Animal Nutrition 1 (2015) 12–18

Contents lists available at ScienceDirect

Animal Nutrition

journal homepage: http://www.keaipublishing.com/en/journals/aninu/

Original article

Effect of medium-chain triglycerides on growth performance, nutrient digestibility, plasma metabolites and antioxidant capacity in weanling pigs

Yue Li, Hao Zhang, Li Yang, Lili Zhang, Tian Wang*

College of Animal Science and Technology, Nanjing Agricultural University, Nanjing 210095, China

ARTICLE INFO

Article history:
Received 30 October 2014
Accepted 9 January 2015
Available online 10 March 2015

Keywords:
Medium-chain triglycerides
Growth performance
Nutrient digestibility
Metabolites
Lipid peroxidation
Piglets

ABSTRACT

The aim of this study was to investigate the effect of medium-chain triglycerides (MCTs) on growth performance, nutrient digestibility, plasma metabolites and antioxidant capacity in weanling pigs. A total of 160 weanling (Duroc × Landrace × Yorkshire) pigs (age: 21 ± 1 d; body weight: 7.50 ± 0.28 kg) were randomly allotted to 4 treatments, receiving the following diets for 28 d: control diet [containing 3.5% soybean oil (SO)], MCT1 diet (containing 0.7% MCTs and 2.8% SO), MCT2 diet (containing 1.4% MCTs and 2.1% SO) and MCT3 diet (containing 2.1% MCTs and 1.4% SO). Dietary inclusion of MCTs improved the average daily gain and feed efficiency (FE) of pigs compared with the control during the first 2 weeks post-weaning ($P < 0.05$). A similar positive effect was also observed for the overall FE in MCT2 group ($P < 0.05$). Compared with the control, apparent total tract digestibility (ATTD) of ether extract was improved by MCT2 and MCT3 treatment from day 12–14 post-weaning ($P < 0.05$). In addition, MCT2 treatment also exerted a beneficial effect on the ATTD of dry matter ($P < 0.05$). The increased total protein concentration and decreased urea nitrogen and malondialdehyde levels of plasma were observed in both MCT2 and MCT3 groups on day 14 post-weaning ($P < 0.05$). In conclusion, MCTs could improve growth performance, nutrients utilization, and antioxidant ability of weanling piglets.

1. Introduction

In modern intensive swine production systems, piglets are weaned earlier, usually between 15 and 28 days of age, to maximize the whole herd production (Smith et al., 2008). However, immature development of digestive tract makes weanling swine susceptible to digestive disorders. What's worse, the abrupt changes in feed composition and environment at weaning will aggravate intestinal malabsorption of nutrients and therefore decrease the feed intake of young pigs (Wu, 1998). The decreased feed intake would result in inadequate energy intake of newly weaned pigs, which can damage the growth and development of piglets. Therefore, high energy density diets are usually used to prevent growth lag of weanling piglets.

Long-chain triglycerides (LCTs) are used widely in diets to supply pigs with energy and essential fatty acids. Because of high caloric density, the addition of LCTs to the diet permits the feeding of a smaller volume of diet, a procedure that may help to avoid gastrointestinal distress, regurgitation, and aspiration at birth and in early infancy (Tantibhedhyangkul and Hashim, 1975). However, Cera et al. (1988) have shown that digestibility of LCTs declined to 65–80% at weaning, which may be due to the low activity of pancreatic lipase and intestinal lipase and therefore the absorption of dietary fat from intestine was inefficient (Cera et al., 1988). Furthermore, the newly weaned pigs may require a period of time before they are capable of synthesizing adequate amounts of carnitine, which plays a vital role in facilitating the transport of long-chain fatty acids (LCFAs) into the mitochondria for energy production (Fritz and Yue, 1963). Beyond that, weaning stress can

* Corresponding author.
E-mail address: tianwangnjau@163.com (T. Wang).

Peer review under responsibility of Chinese Association of Animal Science and Veterinary Medicine.

Production and Hosting by Elsevier on behalf of KeAi

http://dx.doi.org/10.1016/j.aninu.2015.02.001

lead to the imbalance of antioxidant defense system, which is involved in the redox balance maintenance (Durak et al., 2000; Zhu et al., 2012). The unsaturated bond of LCFAs is vulnerable to attack by free radicals, and this process can form organic free radicals which will trigger a cascade of damage to endogenous lipids and lead to lipid peroxidation. There is a positive correlation between the degree of unsaturation of dietary fat and the lipid peroxidation of the body (Mehta et al., 1994). Thus, the post-weaning diet must be formulated to well match the young pig's digestive insufficiencies and to improve the symptoms caused by weaning stress.

Medium-chain fatty acids (MCFAs) refer to a mixture of fatty acids which generally consist of 6–12 carbons. Medium-chain triglycerides (MCTs) are MCFAs esters of glycerol, and MCTs-oils are obtained from edible fats (such as coconut oil and milk) through lipid fractionation. Commercial MCTs products are predominantly comprised of C8:0 and C10:0 in worldwide (Babayan, 1987; Hashim and Tantibhedyangkul, 1987). In comparison with LCTs, MCTs are more easily degraded to fatty acids and glycerol by pancreatic lipase, which are then absorbed directly into the portal circulation and transported to the liver for rapid oxidation (Bach et al., 1988; Odle et al., 1989, 1991; Ooyama et al., 2009). Moreover, MCFAs are fully saturated and therefore have a greater oxidative stability than that of LCTs. It has been reported that MCTs exerted a positive effect in improving the growth performance of weanling pigs. Rodas and Maxwell (1992) found that the average daily gain (ADG) and feed efficiency (FE) of weanling pigs were linearly enhanced by MCFAs inclusion (from 20 to 60 g/kg diet) during the first week when compared to those given tallow or milk fat. Similar results were also reported in the result by Hong and his colleagues, who found that MCFAs inclusion enhanced ADG of pigs during the first 2 weeks post-weaning (Hong et al., 2012). Additionally, Price et al. (2013) showed that the digestibility was greater for the MCTs than the LCTs diet (98.5% vs. 93.4%) in newly weaned pigs. Dietary inclusion of MCTs improved the apparent total tract digestibility (ATTD) of dry matter (DM) and nitrogen of piglets at the end of 2nd and 5th week after weaning, and the similar effect exerted by MCTs was also found for energy digestibility (Hong et al., 2012). Study on energetics in newborn piglets clearly demonstrated a superior energetic exploitation of the MCFAs in comparison with the LCFAs. Although our comprehension regarding the benefits of MCTs in swine production has grown significantly, it was far from being complete or even satisfactory. Thereby, the objective of this study was to investigate the effects of MCTs on growth performance, nutrient digestibility, plasma metabolites and antioxidant capacity in weanling pigs.

2. Methods and materials

2.1. Materials

MCTs (consisting of caprylin and decanoin) and soybean oil (SO) were obtained from Yihai Oils & Grains Industries Co., Ltd (Lianyungang, Jiangsu, China). The fatty acid constituents of the test oils as measured by gas chromatography (GC7890; Agilent Technologies, Palo Alto, CA, USA) are presented in Table 1.

2.2. Experimental design, diets and management

The experimental protocols were permitted by the Institutional Animal Care and Use Committee of Nanjing Agricultural University. In total, 160 pigs (Duroc × Landrace × Yorkshire) weaned at 21 ± 1 d of age with a similar body weight (7.50 ± 0.28 kg) were randomly allotted to 4 treatments in a randomized complete block design according to their sex and body weight (4 replicates with 5 gilts and 5 barrows per pen), and then fed 4 formulas (identical in nutrient content except for the type of oil) for 28 d. The 4 diets were as follows: control diet (containing 3.5% SO), MCT1 diet (containing 0.7% MCTs and 2.8% SO), MCT2 diet (containing 1.4% MCTs and 2.1% SO), and MCT3 diet (containing 2.1% MCTs and 1.4% SO). The diets were formulated to meet or exceed the NRC (1998) nutrient requirements (Table 2). The pigs were housed in a total confinement pen (3.7 m × 4.0 m) with concrete-slatted floors. The target room temperature and humidity were 26.1 ± 2.6 °C and 60.9 ± 9.8%, respectively. Feed and fresh water were fed *ad libitum* at all experimental period.

Table 1
Fatty acid constituents of test oils (g/100 g total fatty acids).

Fatty acid	Diets	
	Soybean oil	Medium-chain triglycerides
8:0	0.1	55.8
10:0	0.1	43.8
12:0	ND[a]	0.2
16:0	12.5	ND
18:0	3.3	ND
18:1	23.1	ND
18:2n-6	52.1	ND
18:3n-3	5.0	ND
Other	3.8	0.2

[a] ND, not detected.

2.3. Sample collection and procedures

Freshly-voided faeces were collected from 0800 to 1600 by hand grab-sampling from pen floors on day 12–14 and 26–28, respectively. Faeces were pooled by pen and frozen at −20 °C. Upon

Table 2
Composition of diets (as fed basis, g/kg).

Item	Diets[a]			
	Control	MCT1	MCT2	MCT3
Ingredients				
Corn	449	449	449	449
Wheat flour	100	100	100	100
Soybean meal	120	120	120	120
Extruded soybean	80	80	80	80
Fermented soybean meal	40	40	40	40
Fish meal	82	82	82	82
Glucose	54	54	54	54
Soybean oil	35	28	21	14
Medium-chain triglycerides	0	7	14	21
Premix[b]	40	40	40	40
Nutrient level[c]				
Digestible energy, MJ/kg	14.52	14.51	14.49	14.49
Crude protein	198.2	198.4	198.0	198.5
Lysine	12.9	12.6	12.8	12.7
Methionine + cystine	6.8	6.8	6.8	6.8
Threonine	7.0	7.1	7.0	7.2
Tryptophan	2.0	2.0	2.0	2.0
Calcium	7.8	7.8	7.7	7.8
Total phosphorus, %	6.1	6.0	6.0	6.0
Available phosphorus, %	4.0	4.0	4.0	4.0

[a] Control, diet contained 3.5% soybean oil (SO); MCT1, diet contained 0.7% medium-chain triglycerides (MCTs) and 2.8% SO; MCT2, diet contained 1.4% MCTs and 2.1% SO; MCT3, diet contained 2.1% MCTs and 1.4% SO.

[b] Premix provided per kilogram of diet: Fe, 180 mg as $FeSO_4$; Cu, 230 mg as $CuSO_4$; Zn, 180 mg as $ZnSO_4$; Mn, 50 mg as $MnSO_4$; I, 0.5 mg as $Ca(IO_3)_2$; Se, 0.2 mg as Na_2SeO_3; vitamin A, 15,000 IU; vitamin D_3, 3000 IU; vitamin E, 100 mg; vitamin K-3, 3 mg; vitamin B_1, 3 mg; vitamin B_2, 8 mg; vitamin B_6, 5 mg; vitamin B_{12}, 0.04 mg; biotin, 0.3 mg; pantothenic acid, 20 mg; niacin, 45 mg; folic acid, 2 mg; choline chloride, 450 mg; vitamin C, 160 mg.

[c] All nutrient contents, except digestible energy and available phosphorus, were analyzed values.

completion of the growth trial, faeces were thawed, homogenized, sub-sampled and then freeze-dried by lyophilization under −60 °C (Christ Alpha 1–4 LSC, Christ, Osterode, Germany). On day 14 and 28, heparinized blood samples (one gilt and one barrow per pen) were drawn randomly by jugular vein puncture after feed deprivation for 8 h, and then centrifuged at 1500 *g* for 10 min at 4 °C. The acquired plasma was stored at −80 °C for further analyses.

2.4. Growth performance and chemical analysis

Pig body weight and feed consumption were recorded and measured on a pen basis at the beginning, the end of the second week (day 14) and the end of entire experimental period (day 28) to calculate ADG, average daily feed intake (ADFI) and FE.

Diets and faeces were analyzed (AOAC, 1990) for DM (934.01), crude protein (CP, 954.01), ether extract (EE, 920.39) and gross energy (GE) using an adiabatic bomb calorimeter (TX-6000, Tianxin instrument, Hebi, China). Coefficients of ATTD were determined using acid-insoluble ash for the indicator method described by Vogtmann et al. (1975).

Plasma metabolites [total cholesterol (TC), triacylglycerides (TG), glucose (GLU), urea nitrogen (UN) and total protein (TP)] were measured with enzymatic kinetic method by automatic biochemistry analyzer (Selecta E, Wasson, Eindhoven, Holland) with commercial kits according to the manufacturer's protocol. The concentration of malondialdehyde (MDA) and the activities of total antioxidative capacity (T-AOC), superoxide dismutase (SOD), glutathione peroxidase (GPX), catalase (CAT) were determined using colorimetric kits with spectrophotometer according to the instructions of the commercial kits (Nanjing Jiancheng Institute of Bioengineering, Jiangsu, China). Briefly, the SOD activity was assayed at 550 nm by use of a xanthine and xanthine oxide system according to the method of Sun et al. (1988). One unit of SOD was defined as the amount of SOD required to produce 50% inhibition of the rate of nitrite production at 37 °C in 1 min. The GPX activity was assayed at 412 nm using glutathione (GSH) as a substrate by measuring the GSH decrease in the enzymatic reaction (except for the effect of the non-enzymatic reaction). Hafeman et al.'s (1974) dithio-nitro benzene method was used for determining the GPX activity. One unit of GPX activity was defined as the amount of enzyme depleting 1 μmol of GSH at 37 °C in 1 min. The CAT activity was assayed by measuring the decomposition of hydrogen peroxide according to the method by Beers and Sizer (1952). One unit of CAT activity was defined as the amount required to decompose 1 μmol of hydrogen peroxide at 37 °C in 1 min. The activity of T-AOC was measured at 520 nm by the method of ferric reducing-antioxidant power assay (Benzie and Strain, 1996). One unit of T-AOC was defined as the amount that increased the absorbance by 0.01 at 37 °C in 1 min. MDA concentration was measured by the thiobarbituric acid method as described previously by Placer et al. (1966) and was expressed as nmol/mL.

2.5. Statistical analysis

Data were analyzed by one-way analysis of variance (ANOVA) using the SPSS statistical software (Ver.16.0 for windows, SPSS Inc., Chicago, IL, USA). Polynomial orthogonal contrasts were used to determine the linear and quadratic effects of MCTs inclusion level. Differences among treatments were examined using the Duncan's multiple range tests, which were considered significant at $P < 0.05$. The means and standard error of the means are presented.

3. Results

3.1. Growth performance

The substitution of MCTs for SO at different dose all improved the body weight of pigs during the first 2 weeks post-weaning when compared with those fed the diet without MCTs, which appeared to result from simultaneously increased ADG (linear, $P = 0.011$; quadratic, $P = 0.041$; Table 3) and FE (linear, $P < 0.001$). However, there were no differences in ADG, ADFI and FE among groups from day 15–28 post-weaning. Overall, the FE of piglets in MCT2 group was greater than that of control group ($P < 0.05$). Increasing inclusion of MCTs resulted in a linear decrease in ADFI of pigs (linear, $P = 0.028$).

3.2. Apparent total tract digestibility

Dietary inclusion of MCTs improved the ATTD of DM linearly from day 12–14 post-weaning (linear, $P = 0.032$, Table 4). Likewise, the ATTD of EE increased linearly with the increasing MCTs levels in the diets (linear, $P = 0.004$). In comparison with the control group, an increased ATTD of EE was observed in both MCT2 and MCT3 groups from day 12–14 post-weaning ($P < 0.05$). Additionally, there was a significant increase in the ATTD of DM in the MCT2 group ($P < 0.05$). However, there were no differences in the ATTD of CP and GE among the groups from day 12–14 post-weaning. Dietary

Table 3
Effect of dietary substitution of medium-chain triglycerides on growth performance of weanling pigs (n = 4).[a]

Item[b]	Control	MCT1	MCT2	MCT3	SEM	*P*-value	
						Linear	Quadratic
Day 1 to 14							
Average daily gain, g/d	218.02b	249.82a	265.89a	254.73a	6.23	0.011	0.041
Average daily feed intake, g/d	413.58	425.03	415.97	400.13	6.08	0.397	0.299
Feed efficiency[c], g/g	0.53b	0.59a	0.64a	0.64a	0.01	<0.001	0.093
Day 15 to 28							
Average daily gain, g/d	445.00	426.79	441.25	402.50	7.80	0.108	0.494
Average daily feed intake, g/d	780.21	751.80	723.28	700.74	14.92	0.058	0.920
Feed efficiency, g/g	0.57	0.57	0.61	0.58	0.01	0.591	0.437
Day 1 to 28							
Average daily gain, g/d	331.51	338.30	353.57	328.62	4.75	0.873	0.105
Average daily feed intake, g/d	596.89	588.42	569.63	550.44	7.85	0.028	0.712
Feed efficiency, g/g	0.56b	0.58ab	0.62a	0.60ab	0.01	0.051	0.220

SEM = standard error of the means.
Values with different lowercase letters in the same row are different ($P < 0.05$).
[a] Four replicates with five barrows and five gilts per pen.
[b] Control, diet contained 3.5% soybean oil (SO); MCT1, diet contained 0.7% medium-chain triglycerides (MCTs) and 2.8% SO; MCT2, diet contained 1.4% MCTs and 2.1% SO; MCT3, diet contained 2.1% MCTs and 1.4% SO.
[c] Feed efficiency was calculated by dividing the average daily gain by its average daily feed intake.

Table 4
Effect of dietary medium-chain triglycerides levels on apparent total tract digestibility of nutrients of weanling pigs (n = 4).[a]

Item[b]	Control	MCT1	MCT2	MCT3	SEM	*P*-value	
						Linear	Quadratic
Day 12 to 14							
Dry matter, %	81.25b	82.35ab	84.74a	83.87ab	0.55	0.032	0.321
Crude protein, %	67.68	68.07	71.89	69.89	0.98	0.259	0.557
Gross energy, %	78.41	80.88	81.74	83.34	0.89	0.063	0.803
Ether extract, %	65.60b	68.48ab	73.31a	75.03a	1.35	0.004	0.785
Day 26 to 28							
Dry matter, %	87.14	88.00	87.79	89.54	0.42	0.067	0.578
Crude protein, %	77.54	77.80	79.89	81.67	0.89	0.088	0.672
Gross energy, %	85.33	85.79	86.16	87.73	0.43	0.056	0.719
Ether extract, %	79.72b	82.52b	83.30ab	86.76a	0.87	0.003	0.805

SEM = standard error of the means.
Values with different lowercase letters in the same row are different ($P < 0.05$).
[a] Four replicates with five barrows and five gilts per pen.
[b] Control, diet contained 3.5% soybean oil (SO); MCT1, diet contained 0.7% medium-chain triglycerides (MCTs) and 2.8% SO; MCT2, diet contained 1.4% MCTs and 2.1% SO; MCT3, diet contained 2.1% MCTs and 1.4% SO.

inclusion of MCTs from day 26–28 post-weaning increased the ATTD of EE in a dose-dependent manner (linear, $P = 0.003$). The ATTD of EE in the MCT3 group was greater than that of the control from day 26–28 after weaning ($P < 0.05$), whereas MCTs treatment did not affect the ATTD of DM, CP and GE of pigs at this phase.

3.3. Plasma parameters

The plasma biochemical analyses revealed that plasma UN linearly decreased (linear, $P = 0.010$) with increasing MCTs in the diets on day 14 post-weaning. In contrast, dietary inclusion of MCTs linearly increased plasma TP concentration (linear, $P = 0.006$). An increased concentration of plasma TP was observed in both MCT2 and MCT3 groups compared with those fed a pure LCTs diet on day 14 post-weaning, which was in agreement with the simultaneously decreased plasma UN concentration ($P < 0.05$; Table 5). Dietary treatment did not affect the concentrations of plasma TC, TG and GLU of pigs on day 14 post-weaning. On day 28 post-weaning, increasing MCTs inclusion resulted in a linear decrease in the concentration of plasma GLU (linear, $P = 0.043$). There were no differences in plasma metabolites among the groups on day 28 post-weaning.

Dietary inclusion of MCTs linearly decreased plasma MDA concentration on day 14 (linear, $P = 0.005$) and 28 (linear, $P = 0.034$) post-weaning, respectively. Compared with the control, there was a significant decrease in the concentration of plasma MDA in both MCT2 and MCT3 groups on day 14 after weaning ($P < 0.05$), similar effect was also observed in the plasma MDA of MCT3 group on day 28 post-weaning ($P < 0.05$). There were no differences in the activities of plasma T-AOC, SOD, GPX and CAT among groups on day 14 and 28 after weaning (Table 6).

4. Discussion

Dietary inclusion of fat could enhance the fatty acids digestibility, body weight gain, and FE in the early weaned pigs (Frobish et al., 1970; Lawrence and Maxwell, 1983; Li et al., 1990). However, contradictory result was also observed by Cera et al. (1988). The discrepancy may due to the differences in the composition of diet, the source, constituent, saturation degree and supplementation level of dietary fat. In the present study, the substitution of MCTs for SO in the diet of weanling pigs improved the body weight gain and FE during the first 2 weeks post-weaning, which was in consistent with the findings of Dove et al. (1993), who reported an advantage in the body weight gain and feed conversion ratio of pigs when MCTs was added during the first 2 weeks post-weaning, as compared with those fed diets containing either SO or animal fat. The improved growth performance of weaned pigs may be due to the unique physiological and biological properties of MCTs, ensuring MCTs can be digested and absorbed under the

Table 5
Effect of dietary medium-chain triglycerides levels on plasma metabolites of weanling pigs (n = 4).[a]

Item[b]	Control	MCT1	MCT2	MCT3	SEM	*P*-value	
						Linear	Quadratic
Day 14							
Total cholesterol, mg/100 mL	56.17	38.00	46.60	43.70	3.36	0.340	0.261
Triacylglycerides, mg/100 mL	25.47	22.81	28.79	24.14	1.88	0.913	0.808
Glucose, mg/100 mL	85.30	91.70	90.53	92.06	1.87	0.292	0.542
Urea nitrogen, mg/100 mL	10.79a	8.85ab	8.15b	7.62b	0.46	0.010	0.362
Total protein, g/100 mL	3.96b	4.17ab	4.55a	4.54a	0.09	0.006	0.433
Day 28							
Total cholesterol, mg/100 mL	51.53	47.18	48.43	41.09	1.79	0.069	0.664
Triacylglycerides, mg/100 mL	19.04	17.71	16.39	18.60	1.00	0.787	0.427
Glucose, mg/100 mL	85.07	79.17	76.88	64.31	3.49	0.045	0.616
Urea nitrogen, mg/100 mL	6.67	6.32	4.95	5.61	0.30	0.091	0.379
Total protein, g/100 mL	4.52	4.37	4.46	4.54	0.12	0.908	0.663

SEM = standard error of the means.
Values with different lowercase letters in the same row are different ($P < 0.05$).
[a] Four replicates with one barrow per pen.
[b] Control, diet contained 3.5% soybean oil (SO); MCT1, diet contained 0.7% medium-chain triglycerides (MCTs) and 2.8% SO; MCT2, diet contained 1.4% MCTs and 2.1% SO; MCT3, diet contained 2.1% MCTs and 1.4% SO.

Table 6
Effect of dietary medium-chain triglycerides levels on plasma redox status of weanling pigs (n = 4).[a]

Item[b]	Control	MCT1	MCT2	MCT3	SEM	*P*-value	
						Linear	Quadratic
Day 14							
Total antioxidative capacity, U/mL	4.44	4.01	5.06	4.69	0.20	0.311	0.936
Superoxide dismutase, U/mL	123.14	103.52	101.04	109.79	4.25	0.265	0.106
Glutathione peroxidase, U/mL	321.33	320.89	320.10	331.53	4.91	0.543	0.587
Catalase, U/mL	2.52	2.31	2.52	2.31	0.09	0.647	1.000
Malondialdehyde, nmol/mL	2.21a	2.11a	1.65b	1.65b	0.09	0.005	0.735
Day 28							
Total antioxidative capacity, U/mL	6.04	6.32	6.66	6.44	0.29	0.602	0.708
Superoxide dismutase, U/mL	109.71	106.29	106.35	108.69	4.04	0.942	0.754
Glutathione peroxidase, U/mL	248.58	243.24	242.16	248.45	3.50	0.966	0.461
Catalase, U/mL	2.87	2.69	2.89	2.95	0.14	0.761	0.714
Malondialdehyde, nmol/mL	2.31a	1.90ab	1.72ab	1.49b	0.14	0.034	0.714

SEM = standard error of the means.
Values with different lowercase letters in the same row are different ($P < 0.05$).
[a] Four replicates with one barrow per pen.
[b] Control, diet contained 3.5% soybean oil (SO); MCT1, diet contained 0.7% medium-chain triglycerides (MCTs) and 2.8% SO; MCT2, diet contained 1.4% MCTs and 2.1% SO; MCT3, diet contained 2.1% MCTs and 1.4% SO.

conditions as immediately post-weaning, these changes in the functions of intestinal digestion and absorption might exert negative effects on the utilization of LCTs. Furthermore, MCFAs cross the double mitochondrial membrane very rapidly and, unlike the LCFAs, they do not require the presence of carnitine (Sidossis et al., 1996). Thus, MCTs represent an immediately available source of energy that can be supplemented to the diet of weanling pigs to meet their energy need in stress. However, there was a small disadvantage in the feed intake and body weight gain of pigs fed the diet containing 2.1% MCTs from day 15–28 post-weaning in the present study. Since MCFAs are rapidly cleared from circulation and principally oxidized compared with the LCFAs, thus, resulted in a lower rate of fat deposition (Bach et al., 1988). Moreover, fatty acid oxidation in the liver could increase the satiety and therefore might decrease the feed intake (Leonhardt and Langhans, 2004). It is worth noting that pig with weaning-associated wasting syndrome has basically been restored after the first 2 weeks post-weaning (Lewis and Southern, 2001), which occurred alongside the improvement of LCTs utilization. Hence, the optimal phase for the replacement of dietary SO with MCTs may be the first 2 weeks post-weaning.

In the current study, a significant increased ATTD of EE was observed in the pigs fed the MCTs-rich diet, which was consistent with a previous study by Bennett (1964), in which rat small intestine had the capacity to absorb MCTs four times as efficiently as LCTs by a study of duodenal perfusion of lipids. Similarly, Cancio and Menendez (1964) also found that the replacement of LCTs with MCTs in a substantial degree could ameliorate the fat malabsorption in case of diminished absorptive surface or atrophied intestinal villi. Bile salts and pancreatic lipase are limiting factors in the hydrolysis of LCTs in the intestinal lumen, whereas the process may not be necessary for the absorption of MCTs. Clark and Holt (1968) found that the diversion of bile from the small bowel in rats did not affect the rate of hydrolysis and absorption of MCTs, while in the absence of pancreatic lipase, the absorption of MCTs was reduced but to a lesser degree than that of LCTs due to higher water solubility of MCFAs and intact MCTs could be partially taken up by the enterocytes and cleaved hydrolytically within the cells (Playoust and Isselbacher, 1964; Valdivieso, 1972). Moreover, replacing SO with MCTs by 1.4% had a positive role in the ATTD of DM, which resulted from an integrated improvement in the digestibility of various nutrients. MCFAs are considered to be anionic surfactants, which, as a result of this property, have antibacterial activity (Zentek et al., 2011). MCFAs can depress the growth of intestinal pathogenic strains, such as *Escherichia coli*, *Salmonella Enteritidis*, *Campylobacter jejuni*, *Helicobacter pylori*, etc (Bergsson et al., 2002; Sprong et al., 2001; Van Immerseel et al., 2004). Some researchers consider that the mechanism resulting in an improved growth performance of piglets after MCTs treatment has certain relationship with the antibacterial effects of MCFAs in the intestinal lumen (Decuypere and Dierick, 2003). Thus, MCFAs could reduce the amount of bacteria in gut, which need nutrients for their own use and therefore compete with the host for the limited nutrients in gastrointestinal tract.

Blood biochemistry is a labile biochemical system which can reflect the condition of the organism and the changes happening to it under influence of internal and external factors (Toghyani et al., 2010). Plasma TP is routinely used as a basic index for health status of animals, and plasma UN is the main dead end product of protein metabolism. The changes of these parameters can reflect the whole body status of protein metabolism and utilization in animals (Eggum, 1970). In the current study, an increased concentration of plasma TP was observed in the pigs fed the MCTs-rich diets on day 14 post-weaning, which had a roughly negative correlation with the plasma UN. These results are in agreement with previous studies, which have hitherto mainly been shown in rats but also in human intensive care unit patients (Lindgren et al., 2001; Maiz et al., 1984; Mendez et al., 1992; Mok et al., 1984; Yamazaki et al., 1984). Furthermore, the improved concentration of plasma TP possibly is partially due to the slight increment in the ATTD of CP from day 12–14 post-weaning, although not significant. This finding, together with the lower UN concentration in the plasma of piglets, indicated a better nitrogen balance after MCTs treatment, which was associated with a more favorable energy production by MCTs. Previous study has found that the improvement in nitrogen retention might occur when the effective calories in the diet were increased by incorporation of efficiently absorbed fat, especially in a situation where malnutrition appeared more often to weanling pigs due to gastrointestinal dysfunction and inadequate feed intake during the early period post-weaning (Drews et al., 1993). Moreover, ketone bodies, though not measured in this study, might also explain the improved nitrogen balance. MCFAs are ketogenic in contrast to LCFAs (Cotter et al., 1987; Miles et al., 1991), and ketone bodies have been demonstrated to increase protein synthesis when administered in animal and human studies (Crowe et al., 1989; Nair et al., 1988; Umpleby et al., 1988). Taken together, MCTs provide a sufficient fuel for energy supply and therefore decrease the expenditure of protein as a source of energy.

Oxygen-free radicals generally known as reactive oxygen species (ROS) are well recognized for playing a dual role as both deleterious and beneficial radical specie. The development of tissue injury and the outcome of the disease depend on the balance between the generation of toxic radicals and tissue antioxidant status (Windrow et al., 1993). However, the concentrations of ROS (such as superoxide anion, hydrogen peroxide, and hydroxy radical) exceeding the antioxidant protection of the cells can elicit widespread damage to DNA, proteins, and endogenous lipids (Yu, 1994). SO contains more than 50% ω-6 polyunsaturated fatty acids (PUFAs), mainly linoleic acid (18: 2n-6). Polyunsaturated fatty acids-rich fat undergoes peroxidation causing free-radical-dependent damage to cells, as evidenced by increased production of pentane and MDA in animal and clinical studies (Levene et al., 1980; Van Gossum et al., 1988). This alkane is produced in free-radical-induced peroxidation of linoleic acid and MDA is the main end product of lipid peroxidation, which can reflect the degree of lipid peroxidation (Gardner, 1989; Pitkanen et al., 1989; Sumida et al., 1989). In the current study, a decreased plasma MDA concentration was observed in pigs fed the MCTs-rich diet. MCFAs have no unsaturated fatty acids present and therefore they are exceptionally stable to oxidation. This finding is potentially instructive for purposefully enhancing the physical health and function of piglets when they're in a high oxidative stress.

5. Conclusion

In conclusion, MCTs could exert a positive role on the growth performance, increase TP concentration and decrease MDA content in the plasma of piglets during the early period post-weaning.

Conflict of interest

The authors declare that they have no competing interests.

Acknowledgments

The authors thank their laboratory colleagues for their assistance. This study was supported by the National Natural Science Foundation of China (31272454).

References

AOAC. Official methods of analysis. 15th ed. Washington, DC: Association of Official Analytical Chemists; 1990.
Beers RJ, Sizer IW. A spectrophotometric method for measuring the breakdown of hydrogen peroxide by catalase. J Biol Chem 1952;195:133–40.
Bennett S. Intestinal absorptive capacity and site of absorption of fat under steady state conditions in the unanaesthetized rat. Q J Exp Physiol Cogn Med Sci 1964;49:210–8.
Babayan VK. Medium chain triglycerides and structured lipids. Lipids 1987;22:417–20.
Bach AC, Storck D, Meraihi Z. Medium-chain triglyceride-based fat emulsions: an alternative energy supply in stress and sepsis. J Parenter Enter Nutr 1988;12:82S–8S.
Benzie IF, Strain JJ. The ferric reducing ability of plasma (FRAP) as a measure of "antioxidant power": the FRAP assay. Anal Biochem 1996;239:70–6.
Bergsson G, Steingrimsson O, Thormar H. Bactericidal effects of fatty acids and monoglycerides on Helicobacter pylori. Int J Antimicrob Agents 2002;20:258–62.
Cancio M, Menendez CR. Absorption of medium chain triglycerides in tropical sprue. Proc Soc Exp Biol Med 1964;117:182–5.
Clark SB, Holt PR. Rate-limiting steps in steady-state intestinal absorption of trioctanoin-1-14C. Effect of biliary and pancreatic flow diversion. J Clin Invest 1968;47:612–23.
Cotter R, Taylor CA, Johnson R, Rowe WB. A metabolic comparison of a pure long-chain triglyceride lipid emulsion (LCT) and various medium-chain triglyceride (MCT)-LCT combination emulsions in dogs. Am J Clin Nutr 1987;45:927–39.
Cera KR, Mahan DC, Reinhart GA. Weekly digestibilities of diets supplemented with corn oil, lard or tallow by weanling swine. J Anim Sci 1988;66:1430–7.
Crowe PJ, Royle GT, Wagner D, Burke JF. Does hyperketonemia affect protein or glucose kinetics in postabsorptive or traumatized man? J Surg Res 1989;47:313–8.
Dove CR. The effect of adding copper and various fat sources to the diets of weanling swine on growth performance and serum fatty acid profiles. J Anim Sci 1993;71:2187–92.
Drews D, Schluter MD, Stein TP. Glycerol kinetics with parenteral lipid emulsions (long-chain triglycerides, medium-chain triglycerides, and structured lipids) in rats. Metabolism 1993;42:743–8.
Durak I, Bingol NK, Avci A, Cimen MY, Kacmaz M, Karaca L, et al. Acute effects of smoking of cigarettes with different tar content on plasma oxidant/antioxidant status. Inhal Toxicol 2000;12:641–7.
Decuypere JA, Dierick NA. The combined use of triacylglycerols containing medium-chain fatty acids and exogenous lipolytic enzymes as an alternative to in-feed antibiotics in piglets: concept, possibilities and limitations. Nutr Res Rev 2003;16:193–210.
Eggum BO. Blood urea measurement as a technique for assessing protein quality. Br J Nutr 1970;24:983–8.
Fritz IB, Yue KT. Long-chain carnitine acyltransferase and the role of acylcarnitine derivatives in the catalytic increase of fatty acid oxidation induced by carnitine. J Lipid Res 1963;4:279–88.
Frobish LT, Hays VW, Speer VC, Ewan RC. Effect of fat source and level on utilization of fat by young pigs. J Anim Sci 1970;30:197–202.
Gardner HW. Oxygen radical chemistry of polyunsaturated fatty acids. Free Radic Biol Med 1989;7:65–86.
Hafeman DG, Sunde RA, Hoekstra WG. Effect of dietary selenium on erythrocyte and liver glutathione peroxidase in the rat. J Nutr 1974;104:580–7.
Hashim SA, Tantibhedyangkul P. Medium chain triglyceride in early life: effects on growth of adipose tissue. Lipids 1987;22:429–34.
Hong SM, Hwang JH, Kim IH. Effect of medium-chain triglyceride (MCT) on growth performance, nutrient digestibility, blood characteristics in weanling pigs. Asian-Aust J Anim Sci 2012;25:1003–8.
Levene MI, Wigglesworth JS, Desai R. Pulmonary fat accumulation after intralipid infusion in the preterm infant. Lancet 1980;2:815–8.
Lawrence NJ, Maxwell CV. Effect of dietary fat source and level on the performance of neonatal and early weaned pigs. J Anim Sci 1983;57:936–42.
Leonhardt M, Langhans W. Fatty acid oxidation and control of food intake. Physiology Behav 2004;83:645–51.
Lewis JA, Southern LL. Swine nutrition. 2nd ed. Washington DC: CRC Press; 2001.
Li DF, Thaler RC, Nelssen JL, Harmon DL, Allee GL, Weeden TL. Effect of fat sources and combinations on starter pig performance, nutrient digestibility and intestinal morphology. J Anim Sci 1990;68:3694–704.
Lindgren BF, Ruokonen E, Magnusson-Borg K, Takala J. Nitrogen sparing effect of structured triglycerides containing both medium-and long-chain fatty acids in critically ill patients; a double blind randomized controlled trial. Clin Nutr 2001;20:43–8.
Maiz A, Yamazaki K, Sobrado J, Babayan VK, Moldawer LL, Bistrian BR, et al. Protein metabolism during total parenteral nutrition (TPN) in injured rats using medium-chain triglycerides. Metabolism 1984;33:901–9.
Mok KT, Maiz A, Yamazaki K, Sobrado J, Babayan VK, Moldawer LL, et al. Structured medium-chain and long-chain triglyceride emulsions are superior to physical mixtures in sparing body protein in the burned rat. Metabolism 1984;33:910–5.
Miles JM, Cattalini M, Sharbrough FW, Wold LE, Wharen RJ, Gerich JE, et al. Metabolic and neurologic effects of an intravenous medium-chain triglyceride emulsion. J Parenter Enter Nutr 1991;15:37–41.
Mendez B, Ling PR, Istfan NW, Babayan VK, Bistrian BR. Effects of different lipid sources in total parenteral nutrition on whole body protein kinetics and tumor growth. J Parenter Enter Nutr 1992;16:545–51.
Mehta RS, Gunnett CA, Harris SR, Bunce OR, Hartle DK. High fish oil diet increases oxidative stress potential in mammary gland of spontaneously hypertensive rats. Clin Exp Pharmacol Physiol 1994;21:881–9.
Nair KS, Welle SL, Halliday D, Campbell RG. Effect of beta-hydroxybutyrate on whole-body leucine kinetics and fractional mixed skeletal muscle protein synthesis in humans. J Clin Invest 1988;82:198–205.
National Research Council. Nutrient requirements of swine. 10th rev. ed. Washington DC: National Academic Press; 1998.
Odle J, Benevenga NJ, Crenshaw TD. Utilization of medium-chain triglycerides by neonatal piglets: II. Effects of even- and odd-chain triglyceride consumption over the first 2 days of life on blood metabolites and urinary nitrogen excretion. J Anim Sci 1989;67:3340–51.
Odle J, Benevenga NJ, Crenshaw TD. Utilization of medium-chain triglycerides by neonatal piglets: chain length of even- and odd-carbon fatty acids and apparent digestion/absorption and hepatic metabolism. J Nutr 1991;121:605–14.
Ooyama K, Kojima K, Aoyama T, Takeuchi H. Decrease of food intake in rats after ingestion of medium-chain triacylglycerol. J Nutr Sci Vitaminol (Tokyo) 2009;55:423–7.
Playoust MR, Isselbacher KJ. Studies on the intestinal absorption and intramucosal lipolysis of a medium chain triglyceride. J Clin Invest 1964;43:878–85.
Placer ZA, Cushman LL, Johnson BC. Estimation of product of lipid peroxidation (malonyl dialdehyde) in biochemical systems. Anal Biochem 1966;16:359–64.
Pitkanen OM, Hallman M, Andersson SM. Determination of ethane and pentane in free oxygen radical-induced lipid peroxidation. Lipids 1989;24:157–9.
Price KL, Lin X, van Heugten E, Odle R, Willis G, Odle J. Diet physical form, fatty acid chain length, and emulsification alter fat utilization and growth of newly weaned pigs. J Anim Sci 2013;91:783–92.

Rodas BD, Maxwell CV. The effect of fat source and medium-chain triglyceride level on performance of the early-weaned pig. Pig News Info 1992;13:273.
Sidossis LS, Stuart CA, Shulman GI, Lopaschuk GD, Wolfe RR. Glucose plus insulin regulate fat oxidation by controlling the rate of fatty acid entry into the mitochondria. J Clin Invest 1996;98:2244–50.
Smith AL, Stalder KJ, Serenius TV, Baas TJ, Mabry JW. Effect of weaning age on nursery pig and sow reproductive performance. J Swine Health Prod 2008;6:131–7.
Sprong RC, Hulstein MF, Van der Meer R. Bactericidal activities of milk lipids. Antimicrob Agents Chemother 2001;45:1298–301.
Sumida S, Tanaka K, Kitao H, Nakadomo F. Exercise-induced lipid peroxidation and leakage of enzymes before and after vitamin E supplementation. Int J Biochem 1989;21:835–8.
Sun Y, Oberley LW, Li Y. A simple method for clinical assay of superoxide dismutase. Clin Chem 1988;34:497–500.
Tantibhedhyangkul P, Hashim SA. Medium-chain triglyceride feeding in premature infants: effects on fat and nitrogen absorption. Pediatrics 1975;55:359–70.
Toghyani M, Tohidi M, Gheisari AA. Performance, immunity, serum biochemical and hematological parameters in broiler chicks fed dietary thyme as alternative for an antibiotic growth promoter. Afr J Biotechnol 2010;9:6819–25.
Umpleby AM, Chubb D, Boroujerdi MA, Sonksen PH. The effect of ketone bodies on leucine and alanine metabolism in dogs. Clin Sci (Lond) 1988;74:41–8.
Valdivieso V. Absorption of medium-chain triglycerides in animals with pancreatic atrophy. Amer J Dig Dis 1972;17:129–36.
Vogtmann H, Pfirter HP, Prabucki AL. A new method of determining metabolisability of energy and digestibility of fatty acids in broiler diets. Br Poult Sci 1975;16:531–4.
Van Gossum A, Shariff R, Lemoyne M, Kurian R, Jeejeebhoy K. Increased lipid peroxidation after lipid infusion as measured by breath pentane output. Am J Clin Nutr 1988;48:1394–9.
Van Immerseel F, De Buck J, Boyen F, Bohez L, Pasmans F, Volf J, et al. Medium-chain fatty acids decrease colonization and invasion through hilA suppression shortly after infection of chickens with Salmonella enterica serovar Enteritidis. Appl Environ Microbiol 2004;70:3582–7.
Windrow VR, Winyard PG, Morris CJ, Blake DR. Free radicals in inflammation: second messengers and mediators of tissue destruction. Brit Med Bull 1993;49:506–22.
Wu G. Intestinal mucosal amino acid catabolism. J Nutr 1998;128:1249–52.
Yamazaki K, Maiz A, Sobrado J, Babayan V, Moldawer LL, Bistrian BR, et al. Hypocaloric lipid emulsions and amino acid metabolism in injured rats. J Parenter Enter Nutr 1984;8:360–6.
Yu BP. Cellular defenses against damage from reactive oxygen species. Physiol Rev 1994;74:139–62.
Zentek J, Buchheit-Renko S, Ferrara F, Vahjen W, Van Kessel AG, Pieper R. Nutritional and physiological role of medium-chain triglycerides and medium-chain fatty acids in piglets. Anim Health Res Rev 2011;12:83–93.
Zhu LH, Zhao KL, Chen XL, Xu JX. Impact of weaning and an antioxidant blend on intestinal barrier function and antioxidant status in pigs. J Anim Sci 2012;90:2581–9.