TT in cyclists that supplemented MCTs alone compared with CHOs alone.[12] Notably, the groups taking MCTs in these studies did not show improved speeds or times compared with the groups consuming CHOs alone.[12,15,23] However, all studies demonstrated a notable increase in ketone concentrations when MCTs were consumed.[12,15,23] Theoretically, an abundance of ketones should provide the body with ample amounts of energy. However, while all studies showed increased ketone concentrations, only one[15] reported positive results of increased performance with MCTs.

This review examined the current literature on MCT oil supplementation in conjunction with endurance exercise performance to identify the positive or negative benefits from using MCT oil as an ergogenic aid. Additionally, this review explored whether there were any alterations common in substrate utilization and various physiological components while using MCT oil.

METHODS

Protocol

This systematic review was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) guidelines. A chart of all guidelines (PRISMA 2020 checklist) is shown in Supplementary Table 1. A risk of bias assessment was conducted using the Cochrane Collaboration Tool (RoB 2: Crossover, RevMan Web, 2021) to indicate the validity of each study assessed in this systematic review.

Article search strategy

The PubMed (Medline), Embase, Cochrane Library, and the Cumulative Index to Nursing and Allied Health Literature (CINAHL) were searched from inception through December 2021 for published articles using a combination of keywords and phrases. A complete list of phrases used is shown in Supplementary Table 2. After removing all duplicate records from the databases, articles were screened using eligibility criteria of (1) MCT oil used in one comparable group, (2) an endurance exercise intervention, and (3) a healthy sample population. Additionally, the articles were filtered for English language and human studies. More detailed inclusion and exclusion criteria are listed in Table 1. References from selected articles were screened for other relevant studies that fit the inclusion criteria. A detailed PRISMA flow diagram is shown in Fig. 1 and displays the sources searched, the numbers of articles screened and included, and the reasons for exclusion.

Information collected from articles

All eligible articles were reviewed for the number and sex of participants, type and dosage of MCTs (C8:C10), exercise interven-

tion, and parameters following MCT use during exercise. These parameters were oxygen consumption (VO_2), heart rate, respiratory exchange ratio, fat oxidation, carbohydrate oxidation (CHOO), lactate, ketones, glucose, glycerol, and rate of perceived exertion. All collected data were analyzed for the direction of effect (significant increase, significant decrease, or no effect) based on the effect of MCTs (Table 2). The outcomes were screened by two authors independently, and any disagreements were discussed until consensus was achieved. The direction of effect for the variables was compiled in a summary table (Table 3). Some articles failed to measure all variables, and those that did not include a specific outcome were excluded from the outcome total. Data on adverse reactions such

Table 1. Inclusion and exclusion criteria for study eligibility

Research question: how does acute MCT oil supplementation affect substrate utilization and endurance performance parameters?		
Parameter	Inclusion criteria	Exclusion criteria
Population	≥ 18 years of age Healthy	Chronic disease (obesity, CVD, CKD, respiratory, Alzheimer disease, epilepsy, metabolic disorders) Sedentary (< 60 minutes of exercise per week) Physical disabilities
Intervention	Use of MCT oil alone or in combination with another form of supplementation in conjunction with endurance exercise	Effect cannot be determined between supplementations.
Outcome	Endurance performance outcomes: time trial, time to exhaustion, average cycling speed, and average work rate Physiological parameters: RER, VO_2max, VE, CHO oxidation, fat oxidation, ketones, and lactate	
Study design	Peer-reviewed trial (RCTs, Crossover, etc.) performed on humans and published in English	Abstract Conference proceeding

MCT, medium-chain triglyceride; CVD, cardiovascular disease; CKD, chronic kidney disease; RER, respiratory exchange ratio; VO_2max, maximal oxygen consumption; VE, ventilation; CHO, carbohydrate; RCT, randomized controlled trial.

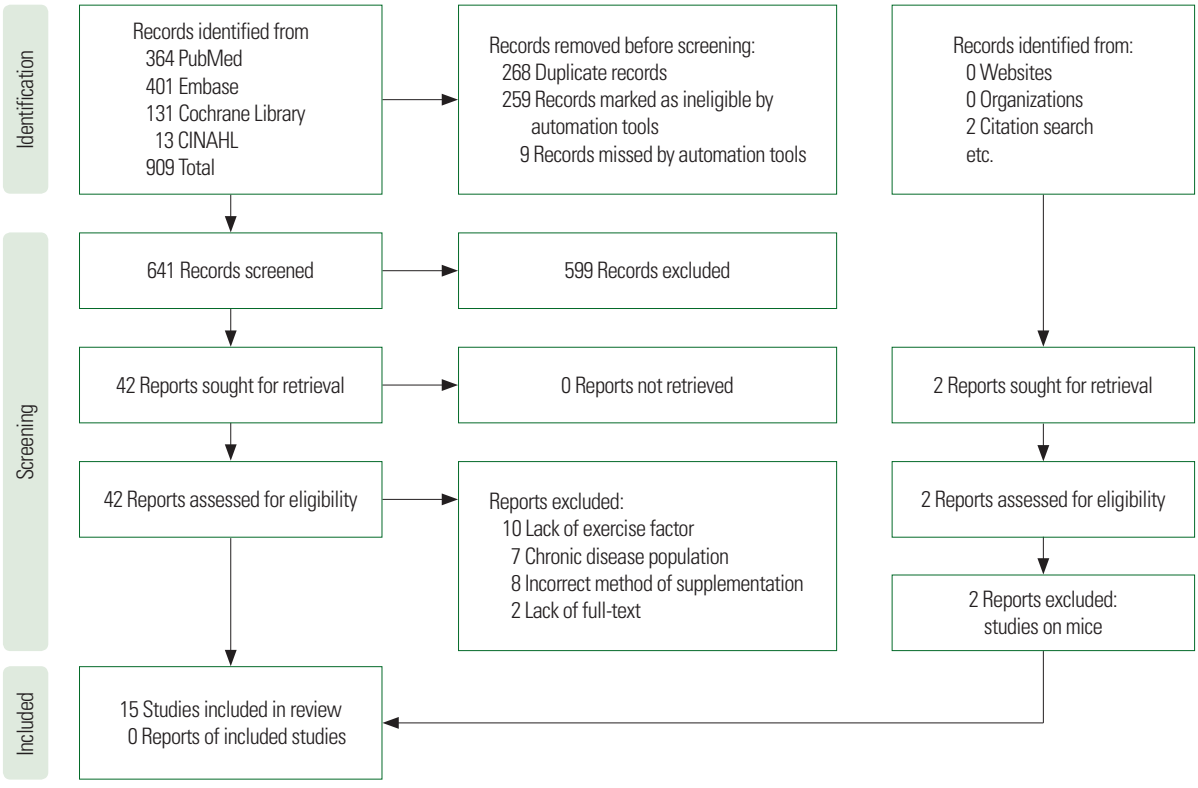

Figure 1. Study flow based on Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) guidelines. CINAHL, Cumulative Index to Nursing and Allied Health Literature.

Table 2. Studies examining effects of acute MCT oil supplementation on various outcomes

Study	Participant (n, sex)	Condition	Type & dose of MCT	Exercise intervention	Result	Outcome*
Angus et al. (2000)[9]	Elite cyclists (8, men)	MCT+CHO CHO Placebo	(71% C8: 23% C10); 6% CHO solution w/ 4.2% MCT solution	100-km TT	No differences were seen when including MCT in a CHO solution compared to CHO alone; however, MCT+CHO and CHO alone were significantly different from placebo.	O_2 consumption = ↔ HR = ↔ RER = ↔ FO = ↔ CHOO = ↔ Lactate = ↔ Glucose = ↔ TT times = ↔
Décombaz et al. (1983)[24]	Healthy individuals (12, men)	MCT+caseinate CHO+caseinate	(NS); 25 g MCT	Cycle 1-H at 60% VO_2max	Ketone concentration increased when taking MCT.	RER = ↔ FO = ↔ CHOO = ↔ Lactate = ↔ Glucose = ↔ Ketones = ↑ Glycerol = ↑
Goedecke et al. (1999)[23]	Endurance cyclists (9, men)	MCT+CHO HMCT+CHO CHO	(NS); 10% CHO+1.72% MCT; 10% CHO+3.44% MCT solution	Cycle 2-H at 63% VO_2max followed by a 40-km TT	MCT ingestion raised ketone concentrations (BOHB) with increasing dose.	RER = ↔ FO = ↔ CHOO = ↔ Lactate = ↔ Glucose = ↔ Ketones = ↑ Glycerol = ↔ avg cycling speed = ↔
Goedecke et al. (2005)[25]	Endurance cyclists (8, men)	MCT+CHO CHO	(NS); 32 g MCT+ (4.3% MCT+ 10% CHO solution during exercise)	Cycle 270 minutes at 50% PPO, interspersed with 75 kJ sprints at 60-minute intervals, followed by a 200-kJ TTE	Hourly sprint and TT times were significantly slower in MCT group than CHO; an increase in HR after 1-H of exercise was seen in MCT+CHO group.	O_2 consumption = ↔ HR = ↑ RER = ↔ FO = ↔ CHOO = ↔ TTE = ↑
Horowitz et al. (2000)[26]	Endurance cyclists (7, men)	MCT+CHO CHO	(99% C10); ~25 g MCT+0.72 g sucrose/kg	Cycle 30 minutes at 84% VO_2max	An increase in ketone concentrations (BOHB) was seen in the MCT group and was greater during exercise.	O_2 consumption = ↔ HR = ↔ RER = ↔ FO = ↔ CHOO = ↔ Lactate = ↔ Glucose = ↔ Ketones = ↑ Glycerol = ↔
Ivy et al. (1980)[27]	Well-trained individuals (10, men)	MCT LCT CHO Nothing	(NS); 30 g MCT	Cycle at ~80 RPM (n = 6); exercise on treadmill at 70% VO_2max (n = 4)	Serum ketone concentration rose only in the MCT group; effects of MCT consumption did not differ from those of CHO and LCT.	HR = ↔ RER = ↔ FO = ↔ CHOO = ↔ Glucose = ↔ Ketones = ↑ Glycerol = ↔
Jeukendrup et al. (1995)[28]	Endurance cyclists (8, men)	EQ MCT+CHO MCT+CHO MCT CHO	(99% C8); 29 g MCT; EQ MCT+CHO	Cycle 180 minutes at 50% Wmax (57% VO_2max)	A significant increase in lactate was seen at 180 minutes in those taking MCT alone.	RER = ↔ FO = ↑ CHOO = ↓ Lactate = ↑ Ketones = ↑ Glycerol = ↔
Jeukendrup et al. (1996)[10]	Elite cyclists (8, Men)	LG: MCT+CHO HG: MCT+CHO LG: CHO HG: CHO	(99% C8); 26.6 g MCT; EQ MCT+CHO	Cycle 90 minutes at 50% Wmax	Ketone concentrations rose when taking MCT regardless of LG or HG group.	RER = ↔ FO = ↔ CHOO = ↔ Glucose = ↔ Ketones = ↑ Glycerol = ↔

(*Continued to the next page*)

Table 2. Continued

Study	Participant (n, sex)	Condition	Type & dose of MCT	Exercise intervention	Result	Outcome*
Jeukendrup et al. (1996)[11]	Endurance trained athletes (9, men)	MCT+CHO MCT+HCHO CHO Nothing	(99% C8); equicaloric suspension CHO+29 g MCT; 150 g CHO+29 g MCT	Cycle 180 minutes at 50% Wmax (57% VO_2max)	MCT ingestion increased total ketone concentrations.	RER = ↔ FO = ↔ CHOO = ↔ Glucose = ↔ Lactate = ↔ Ketones = ↑ Glycerol = ↔
Jeukendrup et al. (1998)[12]	Endurance cyclists (7, men)	MCT+CHO MCT CHO Water	(99% C8); 85 g MCT; 85 g MCT+170 g CHO	Cycle 2-H at 60% VO_2max followed by a 15-minute TT	TT times increased, and avg work rate was lower when consuming MCT; mean HR was lower when taking MCT alone; RER was lower during 2nd hour of exercise when consuming MCT alone.	HR = ↓ RER = ↓ FO = ↔ CHOO = ↔ Lactate = ↔ Glucose = ↓ Ketones = ↑ Glycerol = ↔ avg work rate = ↓ TT times = ↑
Massicotte et al. (1992)[13]	Healthy individuals (6, men)	MCT CHO Water	(NS); 25 g MCT	Cycle 2-H between 62%–68% VO_2max	MCT ingestion increased endogenous fat oxidation rate from 0–60 minutes of exercise and at 0–120 minutes of exercise; ketone concentrations were higher when taking MCT.	RER = ↔ FO = ↑ CHOO = ↔ Glucose = ↔ Ketones = ↑
Van Zyl et al. (1996)[15]	Endurance cyclists (6, men)	MCT+CHO MCT CHO	(NS); 4.3% MCT emulsion; 4.3% MCT+10% CHO	Cycle 2-H at 60% VO_2max followed by a 40-km TT	MCT+CHO showed faster 40-km TT+avg cycling speed; MCT alone had slowest TT+cycle speed; ketone concentration was higher in MCT alone, but MCT+CHO produced had a significant increase; MCT+CHO and MCT alone showed decreased lactate and CHO concentrations.	CHOO = ↓ Lactate = ↓ Glucose = ↔ Ketones = ↑ Glycerol = ↑ TT times = ↓ avg cycling speed = ↑
Vistisen et al. (2003)[16]	Endurance cyclists (7, men)	MLM+CHO CHO	(Pure C8+LCT mixture)	Cycle 3-H at 55% VO_2max followed by 800-kJ TTE	RER was lower during the first hour of cycling; however, after 2-H, no differences were seen.	RER = ↓ Lactate = ↔ Glucose = ↔ TTE = ↔ RPE = ↔
Chronic Use						
Misell et al. (2001)[29]	Endurance runners (12, men)	MCT LCT	(6% < C8: 67% C8: 23% C10: 4% > C10); 30 g MCT	VO_2max; 30 minutes later, run on treadmill for 30 minutes at 85% VO_2max followed by a reduction to 75% VO_2max until exhaustion	RER was significantly different at 15 minutes of exercise; however, there were no differences before 15 minutes.	O_2 consumption = ↔ RER = ↔ Lactate = ↔ Glucose = ↔ Glycerol = ↔ Ketones = ↔ Body weight = ↔ TT times = ↔
Ööpik et al. (2001)[30]	Endurance runners (7, men)	MCT LCT	(NS); ~35 g MCT	VO_2max; TTE measured when running at a range of 73.2%–85.5% (80.3% ± 4.6%) of VO_2max	MCT ingestion caused an increase in ketone concentration.	Hematocrit = ↔ Hemoglobin = ↔ Lactate = ↔ Glucose = ↔ Glycerol = ↑ Ketones = ↑ TTE = ↔

*Outcome symbol: ↔, no significant difference; ↑, a significant increase (P< 0.05); ↓, a significant decrease (P< 0.05).
MCT, medium-chain triglyceride; CHO, carbohydrate; TT, time trial; HR, heart rate; RER, respiratory exchange ratio; FO, fat oxidation; CHOO, carbohydrate oxidation; NS, not specified; VO_2max, maximal oxygen consumption; HMCT, high medium-chain triglyceride; BOHB, beta-hydroxy-butyrate; avg, average; PPO, peak power output; TTE, time to exhaustion; LCT, long-chain triglyceride; RPM, rotations per minute; EQ, equicaloric; Wmax, maximum wattage; LG, low glycogen; HG, high glycogen; MLM, mixture of medium-chain and long-chain triglycerides; RPE, rate of perceived exertion.

Table 3. Outcomes from all studies with directions of effect and commonly seen effects

Outcome	Total number of studies	Direction of effect*	Adjusted total	Effect
Cycle speed and avg work rate	3	↑	1	Inconclusive
		↔	0	
		↓	1	
Time trial and time to exhaustion	5	↑↑	2	Inconclusive
		↔↔	2	
		↓	1	
Respiratory exchange ratio	12		0	No change
		↔↔↔↔↔↔↔↔↔↔↔↔	8	
		↓↓	2	
Fat oxidation	11	↑↑	2	No change
		↔↔↔↔↔↔↔↔↔↔↔	7	
			0	
Carbohydrate oxidation	12		0	No change
		↔↔↔↔↔↔↔↔↔↔↔↔	8	
		↓↓	2	
Lactate concentration	9	↑	1	No change
		↔↔↔↔↔↔↔↔↔	6	
		↓	1	
Ketone concentration	10	↑↑↑↑↑↑↑↑↑↑	8	Increase
			0	
			0	
Glucose concentration	11		0	No change
		↔↔↔↔↔↔↔↔↔↔↔↔↔	9	
			0	

*Outcome symbol: ↔, no significant difference; ↑, a significant increase ($P<0.05$); ↓, a significant decrease ($P<0.05$). Each individual arrow reflects one study and the effect on that specific outcome; an adjusted total was created by excluding the high risk of bias studies from the risk of bias assessment. Effects were noted as commonly if the majority of studies (>50%) favored a direction (increase, decrease, or no change); if there was no favored effect (≤1), no common effect was noted.
avg, average.

as gastrointestinal (GI) distress, diarrhea, or vomiting were collected and included in a table along with dosages and methodology of consumption for each article. The reported numbers of individuals having specific GI issues are noted in Table 4.

Risk of bias

Assessment for risk of bias was completed using the Cochrane Collaboration Tool (RoB 2: Crossover, RevMan Web, 2021), as shown in Fig. 2. All articles were reviewed independently by two authors, and any disagreements were settled through discussion. There were six domains of assessment: D1, randomization process; DS, bias arising from period and carryover effects; D2, deviations from intended interventions; D3, missing outcome data; D4, measurement of outcome; and D5, selection of reported results. For each category, studies were ranked as "low," "some concerns," or "high," and an overall bias was included for each study.

RESULTS

The results of this review were synthesized into the direction of effects. This methodology of synthesizing results is based on the Cochrane Handbook for Systematic Reviews of Interventions.[31] For each study, outcomes that displayed a significant increase ($P<0.05$) were indicated by an upward arrow. Outcomes that were neutral (no changes) were given a horizontal arrow, and outcomes with a significant decrease ($P<0.05$) were noted with a downward facing arrow (Table 2). The outcome directions were summarized to determine the most common outcome change (Table 3).

Any studies that were deemed to have a high overall risk of bias were excluded from the collective outcomes to provide a more accurate representation of the direction of effect of MCT oil during exercise. The effect or result was deemed inconclusive if there was either a lack of evidence or conflicting results (Table 3).

Table 4. Adverse effects of consuming MCT oil as an ergogenic aid

Study	Dose of MCT	Placebo(s)	Consumption	Adverse reactions (n)
Angus et al. (2000)[9]	6% CHO solution w/4.2% MCT solution	6% CHO solution; sweet placebo	250 mL/15 minutes for ~2 hours	GI discomfort (4); severe symptoms such as vomiting and diarrhea (2/4)
Décombaz et al. (1983)[24]	25 g MCT+2.5 g caseinate	50 g CHO+2.5 g caseinate	1 hour prior to ex	None reported
Goedecke et al. (1999)[23]	10% CHO+1.72% MCT; 10% CHO+3.44% MCT solution	10% CHO solution	Ingested 400 mL prior to ex and then 100 mL every 10 minutes	Vomited with the low MCT dose (1); experienced diarrhea; excessive bloating, cramps, and nausea were reported during the high MCT dose (1)
Goedecke et al. (2005)[25]	32 g MCT+(4.3% MCT+10% CHO solution)	75 g CHO+200 mL of 10% CHO	Ingested prior to ex and every 20 minutes during ex	Experienced GI distress with MCT supplement (4); common reports of nausea, vomiting, stomach cramps, bloating, and diarrhea
Horowitz et al. (2000)[26]	~25 g MCT+0.72 g/kg sucrose	0.72 g/kg sucrose	1 hour prior to ex	Observed GI distress such as nausea and diarrhea (not reported)
Ivy et al. (1980)[27]	30 g MCT+skim milk	Nothing; 30 g LCT+skim milk; cereal+skim milk	1 hour prior to ex	Diarrhea (3)
Jeukendrup et al. (1995)[28]	29 g MCT; equicaloric CHO-MCT suspension; 29 g MCT+CHO suspension	15% CHO solution	4 mL/kg prior to ex+2 mL/kg every 20 minutes during ex	None reported
Jeukendrup et al. (1996)[10]	28.5 g MCT+93.1 g CHO; LG vs. HG	156.2 g CHO	4 mL/kg prior to ex+2 mL/kg every 20 minutes during ex	None reported
Jeukendrup et al. (1996)[11]	29 g MCT+150 g CHO; 29 g MCT+214 g CHO	150 g CHO solution; nothing	4 mL/kg prior to ex and 2 mL/kg every 20 minutes	Some levels of GI discomfort in all trials including placebo: nausea, intestinal cramps, and belching
Jeukendrup et al. (1998)[11]	85 g MCT; 85 g MCT+170 g CHO	170 g CHO; artificially flavored water	8 mL/kg during the first minute of warm-up followed by 2 mL/kg every 15 minutes	Vomited (2) and experienced diarrhea (3) proceeding MCT trial; GI cramps occurred significantly more frequently with MCT
Massicotte et al. (1992)[13]	25 g MCT	Water; 57 g CHO	MCT taken 1 hour prior, H_2O given in (8) equal portions during ex (125 mL); CHO taken in (8) portions during ex (125 mL H_2O+7.1 g CHO)	None reported
Van Zyl et al. (1996)[15]	4.3% MCT emulsion; 4.3% MCT+10% CHO	10% wt/vol CHO solution	400 mL taken prior to ex; 100 mL of solution given every 10 minutes during ex	None reported
Vistisen et al. (2003)[16]	1.5 g/kg MLM+2.4 g/kg CHO	2.4 g/kg CHO	400 mL taken prior to ex; 200 mL every 15 minutes during ex	No difference in GI distress
Chronic use				
Misell et al. (2001)[29]	30 g MCT	28 g LCT oil	Ingested (2) shakes per day for 2 weeks	All participants experienced GI distress that lessened as they continued use; Not assessed formally
Ööpik et al. (2001)[30]	~35 g MCT	~35 g commercial cooking oil	Ingested in (2) equal portions per day for 2 weeks	Mild GI distress the first few days (2/6)

MCT, medium-chain triglyceride; CHO, carbohydrate; GI, gastrointestinal; ex, exercise; LCT, long-chain triglyceride; LG, low glycogen; HG, moderate-high glycogen.

DISCUSSION

Endurance performance outcomes

Six studies reported performance outcomes of TT, time to exhaustion (TTE), average cycling speed, and average work rate after using MCT oil as an ergogenic aid. The study by Angus et al.[9] included eight male endurance-trained cyclists who performed a 100-km TT after consuming either a 4.2% MCT solution with a 6% CHO solution, a 6% CHO solution, or a placebo (PO). There was no significant improvement in TT from participants who consumed MCTs along with CHOs compared with those receiving CHO alone; however, both treatment groups performed significantly better than the PO group (MCT+CHO, 169 ± 7 minutes; CHO, 166 ± 7 minutes; PO, 178 ± 11 minutes; $P < 0.05$).[9] Goedecke et al.[23] conducted a crossover study on nine trained cyclists who consumed two different doses of MCTs and a 10% CHO solution

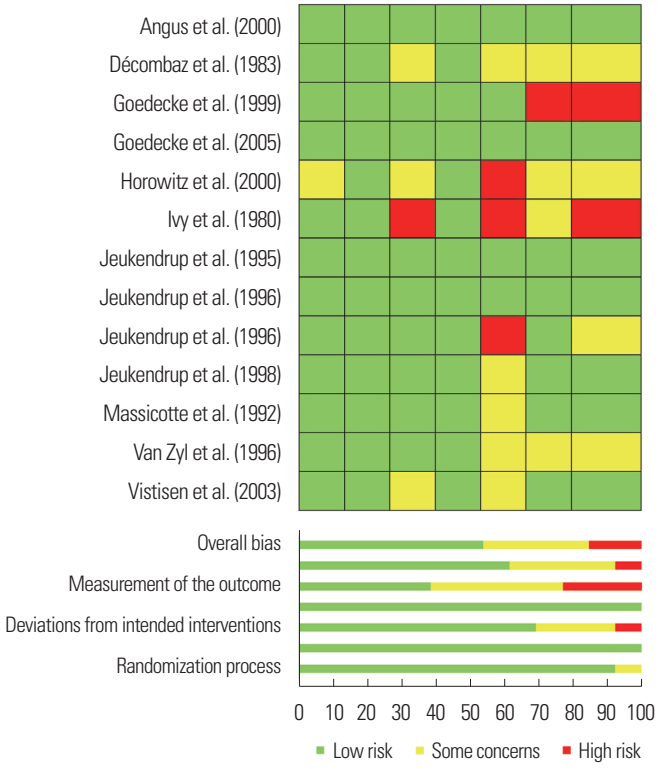

Figure 2. Risk of bias assessment. Six domains of assessment: D1, randomization process; DS, bias arising from period and carryover effects; D2, deviations from the intended interventions; D3, missing outcome data; D4, measurement of the outcome; D5, selection of the reported result; Green, low risk of bias; Red, high risk of bias; Yellow, some concerns.

(1.72% MCT+10% CHO; 3.44% MCT+10% CHO; 10% CHO). Participants ingested 400 mL prior to exercise and then 100 mL every 10 minutes during exercise. After the initial consumption, participants cycled for 2 hours at 63% of their VO_2max followed by a 40-km TT. The average TT speed did not improve for either the low or high MCT dosage (LOW-MCT+CHO, 38.7 ± 3.1 km/hr; HIGH-MCT+CHO, 38.5 ± 2.2 km/hr; CHO, 39.7 ± 2.3 km/hr).

Goedecke et al.[25] conducted another study on eight trained cyclists who consumed 32 g of MCT prior to exercise, along with a solution of 4.3% MCT and 10% CHO during exercise. This solution was given every 20 minutes while participants cycled for 270 minutes at 50% of their peak power output. The cycling was interspersed with four 75-kJ sprints at 60-minute intervals followed by a 200-kJ TTE. Use of MCT supplements increased participants' hourly sprint and TTE compared with results in participants given the CHO PO (MCT+CHO, 14.30 ± 0.58 minutes; CHO, 12.36 ± 1.6 minutes; $P < 0.001$), indicating that cyclists consuming MCTs were slower.

Jeukendrup et al.[12] examined the effects of high doses of MCTs taken alone and with a large amount of CHOs (8 mL/kg during warm-up; 2 mL/kg every 15 minutes during exercise). The endurance-trained cyclists cycled for 2 horus at 60% of their VO_2max followed by a 15-minute TT. The TT times were significantly higher for cyclists taking MCTs alone (MCT, 17.33 ± 1.10 minutes; MCT+CHO, 14.02 ± 0.32 minutes; CHO, 14.18 ± 0.57 minutes; PO, 14.43 ± 0.70 minutes; $P < 0.05$). Average work rates were also lower in the MCT alone group (MCT, 263.1 ± 22.4 W; MCT+CHO, 313.9 ± 13.0 W; CHO, 314.4 ± 18.5 W; PO, 311.6 ± 17.8 W; $P < 0.05$).[12] Thus, not only did MCTs fail to provide a positive benefit in these two studies, but they hindered performance compared with the CHO solution.

In contrast to the reports discussed above, one study concluded that MCTs, along with a CHO solution (4.3% MCT+10% CHO), significantly improved TT times.[15] Van Zyl et al.[15] conducted a crossover-design study in which six endurance-trained cyclists performed under three conditions: consumption of (1) a 4.3% MCT emulsion, (2) 4.3% MCT+10% CHO, or (3) 10% weight/volume CHO solution. For each solution, cyclists consumed 400 mL prior to exercise and then 100 mL every 10 minutes during exercise. Participants cycled for 2 hours proceeded by a 40-km TT. MCT alone yielded significantly poor results, with slower TT and average cycle speeds. However, MCTs consumed with CHO solution drastically improved 40-km TT times and average cycling speed (TT times: MCT [72.1 ± 0.6 minutes, $P < 0.001$], MCT+CHO [65.1 ± 0.5 minutes, $P < 0.05$], CHO [66.8 ± 0.4 minutes]).[15]

Three of the six studies showed that MCTs provided no positive or negative performance benefit for those who consumed it during exercise. Additionally, two of the six studies demonstrated that MCTs caused negative effects on exercise performance, while only one study showed that MCTs improved endurance performance. However, the one study that demonstrated a positive benefit of combined MCTs and CHOs also showed that using MCTs alone significantly hindered performance.

Fat and CHOO

Most studies that reported fat and CHOO rates indicated no significant changes. Nine of 11 studies demonstrated static fat oxidation during exercise when consuming MCT, while 10 of 12 studies

showed no impact on CHOO. Theoretically, when supplementing MCT oil during exercise, fat oxidation should be increased along with the increased oxidation of MCTs. Jeukendrup et al.[28] also noted high metabolic availability of MCTs after ingestion (77%).

Jeukendrup et al.[28] examined the influence of four conditions (MCT alone, MCT+CHO, MCT+high-CHO, and CHO alone) on exogenous MCT oxidation rates during a 3-hour cycling bout (57% of VO_2max) in trained cyclists. The exogenous MCT oxidation rates increased as the duration of exercise increased. However, when the trained cyclists consumed MCT+CHO, the fat oxidation rate increased much more rapidly than rates with MCT (29 g) alone.[28] CHOO increased only when the cyclists consumed CHOs. Fat oxidation significantly increased only during the last hour of exercise when trained cyclists took MCT alone.[28] In another study, Jeukendrup et al.[12] found that the addition of MCTs to a CHO solution did not decrease the oxidation rate of CHOs. However, the consumed MCTs contributed a very minimal amount to total energy expenditure,[12] implying that the increased oxidation of MCTs and CHOs after consumption did not reflect their use as the primary energy source.

Additionally, Massicotte et al.[13] examined the oxidation rates of exogenous fat and glucose during exercise. Over 2 hours, approximately 13.6 ± 3.5 g of exogenous MCTs (54% of the total amount consumed) and 36.4 ± 8.2 g (64% of the total amount consumed) of exogenous glucose were oxidized. Furthermore, with the consumption of glucose and MCTs, oxidation of fat stores was reduced during exercise (MCT, 44.7 ± 8.7 g; CHO, 42.3 ± 8.1 g; control, 57.8 ± 6.8 g; $P \leq 0.05$); however, CHOO was not altered in either condition.[13] In contrast, Van Zyl et al.[15] reported slower rates of CHOO when ingesting both MCTs and CHOs, attributed to oxidation of muscle glycogen and not a reduced rate of glucose oxidation.[15] It is possible that their continuous provision of MCTs (up to 86 g) over three hours of submaximal exercise did accompany a decrease in glucose oxidation rate, while MCTs were being oxidized throughout the cycling session. This is supported by the likelihood that trained cyclists would likely be utilizing fat as their predominant energy source when cycling at 60% of their VO_2max.[15] However, during the subsequent 40-km TT (~80% of VO_2max), the MCT alone condition resulted in a decrease of CHO energy production from 51% to 36%,[15] while MCTs combined with CHOs or CHOs alone resulted in CHOO rates of 55% and 65%, respectively. This result supports those of Jeukendrup et al.[12] that consuming MCTs with CHOs does not alter the CHOO rate. However, Jeukendrup et al.[12] and several others did not observe the performance benefits noted by Van Zyl et al.[15]

One explanation for the rapid oxidation of MCTs at the beginning and during aerobic exercise is that MCTs are released into the bloodstream through the portal circulation and pass through the mitochondrial membrane without the need for carnitine palmitoyl transferase. However, these studies show that the body does not use this abundant secondary energy source as its primary source of energy unless it is exercising at a lower intensity that does not utilize CHO. Thus, we conclude that MCTs likely do not result in a shift in energy sources during exercise and are not sparing glycogen in endurance athletes.

Ketone concentration

Total ketone concentrations were examined in 10 of the 13 studies. All these studies found that consumption of MCT oil, whether before or during exercise, increased ketone concentrations. Décombaz et al.[24] examined the effects of 25 g of MCTs along with 2.5 g of caseinate consumed 1 hour prior to exercise versus 50 g of a CHO PO with 2.5 g of caseinate. Participants cycled for 1 hour at 60% of their VO_2max and showed no beneficial effect on any physiological parameters. Participants consuming MCTs had higher circulating levels of BOHB and AcAc.[24] Body pools of BOHB and AcAc increased substantially during exercise compared with the group consuming the CHO PO (BOHB+AcAc: MCT, 3,779 ± 1,389; CHO, 109 ± 228; $P < 0.05$).[24] Similarly, Ivy et al.[27] found that serum ketone concentrations increased in well-trained individuals consuming 30 g of MCTs compared with those consuming LCTs, providing further support that consumption of MCT alone increases ketone concentrations. Thus, supplying the body with an ample amount of a different energy source does not indicate that the body will use that material as its primary energy source.

Other researchers identified similar findings in participants taking MCTs along with a CHO solution. Jeukendrup et al.[28] investigated the consumption of either 29 g of MCTs along with 150 g CHOs, an equicaloric suspension (29 g MCTs+~214 g CHOs), or a 150 g CHO solution. These solutions (at 4 mL/kg) were consumed by

nine endurance-trained men prior to exercise, followed by 2 mL/kg every 20 minutes during a cycling bout of 180 minutes at 50% of participants' maximum wattage (Wmax; or 57% of VO_2max). Total ketone concentrations from participants consuming MCTs along with the CHO suspension were significantly higher (MCT: ~800 μmol/L; MCT+CHO, MCT+HIGH-CHO: ~500 μmol/L; CHO: ~300 μmol/L, $P < 0.05$).[28] Horowitz et al.[26] showed a similar finding in endurance-trained cyclists. Participants were given up to 25 g MCTs in conjunction with 0.72 g/kg of sucrose and cycled for 30 minutes at 84% of their VO_2max. Total ketone concentrations were significantly higher during exercise compared with concentrations of those consuming CHOs alone (0.72 g/kg of sucrose) (MCT+CHO, 40 ± 8; CHO, 18 ± 3 mM; $P < 0.05$).[26] Further analysis of our findings supports the notion that, regardless of co-consumption with MCTs, it is highly likely that an increase in ketone concentration will occur. Some studies that reported more than one type of ketone body found that BOHB levels tended to be higher than AcAc. However, this may be anecdotal, and future research may help identify the causes of these changes.

The increase in ketone concentration with ingestion of MCT during exercise suggests that the athlete or individual has a secondary supply of energy. However, in many cases, these individuals are not using ketones as their predominant energy source during exercise if they are consuming CHOs with MCTs. Thus, examination of ketone concentration may simply demonstrate that MCTs are broken down into ketone bodies but have no effect on improving performance. This indicates MCT oil may be an impractical supplement to enhance physiological functions during endurance exercise.

Lactate concentration

Of 13 articles, eight reported lactate concentrations of the exercising participants, with seven noting no significant change in participants consuming MCT oil. However, one study observed a decrease in lactate concentration in participants taking MCTs alone and in those taking MCTs with a CHO solution. Van Zyl et al.[15] demonstrated that a 4.3% MCT emulsion with or without a 10% CHO solution decreased participants' lactate concentration proceeding a subsequent 40-km TT (MCT, 2.2 ± 0.4 to 1.0 ± 0.2 mmol/L; MCT+CHO, 3.2 ± 0.1 to 1.9 ± 0.4 mmol/L; CHO, 3.7 ± 0.4 mmol/L and remained roughly constant; $P < 0.01$), implicating that metabolism was altered toward fat oxidation as the utilized energy source.

In contrast to these findings, Jeukendrup et al.[12] completed a very similar study where participants cycled for 2 hours at 60% of VO_2max with an ensuing 15-minute TT. However, the participants were given much larger doses of MCTs. Seven endurance-trained cyclists were given either 85 g of MCT, 85 g of MCTs in conjunction with a 150 g CHO solution, a 170 g CHO solution, or artificially flavored water. Each experimental solution was consumed at 8 mL/kg during warm-up, followed by 2 mL/kg every 15 minutes of the endurance bout. Researchers concluded that lactate was not significantly different in individuals taking MCTs alone or with a CHO solution during their 2 hours of submaximal cycling bout (0.7–0.9 mmol/L).[12] However, during the TT, MCTs did not increase lactate concentration as substantially as did other conditions (MCT, 3.6 mmol/L vs. ~9–12 mmol/L). Notably, the participants were less inclined, due to GI issues, to achieve maximal effort when taking MCTs alone.[12] This study resembles that of Van Zyl et al.,[15] although the quantities given to participants were substantially larger in the latter study. The reasons for the contradictory findings are unclear because their study designs and populations were similar. Even more puzzling is how one study that provides fewer MCTs demonstrated decreased lactate concentration while another offering substantial MCTs showed no benefit.

Several other studies reported that lactate concentration did not significantly change with MCTs and CHOs during exercise. Décombaz et al.[24] demonstrated that lactate levels did not increase beyond 2.1 mM for both MCT alone and CHO alone treatments during 1 hour of cycling at a submaximal intensity (60% of VO_2max). Similarly, Horowitz et al.[26] showed no difference between participants who consumed MCT along with CHO and those ingesting CHOs alone when cycling at 84% of VO_2max for 30 minutes. Ingestion of MCTs and CHOs versus CHOs alone increased lactate concentration from ~2 mM to 11.8 ± 1.3 and 11.8 ± 1.9 mM, respectively, by the end of the exercise,[26] suggesting a metabolic shift toward glycolysis as exercise intensity increases, despite available fat sources.

Many cyclists use onset blood lactate accumulation or lactate threshold to train for competitions. Supporting evidence from Table 3 implies that the use of MCT oil will not affect blood lactate concentration. Current indications do not show promising advantages of MCT oil; however, additional research is needed. Thus,

cyclists or endurance athletes trying to lower their onset blood lactate accumulation with the use of MCT oil likely will experience no benefit as exercise intensity increases.

Adverse reactions

Interestingly, many studies reported GI issues with the acute use of MCT oil, which could hinder athletic performance. Individuals planning endurance aerobic exercise prefer to avoid bowel movements or flatulence when exercising. It may also be a dose-response that is causing the trained cyclists to experience adverse reactions. Ivy et al.[27] and several others[28] have suggested that the maximum dosage of MCT oil should be 30 g because any amount above this may result in a GI episode either during or briefly after exercise. Seven of 13 studies reported GI distress during or after exercise with the use of MCTs, and most studies administered more than 30 g of MCTs. In one study, seven cyclists were given 85 g of MCTs; two cyclists vomited, and another three experienced diarrhea, supporting that such a high dose would lead to a GI episode.[12] Although it is unclear if the studies not reporting adverse reactions monitored and recorded adverse reactions, a majority of them used MCTs at less than 30 g.[11,13,27,28] As mentioned earlier, an MCT dose less than 30 g seems to be the most common maximal dosage to minimize or avoid GI distress and other adverse reactions during or after exercise.[27,28] Thus, supplementing more than 30 g of MCTs during exercise should be taken with caution due to the likelihood of an adverse reaction.

Strengths and limitations

This review has several notable strengths in an analysis of the acute use of MCT oil in endurance performance. First, all the studies were performed in men and not in women; sex differences are likely to have no influence on the synthesis of our results. In addition, 11 of 13 studies were performed on endurance cyclists. The strong similarities seen in the populations of this review should be accounted for when addressing the applicability of our results.

There are several limitations in this review that need to be taken into consideration. Studies examining chronic MCT oil use are commonly performed in patients with chronic diseases, such as epilepsy and Alzheimer disease, rather than in terms of endurance exercise. Since the current review focused on the role of MCT oil in endurance performance and substrate utilization, studies examining chronic consumption of MCTs were not evaluated. Two articles were included to represent the current literature on chronic use but were excluded from the direction of effect analysis.[29,30] Another limitation of this review is that it examined the direction of effect for each outcome. The method used in this review was deemed a better alternative because many of the studies were not randomized controlled trials and were designed in a crossover fashion. Thus, if data points were compiled from various study designs, a meta-analysis using specific quantitative methods would have been more appropriate. Last, this systematic review includes only studies published between inception and December 2021. It is possible that previous poor results of using MCT oil deterred scientists from continuing investigation in healthy populations, which might explain the lack of studies in more recent years.

Conclusion

Based upon the results of this review, coaches and health practitioners should use caution when suggesting MCT oil for athletes. Most studies demonstrated little to no improvement in endurance performance when taking MCT oil as an ergogenic aid. Furthermore, these studies did not show an increase in fat and CHOO rates and lactate concentration when supplementing with MCTs. Although ketone bodies were significantly elevated with MCTs, indicating high metabolic availability, individuals were not able to use ketones as a predominant energy source during exercise. Moreover, many studies reported some sort of GI distress when taking more than 30 g of MCT oil. Thus, ingesting a large amount of MCT oil to improve performance further may prove fruitless due to potential adverse reactions that can hinder exercise performance. Therefore, future research should examine the effects of chronic use of MCT oil alongside various diets in endurance training. It is also crucial to investigate the role of MCTs in individuals on ketogenic diets due to their pre-existing adaptation to using ketone bodies as an energy source.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

Study concept and design: TJC and YK; analysis and interpretation of data: TJC and YK; drafting of the manuscript: TJC and YK; critical revision of the manuscript: TJC and YK; and study supervision: YK.

SUPPLEMENTARY MATERIALS

Supplementary materials can be found online at https://doi.org/10.7570/jomes22028.

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