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Review

Functional lipid components for obesity management: a review

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Abstract

Obesity is globally acknowledged as a major public health concern and future threat which is associated with its co-morbidities in particular diabetes, hypertension, cardiovascular diseases, osteoarthritis, stroke and inflammatory diseases. It was suggested that a high-fat diet promotes the development of obesity and that there is a direct relationship between the amount of dietary fat and the degree of obesity. Fats and oils, particularly higher molecular weight and saturated fats, lead to a positive fat balance, and consequent adipose mass accumulation; therefore, for good health, the type of fats/oils people eat is far more important that the amount, and there is some evidence that the same may be true for weight control. Advancements in food processing sector and modernisation of the societies lead to changes in lifestyle which attracts the consumers to modify their diet accordingly. Therefore, there is great scope of designer foods that could help in prevention or management of obesity. Lipid components, including medium chain triglycerides (MCTs), diacylglycerides (DAGs), conjugated linoleic acids (CLAs) and omega-3 fatty acids (ω-3 FAs) are extensively studied for their anti-obesity effects. The same may give a way in the area of research on weight management by incorporating them in the regular diet or in food formulation as functional components because of their beneficial effects on energy intake and expenditure.

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Introduction

Obesity is a disorder, caused either from the lack of energy balance in the body or by positive energy balance. Nowadays, it is one of the most common and neglected public health problem in developing as well as developed countries (WHO, 2000). Worldwide, one out of six adults is obese and nearly 2.8 million individuals die each year due to being overweight or obese (WHO, 2012). Obesity is now being recognised as a disease in its own right because of the associated risk of morbidity and mortality. Additionally, obesity is strongly associated with many metabolic disorders, including hypertension, diabetes, dyslipidaemia, cardiovascular diseases and even some cancers. The risk for these associated disorders begins when the body mass index (BMI) reaches about 21 kg/m2 (James *et al*., 2004). People with corpulence have higher rates of mortality and morbidity as compared to non-corpulent people (Flegal *et al*., 2013). The thermogenic reaction initiated by the high-fat eating routine was offset by increased energy efficiency and time-dependent decrease in physical activity, thereby favouring fat aggregation. These adaptations are for the most part determined by the nutrient composition of the eating regimen since control and high fat animals suddenly evoke isoenergetic intake (So *et al*., 2011).

India has the third highest number of obese and overweight individuals (11% of young people, and 20% of all grown-ups) after US and China. Undernutrition due to poverty is being rapidly replaced by obesity associated with affluence (Mohan and Deepa, 2006). Industrialisation and urbanisation also contribute to the increased prevalence of obesity. Studies from various parts of India have also indicated the rising prevalence of obesity (Mishra and Khurana, 2008; Deepa *et al*., 2009; Bhardwaj *et al*., 2011).

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Natural fats and oils occupied a very important role in the human diet and are useful for providing energy along with bioactive components like essential fatty acids, vitamins and antioxidants. It has been suggested that the quality of dietary lipids may be an important modulator of the risks associated with obesity development (Hill *et al*., 1993; Nagao and Yanagida, 2008). In this manner, there is expanded mindfulness among the general population to lessen the intake of calories derived from fats/oils keeping in mind the end goal is to bring down the fats/oils related medical issues such as obesity, diabetes and heart attack.

Functional foods have long been used for preventing the risk of diseases and promoting good health. The purpose of the present review is to discuss the studies already carried out on the effect of selected functional lipid components like medium chain triglycerides (MCTs), diacylglycerides (DAGs), conjugated linoleic acids (CLAs) and omega-3 fatty acids (ω-3 FAs) on obesity management.

Medium chain triglycerides

Medium chain fatty acids (MCFAs) generally refer to a blend of fatty acids comprising of 6-12 carbons which include caproic acid (hexanoic acid, C6:0), caprylic acid (octanoic acid, C8:0), capric acid (decanoic acid, C10:0) and dodecanoic acid (lauric acid, C12:0). The content of MCFAs in coconut oil, palm kernel oil, butter, milk, yogurt and cheese are about 15, 7.9, 6.8, 6.9, 66 and 7.3% (of total fatty acids), respectively (Roberfroid, 2000). MCFAs are essentially suggested for patients who suffer from malabsorption caused by intestinal resection and as a component for infant feeding formulas. Medium chain triglycerides are MCFAs esters of glycerol and edible MCT oils which are obtained through lipid fractionation from edible fats/oils (Babayan, 1987; Zaidul *et al*., 2006), chemical esterification (Ghosh and Bhattacharya, 1997), and/or enzymatic esterification (Kim and Rhee, 1991; Langone and Sant'Anna, 1999; 2002; Nandi *et al*., 2005) of oils using glycerol. Since 1994, the utilisation of MCTs in food products is generally recognised as safe (GRAS) by the US Food and Drug Administration. Human consumption of MCTs is at a lower level as of now, but intake is perhaps greater due to the distinctive properties of MCTs, which cause an increase in energy expenditure (EE) and increased satiety that may contribute to weight loss. The energy density of MCFAs is not as much as that of long chain fatty acids (LCFAs) because of their shorter chain length. MCT gives about 10% fewer calories than that given by LCT, -8.3 Cal/g for MCT versus 9 Cal/g for LCT (Bach *et al*., 1972). In this manner, the utilisation of MCT can reduce calorie intake, body weight and body fat in the long term. MCTs are likewise hydrolysed quickly and the subsequent MCFAs are absorbed by the liver by means of the portal vein and are utilised as an energy source without utilising the carnitine transport framework for mitochondrial passage (Hashim and Tantibhedyangkul, 1987). A study showed that the consumption of MCTs negatively affects the lipid profile (Kern *et al*., 2000), while another study showed a non-significant effect (Mumme and Stonehouse, 2015). Future studies ought to decide the impact of longer periods of MCTs supplementation on serum lipids of various groups of individuals. The experimental and clinical evidence for the physiological impact of MCTs on weight reduction is discussed in subsequent paragraphs.

Effects of MCTs on obesity

MCTs have long been studied for their anti-obesity properties. It has been accounted that MCTs influence the body composition as compared to LCTs. MCTs are specifically utilised by the liver and serve as an energy source in diet, and cause the decrease in fat deposition by enhancing thermogenesis. Thus, MCTs can be considered as agents that aid in the prevention of obesity or possibly stimulating weight loss (Papamandjaris *et al*., 1998; 2000; St-Onge and Jones, 2003). MCTs resulted in higher short-term increase of total energy expenditure (TEE) as compared to that produced by LCTs. Subsequently, compensatory mechanism may exist which limit the effects of MCTs on energy components over long term (Papamandjaris *et al*., 1999). The expanded energy expenditure due to lipogenesis in the liver suggests that the energy is stored to a lesser extent in the case of MCTs than that from dietary LCTs (Hill *et al*., 1989). The inclusion of MCTs in the subjects with BMI $\geq$ 23 Kg/m^2 resulted in lowered body weight and muscle to fat quotients in contrast to from only LCTs (Tsuji *et al*., 2001). Triglycerides containing medium and long chain fatty acids may possibly prevent hypertriglyceridemia, and obesity brought on by the utilisation of a high-fat diet when compared with soybean oil (Takeuchi *et al*., 2002). MCTs in the diet result in significant increase in postprandial thermogenesis and may be useful for the dietary administration of obesity (Kasai *et al*., 2003). The effect of MLCT on body fat may be influenced by the dietary fat content or by energy adequacy (Matsuo and Takeuchi, 2004). Although, some workers reported that structured medium and long-chain triglyceride oil enhance short-term fat oxidation but fails to modulate body weight or adiposity through a

change in energy expenditure (EE) (Roynette *et al*., 2008). It was also observed that for pre-menopausal normal weight women consuming a diet with 25% of the energy content from MCTs, there was no change in resting metabolic rate, transient increase in postprandial energy expenditure and significant increase in postprandial fat oxidation (Alexandrou *et al*., 2007). Therefore, little change in the nature of fat intake can greatly impact weight loss (St-Onge *et al*., 2008) and MCT-oil can be incorporated into a weight loss plan without the dread of unfavourably influencing metabolic risk factors. A distinction ought to be made with respect to chain length with regard to examining the impact of saturated fats on metabolic risk factors (St-Onge and Bosarge, 2008). The utilisation of MLCTs can diminish body fat weight and serum triacylglycerol and LDL-cholesterol in overweight hypertriglyceridemic subjects under a suitable dietary regime (Zhang *et al*., 2009; Xue *et al*., 2009). The combined intervention of MCTs diet and exercise has been suggested because of the additive effect on reduction of visceral and subcutaneous fat accumulation and that this impact might be partially related to increased energy expenditure (Ooyama *et al*., 2008).

Recently, it was reported that consumption of MLCT oil may decrease body weight, body fat and blood TAGs and low-density lipoprotein-cholesterol (LDL-C) levels in overweight hyper triacylglycerolemic Chinese subjects, but may not induce these changes significantly in normal or obese hypertriacylglycerolemic subjects (Zhang *et al*., 2010). The consumption of MCFAs in diet during pregnancy might protect the offspring from obesity in later life. Furthermore, the improvement of obesity might be associated with programmed changes in expression of the genes involved in fatty acid oxidation and synthesis (Dong *et al*., 2011). Adding chilli and MCTs to meals increases diet-induced thermogenesis (DIT) by over 50%, which over time may help induce weight loss and prevent weight gain or regain. Capsaicin, the active ingredient of chilli and MCTs has been shown to enhance diet-induced thermogenesis (DIT), increase satiety and lower down energy intake (Clegg *et al*., 2013). Structured lipid medium and long chain triacylglycerols (MLCT) have been claimed to have capability to manage obesity. Low-fat and high-fat dosage containing palm based-MLCTs were shown to suppress body fat accumulation. This effect is more effective with low-fat dosage (Lee *et al*., 2014). Medium chain triglycerides increase thermogenesis and may reduce food intake vis-a-vis long chain triglycerides. MCTs consumption diminishes food intake acutely, but this does not seem to be mediated by changes in glucagon-like peptide (GLP-1), peptide YY (PYY) and insulin (St-Onge *et al*., 2014). MCTs stimulate the activation of brown adipose tissue, possibly through norepinephrine pathway, which may in part add to the reduction of the body fat mass in obese mice fed a high-fat diet (Zhang *et al*., 2015). Supplanting LCTs with MCTs in the diet could possibly induce modest reduction in body weight and composition without adversely affecting lipid profiles. However, further research is required to confirm the efficacy of MCTs and to determine the dosage needed for the management of healthy body weight and composition (Mumme and Stonehouse, 2015; Bueno *et al*., 2015). A study reveals that both CLA and MCT can increase satiety and decrease food intake over a period of 24 hours. Therefore, CLA may be proposed as an alternative food ingredient to increase satiety because of having similar satiating effects. This may be useful for future prevention and/or treatment of obesity (Coleman *et al*., 2016). However, more research is required which should include longer duration laboratory trials particularly on MCFAs and its effect on satiety and food intake.

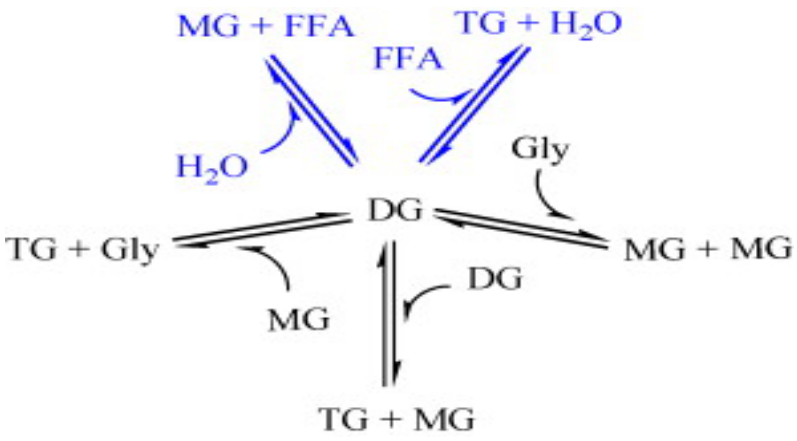

Figure 1. Different pathways of enzymatic formation and degradation of diglycerides. MG = monoglyceride, DG = diglyceride, TG = triglyceride, FFA = free fatty acid, Gly = glycerol.

Diacylglycerides

DAGs are a minor component of many seed oils and are normally present at ~1-6% level; or in the case of cottonseed oil as much as 10% (Flickinger and Matsuo, 2003). As demonstrated in Figure 1, there are a wide range of pathways for the synthesis of DAG, an intermediate product of triacylglyceride (TAGs) degradation. Industrial production is primarily accomplished by a glycerolysis reaction between triglycerides and glycerol, the raw material for which may be either vegetable or animal fats and oils (Sonntag, 1982) and latterly, it is produced using enzymes with or without solvents (Weber and Mukherjee, 2004; Valério *et al*., 2009; Wang *et al*., 2011) and ionic liquids (Guo *et al*., 2009; Kahveci *et al*., 2010). Diglycerides along with monoglycerides, produced using oils such as soybean, cottonseed, sunflower, or palm oil act as emulsifiers (provide a consistent texture and prevent separation), and are used in most baked products to keep them from turning stale. In ice cream and other processed foods like margarine, instant potatoes and chewing gum, they serve as stabilisers, thereby improving the body and consistency of the foods.

Effects of DAGs on obesity

The mechanism of action of DAGs in obesity management is by diminishing the re-synthesis of chylomicrons and shunting them directly to the liver through the portal vein, where they are oxidised. This expanded fat oxidation may impact the control of food intake by increasing satiety. It was shown, that DAGs, rather than TAGs, suppress both body weight and regional fat deposition, including visceral and hepatic fat in healthy men. DAGs, if utilised in place of the ordinary cooking oil, might be advantageous to health by suppressing visceral fat deposition (Nagao *et al*., 2000; Murase *et al*., 2001; Maki *et al*., 2002). It was illustrated that the structure of acylglycerol as given in Figure 2 (i.e., the structural difference between TAG and DAG) affects the body fat accumulation, expression of genes involved in lipid metabolism and thermogenesis, and their metabolic fate in the small intestine in C57BL/6J mice. Thus, dietary DAGs prevent weight gain that accompanies the stimulation of intestinal lipid metabolism, and these effects may be related to the characteristic metabolism of DAG in the small intestine (Murase *et al*., 2002). In the same context, Kamphuis *et al*. (2003) reported that the consumption of DAGs in contrast to TAGs does not alter EE but produces metabolic effects, particularly an increase in fat oxidation, which may be associated with improved appetite control and energy balance. One study showed that ingestion of DAGs for three months could reduce the amount of abdominal fat and improved serum lipid profiles in free-living haemodialysis (HD) patients (Teramoto *et al*., 2004). The effect of DAGs on postprandial lipid metabolism in non-diabetic subjects with and without insulin resistance was studied, and it was found that DAGs reduced postprandial lipidemia especially in subjects with insulin resistance and may also be beneficial in preventing atherosclerosis and related diseases (Takase *et al*., 2005). Compared with TAG-containing meal, DAG-containing meal produce higher postprandial energy expenditure and a significantly lower postprandial respiratory quotient. Therefore, it was suggested that the DAG-containing meal has high postprandial lipid oxidation activity and a potential effect on high diet-induced thermogenesis (Saito *et al*., 2006). It was suggested that DAG-oil in routine eating regime is useful for the prevention of postprandial hyperlipidaemia and related disorders (Tomonobu *et al*., 2006). Weight loss impact of dietary DAGs was also studied in obese dogs which showed a significant reduction in body weight as well as serum triglycerides and total cholesterol (Umeda *et al*., 2006). Enhanced fat utilisation with DAGs treatment and fast oxidation of ingested DAGs may, at least in part, explain the

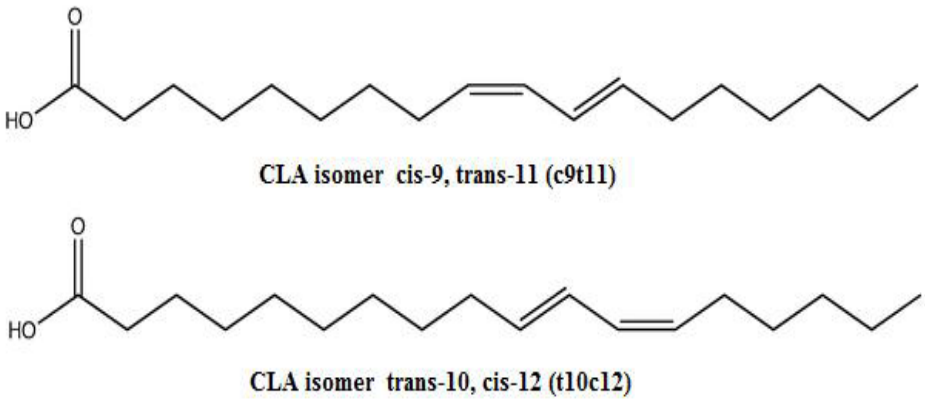

Figure 2. Main isomers of conjugated linoleic acid (CLA).

greater loss of body weight and body fat related to DAGs consumption found in the weight-reduction studies (Hibi *et al*., 2008a). Similarly, a modest body weight reduction was observed after 1-year ad libitum consumption of diacylglycerol oil as part of a regular diet in comparison to that of TAG-oil; weight loss was greater in participants who were obese at baseline. The weight reduction observed in diacylglycerol group was attributed to the substitution of usual home cooking oil with diacylglycerol because total energy intake and physical activity did not differ between the groups (Kawashima *et al*., 2008; Hibi *et al*., 2008b; Osaki *et al*., 2008). Although Hue *et al*. (2009) reported that DAG and DAG-CLA did not decrease body weight, although they may play an important role in lipid metabolism, resulting in improved human health.

Recently, it was reported that DAG-oil consumption increased the total and dietary fat oxidation in overweight subjects as compared to TAG-oil. The enhanced fat metabolism in overweight subjects that consumed DAG-oil resulted in greater loss of body weight and body fat (Hibi *et al*., 2011). A research was carried out in male Wistar rats by feeding four experimental diets containing 10% DAG butter blend (BDAG), triacylglycerol (TAG) butter blend (BTAG), DAG oil (ODAG) or TAG oil (OTAG), and it was observed that the ratio of abdominal fat weight/body weight was significantly higher in rats fed with BDAG-diet than in rats fed with the BTAG and ODAG-diets (Kristensen *et al*., 2012). In another animal study, the effects of rice bran oil (RBO) and DAG-rich rice bran oil was evaluated, and it was found that DAG-rich rice bran oil significantly decreased body weight of rats and total cholesterol and triglycerides content in plasma as compared to that by control RBO (Dhara *et al*., 2012). One clinical study revealed that the consumption of DAG-oil at a dose of 0.5 g/kg of body weight/day as a part of the diet showed no significant or treatment-related adverse effects (Yasunaga *et al*., 2004; Morita and Soni, 2009). Recently, DAGs products have faced safety issues as the glycidyl esters may get hydrolysed to the harmful parent glycidol by lipases in the gastrointestinal tract, which is considered as a genotoxic carcinogen and may induce tumours in numerous organs of rodents (Bakhiya *et al*., 2011). Therefore, its safety must further be validated by conducting in vivo studies.

Conjugated linoleic acids

Conjugated linoleic acids refer to a group of conjugated octadecadienoic acid isomers derived from linoleic acid, a fatty acid that contains 18 carbons and two cis double bonds at the 9th and 12th position (i.e. cis-9, cis-12 octadecadienoic acid). Microbes in the gastrointestinal tract of ruminants are mainly responsible for the conversion of linoleic acid into various isoforms of CLA through biohydrogenation. This bioprocess changes the position and configuration of the double bonds, resulting in isomers with a single bond at one or both positions (Silva *et al*., 2014). Out of these isomers, two (Figure 2) have been heavily researched and reported to be safe with significantly unique effects in the body, viz. trans-10, cis-12 isomer (t-10,c-12) and cis-9, trans-11 isomer (c-9,t-11) (Gaullier *et al*., 2002). These isomers are unique among the naturally occurring lipid segment in that they are potent at extremely low concentrations. Moreover, they are present in dairy products of ruminants and may affect the onset and severity of several chronic diseases, including various cancers, atherosclerosis, obesity, bone density loss and diabetes (McGuire and McGuire, 2000; Scimeca and Miller, 2000; Khanal, 2004; Crescenzo *et al*., 2015).

Effects of CLA on obesity

The proportion of CLA ranges from 0.3 to 1.07% of the total fat in dairy products, and from 0.12 to 0.68% of the total fat in raw or processed beef products (Dhiman *et al*., 2005; Silveira *et al*., 2007; Mendis *et al*., 2008). However, the CLA content of food is affected by few variables like season, breed, nutritional status and age of animal (Dhiman *et al*., 2005). The 9,11 isomers, also known as rumenic acid, is the predominant form of CLA found in naturally occurring foods. Out of the total CLAs, the 9,11 CLA isomer comprises approximately 90% of the CLA found in ruminant meat and dairy products while the 10,12 isomer represents the remaining 10%. Although, several other isoforms of CLA have been identified (i.e., trans-9, trans-11; cis-9, cis-11; trans-10, trans-11; and cis-10, cis-12), 9,11 and 10,12 isomers appear to be the most biologically active (Wallace *et al*., 2007). The average daily intake of CLA is approximately 152 mg to 212 mg for non-vegetarian women and men, respectively (Ritzenthaler *et al*., 2001) and human serum levels range from 10 µmol/L to 70 µmol/L (Mougios *et al*., 2001; Petridou *et al*., 2003).

The role of CLA in obesity management is well established. According to Blankson *et al*. (2000), a dose of 3.4 g CLA/day for 12 weeks seems to be sufficient to significantly reduce body fat in overweight and obese humans. On the other hand, CLA has been reported to reduce weight gain and fat deposition in rodents, while producing less

significant and inconsistent effects on body weight and composition in pigs and humans, therefore new studies are required to examine isomer-specific effect and mechanism of action of CLA in animals and humans using purified individual CLA isomers (Wang and Jones, 2004). Evidences from the experimental trials showed that the impact of CLA is not the same in all animal models like rats supplemented with 0.5% of CLA, for instance, presented a small, but rapid (seven days) reduction of adipose tissue as compared to that in mice (Gaze *et al*., 2007). Supplementing healthy Wistar rats with CLA at the concentrations of 1, 2 and 4% of the diet on the basis of daily consumption showed that the groups that were supplemented at a concentration of 2 and 4% of CLA presented a greater body fat reduction as compared to that in the control group (Botelho *et al*., 2005). When different diets (supplemented with coconut oil, coconut oil and CLA, maize oil and maize oil and CLA) were compared, it was observed that the triglycerides were reduced in the diet supplemented with coconut oil and CLA, and that the HDL-cholesterol were reduced when supplemented with maize oil diet. The total cholesterol concentration was lower in the rats fed with coconut oil and CLA diet as compared to those fed with maize oil and CLA. Thus, the study revealed that the CLA lowered down the adiposity and improved the lipid profile under certain conditions (Kloss *et al*., 2005). On the contrary, a few trials on the administration of CLA in humans showed a non-significant effect on body weight, body composition or weight regain. In fact, some studies suggested a tendency towards reduction in body fat mass and an increase in lean body mass, while some other studies raised concern about the possibility of deleterious effects of trans-10, cis-12 CLA on lipid profile, glucose metabolism and insulin sensitivity (Silveira *et al*., 2007).

Recently, CLA feeding was found to decrease body fat and possibly improve performance in sports persons (Barone *et al*., 2013). Furthermore, few studies were performed in humans to demonstrate the changes in body composition occurring by supplementation with CLA alone or in combination with physical exercise. It was shown that CLA may reduce the percentage of fat in humans when supplemented over a period of 12-months, besides increasing the lean mass and not providing any additional effect at doses above 3.4 g of CLA per day (Blankson *et al*., 2000). However, it was difficult to assess whether the effect was because of the utilisation of CLA or exercise or by the combination of both because levels of exercise were different among the groups. Similarly, it was observed that the CLA supplementation (4.5 g/day) for the period of 24 months in overweight adults was well tolerated and found to diminish body fat and could help in maintaining initial fat and weight loss over long term (Gaullier *et al*., 2005). Additionally, supplementing CLA for 12 weeks in overweight and grade I obese Chinese subjects yielded lower obesity indices, with no significant adverse effects (Chen *et al*., 2012). A study showed that CLA, especially trans-10, cis-12-CLA, has a potent body fat-reducing effect, which is prominent in mice and to a lesser extent in rats (Yamasaki and Yanagita, 2013). Recently, conjugated linolenic acid (CLNA) isomers were compared with CLA for their role in obesity and related effects (insulin resistance, dyslipidaemia, or inflammation) and it was reported that higher doses of CLNA is required as compared to CLA in order to be effective. However, because of the limited research conducted so far, it is still difficult to reach clear conclusion about the potential use of these CLNAs in obesity management (Miranda *et al*., 2014). It was reported that 10,12 CLA reduced white adipose tissue and brown adipose tissue mass in young, Sv129 male mice which were supplemented with high-fat diet for five weeks to make them fat and glucose intolerant and then subsequently fed with a low-fat diet with or without 0.1% 10,12 CLA, sodium salicylate or were exercised for another seven weeks (Shen *et al*., 2015). The synergistic effect of CLA and MCTs was also established based on the fact that both CLA and MCT increased the satiety and reduced the energy intake, indicating their potential role in aiding the maintenance of energy balance (Coleman *et al*., 2016).

A mixture of the two isomers, viz., 9-cis, 11-trans and 10-trans, 12-cis, in equal proportions have been mostly studied in the past for their safety under in vivo conditions. Several studies proposed that the daily doses of CLA varied from 3 to 6 g/day and these doses appeared to be safe (Iwata *et al*., 2007). Although, some studies indicated that doses above 3.4 g/day would not have any additional effect and suggested that there was great variation in results due to different doses, type of isomer used and body composition which makes it difficult to compare them in different studies (Blankson *et al*., 2000; Chen *et al*., 2012). On the other hand, numerous studies have shown that higher doses of supplemental CLA may result in increased accumulation of fat in the liver, which is a stepping stone towards the study of metabolic syndromes and diabetes (Clément *et al*., 2002; Jaudszus *et al*., 2010; Vyas *et al*., 2012).

Table 1. Relative percentage of fatty acid composition in oils (Soltan, 2012).

Type	Omega-6		Omega-3		
	LA 18:2n-6	AA 20:4n-6	ALA 18:3n-3	EPA 20:5n-3	DHA 22:6n-3
Corn oil	56.95	ND	0.94	ND	ND
Flaxseed oil	10.77	ND	56.31	ND	ND
Fish oil	ND	ND	ND	23.98	15.22

LA = linoleic acid, AA = arachidonic acid, ALA = α-linolenic acid, EPA = eicosapentaenoic acid, DHA = docosahexaenoic , ND = Not detected.

Omega-3 fatty acids

Omega-3 and omega-6 polyunsaturated fatty acids (ω-3/-6-PUFAs) are essential nutrients because they cannot be synthesised in the body and must be supplied from the diet (Russo, 2009). The relative concentration of omega-3 and omega-6 PUFAs in several oils is provided in Table 1 (Soltan, 2012). The three main dietary forms of omega-3 PUFAs are the marine-derived eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA), and the plant-derived alpha-linolenic acid (ALA). The omega-3 long-chain polyunsaturated fatty acids (ω-3 PUFAs) have been reported to improve obesity-associated metabolic disorders, including chronic inflammation, insulin resistance and dyslipidaemia (Martínez-Fernández *et al*., 2015).

Effects of omega-3 fatty acids on obesity

The body weight reducing effects of marine origin ω-3 PUFAs supplementation are controversial because some studies support that ω-3 PUFAs can significantly decrease body weight and fat mass. In the same context, Flachs *et al*. (2005) reported that the anti-adipogenic effect of EPA/DHA may involve a metabolic switch in adipocytes that includes the enhancement of β-oxidation and upregulation of mitochondrial biogenesis. DHA/EPA and rosiglitazone exerted additive effects in the prevention of obesity, adipocyte hypertrophy, low-grade adipose tissue inflammation, dyslipidaemia and insulin resistance, while inducing adiponectin, suppressing hepatic lipogenesis and decreasing muscle ceramide concentration (Kuda *et al*., 2009). Sato *et al*. (2010) found that the EPA supplementation strongly suppresses body weight gain and obesity-related hyperglycaemia and hyperinsulinemia in high fat (HF) / high sucrose (HS)-fed mice (HF/HS + EPA group). The ω-3 polyunsaturated fatty acids, mainly EPA and DHA, exerted hypolipidemic effects, thereby preventing obesity development and insulin resistance in animals fed with high-fat diets (Rossmeisl *et al*., 2009; 2012). Dietary long-chain ω-3 PUFA could reduce both hypertrophy and hyperplasia of fat cells in vivo and the results agree with the involvement of fat cell turnover in control of adiposity (Hensler *et al*., 2011). A similar study showed that the ω-3 PUFA has a preventive effect on the body weight gain, glucose intolerance and dyslipidaemia as induced by a high-fat diet (HFD) in mice with decrease in the hepatic secretion of very low-density lipoprotein (VLDL) TAG by reducing the expression of genes involved in lipogenesis (Kasbi Chadli *et al*., 2012). EPA supplementation in HFD prevents obesity and metabolic alterations in mice especially in skeletal muscle (Bertrand *et al*., 2013). The additional effects of ω-3 FAs supplementation in association with a lifestyle modification program (LSMP) in free living-adults were evaluated. A 20 weeks study on 39 adults was carried out which demonstrated that 360 mg of DHA and 540 mg of EPA from fish oil consumption per day showed a significant decrease in waist circumference (1.3%) followed by metabolic syndrome reduction (29%) mainly due to normalisation of blood pressure (33.3%) and triacylglycerol (27.3%). ω-3 FAs supplementation provided additional benefits to lifestyle modification program in the resolution of metabolic syndrome (de Camargo Talon *et al*., 2015). Some other studies have shown their non-significant action on body weight loss, but a significant reduction in fat depots (Raclot *et al*., 1997; Pérez-Matute *et al*., 2007; Kuda *et al*., 2009).

Conclusion

This review explores the beneficial effects of MCFAs/MCTs, DAGs, CLAs and ω-3 FAs in the prevention and management of obesity. Experimental studies demonstrated that the dietary MCFAs/MCTs suppress the fat deposition through enhanced thermogenesis and fat oxidation in animal and human subjects. DAGs increases thermogenesis to a greater extent as compared to that by triacylglycerols. After the hydrolysis of triacylglycerols into two fatty acids and a glycerol moiety, the DAGs enter the circulation as such and are oxidised by the liver. Protective mechanisms of CLAs against obesity includes increased energy expenditure, decreased energy intake, reduced lipogenesis, enhanced lipolysis and reduced adipocyte proliferation and differentiation. Similarly,

different studies suggested that the incorporation of ω-3 FAs in the diet can reduce adiposity, attenuate postprandial hunger sensation and promote increase in lean tissue mass. Nevertheless, further evaluations will be required to reach a consensus regarding the health benefits of MCFAs/MCTs, DGs, CLAs and ω-3 FAs on obesity and metabolic disorders because their beneficial effects have not been very apparent in conducted human trials. The therapeutic potential of all these functional lipid components against several metabolic syndromes is still promising and requires further experimentation.

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