doi: 10.17221/55/2016-CJAS

Effects of Dietary L-Carnitine and Fat Type on the Performance, Milk Composition and Immunoglobulin in Sows, and Immunological Variables of Sows and Piglets during Late Gestation and Lactation

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ABSTRACT

Tian M., Wang N., Su G., Shi B., Shan A. (2017): **Effects of dietary L-carnitine and fat type on the performance, milk composition and immunoglobulin in sows, and immunological variables of sows and piglets during late gestation and lactation**. Czech J. Anim. Sci., 62, 185–194.

An experiment with a 2 × 2 factorial arrangement of treatments (n = 12 sows/treatment) was conducted to investigate the effect of maternal dietary supplementation with 2 different L-carnitine levels (0 mg/kg and 100 mg/kg) and 2 fat types (3.5% soybean oil and 3.5% fish oil) from day 107 of gestation until weaning (day 21) on performance, milk composition and immunoglobulin, and on the immunological variables of sows and piglets. Blood and milk samples of sows were obtained on days 0 (farrowing), 14, and 21 of lactation. One 21-day-old piglet per litter was selected for the collection of plasma. The average piglet weaning weight and the average daily gain (ADG) were significantly influenced by supplementation with 100 mg/kg of L-carnitine ($P < 0.05$). Furthermore, fish oil (FO) treatment exhibited an increasing trend in average piglet weaning weight and ADG over soybean oil (SO) treatment ($P < 0.1$). The concentrations of fat, immunoglobulin G (IgG), and immunoglobulin A (IgA) were increased in colostrums and milk by day 21 by supplementation with 100 mg/kg of L-carnitine ($P < 0.05$). Supplementation with 100 mg/kg of L-carnitine enhanced the IgG and IgA concentration in the plasma of sows and piglets ($P < 0.05$). Additionally, the concentrations of IgG and IgA were improved in colostrums by the addition of FO ($P < 0.05$). The FO treatment also advanced the IgA concentration in the plasma of sows and the IgG concentration in the plasma of piglets ($P < 0.05$). In conclusion, the addition of 100 mg/kg L-carnitine improved the weight of piglets at weaning, ADG, IgG, and IgA levels in colostrums, and IgG and IgA concentration in the plasma of sows and piglets ($P < 0.05$). The concentrations of IgG and IgA were significantly increased in colostrums by supplementation with 3.5% FO ($P < 0.05$). Overall, no significant difference was observed between L-carnitine and FO or SO treatment in immunological variables in this study.

Keywords: fish oil; immunoglobulin; colostrum; performance; sow; soybean oil

L-Carnitine and fish oil (FO) are important nutrients for the growth, development, and health of animals. Recent studies have shown that supplementation of L-carnitine in sows improves their reproductive performance (Ramanau et al. 2002). Moreover, piglets of sows supplemented with L-carnitine grew faster during the suckling period and exhibited higher body weights at weaning than

Supported by the earmarked fund for China Agriculture Research System (CARS-36), the Key Program of Heilongjiang Province (No. WB13B101), and the Foundation of Heilongjiang Educational Committee (No. 1254CGZH20).

doi: 10.17221/55/2016-CJAS

piglets of control sows (Ramanau et al. 2002, 2004, 2005). Sows supplemented with L-carnitine during pregnancy and lactation were able to produce more milk than control sows (Ramanau et al. 2004). Additionally, L-carnitine may modulate immune function as evidenced by enhanced antibody responses in L-carnitine-supplemented broiler chickens (Mast et al. 2000) and pigeons (Janssens et al. 2000). In addition to taking part in the transfer of long-chain fatty acids, L-carnitine has been reported to enhance the immune response of the body (De Simone et al. 1982). However, the relationship between dietary L-carnitine and the immune system has not yet been well defined in sows.

Adding fat in sows' diets is a potential approach that could be beneficial to sow nutrition, sow health, and piglet health (Cools et al. 2011; Benzoni et al. 2013; Tanghe et al. 2014; Tummaruk et al. 2014). L-Carnitine can facilitate the transport of long-chain fatty acids into the mitochondria for energy production (adenosine triphosphate) via β-oxidation and oxidative phosphorylation. Thus, in instances of L-carnitine insufficiency, movement of long-chain fatty acids into the mitochondria and their subsequent oxidation could be impaired.

Previous reports have shown that addition of fat to the diets of sows during late gestation and/or lactation increases milk production and the fat content of colostrum and milk (Pettigrew 1981). Maternal FO supplementation enriched the n-3 polyunsaturated fatty acids (PUFA) content of the milk of sows (Fritsche et al. 1993; Lauridsen and Danielsen 2004), reduced pre-weaning piglet mortality (Rooke et al. 2001a), and enhanced piglet serum immunoglobulin G concentrations at weaning (Rooke et al. 2003).

Therefore, the aim of the present study was to evaluate the effects of maternal dietary supplementation with FO and L-carnitine from day 107 of gestation until weaning (day 28) on colostrum and milk composition, suckling piglet performance, humoral immune response of sows on days 0 (farrowing), 14, and 21 of lactation, and piglets at weaning. In addition, this study examined any beneficial response to the combination treatment of FO and L-carnitine.

MATERIAL AND METHODS

The protocols used in these experiments were approved by the Northeast Agricultural University Institutional Animal Care and Use Committee of China.

Animals and experimental design. The experiment was designed as a 2 × 2 factorial. Forty-eight crossbred pregnant sows (Large White × Landrace) on day 107 of gestation were randomly allocated, accounting for parity (in the range of 3 to 5) and expected delivery date, to one of four dietary treatments (n = 12 sows per treatment). The dietary treatments included two L-carnitine levels (0 mg/kg and 100 mg/kg) and two fat types (3.5% soybean oil (SO) and 3.5% FO). L-Carnitine was purchased from Lonza (China). The product was composed of L-carnitine and silicon dioxide (L-carnitine purity: 50.0%). The desired amount of L-carnitine in this experiment was 100 mg/kg; thus, due to the purity of 50%, the actual amount added to the diet was 200 mg/kg. The experimental feed was provided from day 107 of gestation until weaning, for a total of 28 days. All diets were formulated to meet or exceed the requirements for all nutrient standards (NRC, 2012). The ingredients and chemical composition of the basal diets with 3.5% SO or 3.5% FO are shown in Table 1.

Housing, feeding, and management. The experiment was initiated on day 107 of gestation when sows were moved to the same farrowing house: sows were offered experimental supplements until weaning at day 21. The sows and piglets were individually housed in farrowing pens (2.2 × 2.4 m) with crates and slatted floors. The parturitions were watched, but the observers interfered as little as possible in the farrowing process. A piglet corner with a heating lamp was available for the piglets. The farrowing room temperature was maintained at 20°C. The sows and piglets had *ad libitum* access to drinking water throughout the experimental period.

Throughout lactation, the sows were fed twice daily at 8:00 and 15:00 h. The sows were initially fed 3.0 kg before partum. On the day of farrowing, the sows were not fed, and after farrowing, the sows were initially fed 1.5 kg on day 1. This amount was increased daily by 0.5 kg until day 7 postpartum, depending on the maternal feed consumption and the recovery after partum. From day 7 postpartum, the sows had free access to their diets until weaning. The piglets did not receive a solid diet and were fed only with colostrum and milk throughout the experimental period.

doi: 10.17221/55/2016-CJAS

On day 3, the piglets received an iron injection (Iron Dextran, Jiangxi Chuangdao Animal Health Co., Ltd., China). Commercial creep feed (15.8 MJ metabolizable energy/kg, 210.0 g crude protein (CP)/kg, 15.6 g lysine/kg) was offered to the piglets 7 days after birth. The intake of the creep feed was not recorded.

Diet collection and analyses. Samples of feed were obtained from each dietary treatment. The diets were analyzed for crude protein, crude fat, calcium, and phosphorus (Avelar et al. 2010).

Sow and litter performance. Sows were weighed (using scales with an accuracy of ± 100 g) on day 107 of pregnancy and at the time of weaning. Backfat thickness was measured at the P2 position (left side of the 10th rib and 6 cm lateral to the spine) during times of weighing using a B-mode ultrasound (Renco Lean Meater type 7, USA).

The following parameters were recorded: total number of piglets born, born alive, stillborn and mummified; and litter weights and piglet weights at birth and on day 21 of lactation. The litter piglets were weighed from parturition until weaning to calculate average daily gain (ADG) per litter. The individual piglet body weight (BW) was recorded at birth and weaning (day 21), and ADG was calculated.

Milk collection and analysis. Colostrum samples (30 ml) were collected 1 h after the birth of the first piglet, and milk (30 ml) was collected from

Table 1. Ingredients and chemical composition of the basal diets

Item	0 mg/kg L-carnitine diet		100 mg/kg L-carnitine diet	
	3.5% SO	3.5% FO	3.5% SO	3.5% FO
Ingredients (g/kg of diet)				
Corn grain	650	650	650	650
Soybean meal	170.5	170.5	170.5	170.5
Wheat bran	80	80	80	80
Fish meal	30	30	30	30
Soybean oil	35		35	0
Fish oil	0	35	0	35
Dicalcium phosphate	10	10	10	10
Limestone	7	7	7	7
Choline chloride (50%)	2.5	2.5	2.5	2.5
Vitamin and mineral premix[1]	15	15	15	15
Chemical composition (g/kg of diet)				
DE (Mcal/kg)[2]	3.37	3.37	3.37	3.37
Crude protein[3]	175.4	175.4	175.4	175.4
Crude fat[3]	61.5	61.5	61.5	61.5
Lysine[2]	9.5	9.5	9.5	9.5
Tryptophan[2]	2.1	2.1	2.1	2.1
Threonine[2]	6.4	6.4	6.4	6.4
Methionine[2]	3.1	3.1	3.1	3.1
Calcium[3]	8.4	8.4	8.4	8.4
Total phosphorus[3]	6.4	6.4	6.4	6.4
Available phosphorus[2]	3.7	3.7	3.7	3.7

SO = soybean oil-based diet, FO = fish oil-based diet, DE = digestible energy

[1]premix provided per kg of diet: vitamin A = 13 500 IU, vitamin D_3 = 3000 IU, vitamin E = 44 IU, vitamin K_3 = 3 mg, vitamin B_1 = 1.8 mg, vitamin B_2 = 6 mg, vitamin B_6 = 0.3 mg, vitamin B_{12} = 0.024 mg, biotin = 0.03 mg, niacin = 24 mg, pantothenic acid = 15 mg, folic acid = 0.9 mg, 20 mg of Cu as $CuSO_4 \cdot 5H_2O$, 120 mg of Zn as $ZnSO_4$, 0.3 mg of Se as $Na_2SeO_3 \cdot H_2O$, 40.07 mg of Mn as $MnSO_4 \cdot H_2O$, 100.50 mg of Fe as $FeSO_4 \cdot 7H_2O$, 0.3 mg of I as $Ca(IO_3)_2$

[2]calculated values according to NRC (2012)

[3]analyzed values

doi: 10.17221/55/2016-CJAS

8 sows per treatment on days 14 and 21 of lactation after hand milking each functional gland. To facilitate milk collection, oxytocin (1 ml) was injected into the ear vein and milk was collected approximately 1 min later. Colostrum and milk samples were frozen at –20°C until analysis. Prior to analysis, the colostrum and milk were delipidated by centrifugation at 3000 *g* at 4°C for 20 min.

The colostrum and milk samples were analyzed for lactose, protein, fat, and total solids with a fully automatic milk analyzer (MilkoScan™ FT1 Analyser; Foss, Denmark). Assays for colostrum and milk concentrations of immunoglobulin G (IgG), immunoglobulin A (IgA), and immunoglobulin M (IgM) were performed using specific pig-ELISA IgG, IgA, IgM quantification kits (Bethy Laboratories Inc., USA). The IgG, IgA, and IgM concentrations were quantified according to the manufacturer's instructions.

Blood samples collection and analysis. Blood samples (5 ml) of 8 sows per treatment were obtained using heparin tubes from the ear vein on days 0 (farrowing), 14, and 21 of lactation and were immediately placed on ice until they were centrifuged at 1000 *g* for 15 min. The plasma was immediately stored at –80°C until further analysis.

During the suckling period, blood samples (5 ml) from 1 piglet per litter were collected after having an empty stomach for 24 h from the anterior *vena cava* by puncture into heparin tubes at weaning (day 21) to facilitate immunoglobulin quantification. The blood samples were immediately placed on ice until they were centrifuged at 1000 *g* for 15 min. The plasma was immediately stored at –80°C until further analysis.

Assays for serum concentrations of IgG, IgA, and IgM were performed using specific pig-ELISA

Table 2. Effect of L-carnitine and different fat type supplementation during gestation and lactation on sow and piglets' performance (n = 12)

Item	Treatment				SEM	*P*-value		
	0 mg/kg L-carnitine diet		100 mg/kg L-carnitine diet			L-carnitine	fat type	L-carnitine × fat type
	3.5% SO	3.5% FO	3.5% SO	3.5% FO				
Days 7–21 ADFI (kg)	5.29	5.35	5.34	5.42	0.038	0.447	0.405	1.000
Sow BW on day 107 of gestation (kg)	258.23	254.38	250.37	256.01	3.054	0.628	0.890	0.461
Sow BW at weaning (kg)	222.36	223.41	218.01	224.00	2.326	0.699	0.471	0.612
Sow BW change (kg)	35.85	30.96	32.37	32.01	1.649	0.723	0.446	0.510
Sow backfat at farrowing (mm)	20.87	21.63	21.00	21.86	0.227	0.681	0.083	0.891
Sow backfat at weaning (mm)	18.13	18.88	18.25	19.00	0.233	0.792	0.121	1.000
Sow backfat change	2.74	2.75	2.75	2.86	0.133	0.824	0.824	0.824
Number of piglets born alive/litter	10.87	10.75	10.75	11.25	0.158	0.566	0.566	0.342
Number of piglets at weaning/litter	9.75	9.50	9.50	10.00	0.130	0.638	0.638	0.165
Survival rate of piglets (%)	89.6	88.3	88.6	89.0	0.005	0.841	0.703	0.482
Piglet weight at birth (kg)	1.49	1.51	1.48	1.49	0.029	0.835	0.757	0.958
Piglet weight at weaning (kg)	4.98^{b}	5.31^{a,b}	5.69^{a}	5.89^{a}	0.089	< 0.001	0.056	0.619
Days 0–21 ADG (g/day)	166^{b}	181^{a,b}	198^{a}	209^{a}	4.44	< 0.001	0.074	0.797

SO = soybean oil-based diet, FO = fish oil-based diet, ADFI = average daily feed intake, BW = body weight, ADG = average daily gain; ^{a,b}means within a row without a common superscript differ significantly ($P < 0.05$)

doi: 10.17221/55/2016-CJAS

IgG, IgA, IgM quantification kits (Bethy Laboratories Inc.). The IgG, IgA, and IgM concentrations were quantified according to the manufacturer's instructions.

Statistical analyses. Data were analyzed by the analysis of variance (ANOVA) as a 2 × 2 factorial arrangement of treatments using the General Linear Model (GLM) procedure of SPSS 20.0 software (IBM-SPSS Inc.). The results were presented as mean values and the standard error of the mean (SEM). The model accounted for the effect of L-carnitine, fat type, and the interaction between the two. Differences were considered significant at $P < 0.05$.

RESULTS

Sow and litter performance. The effect of maternal dietary treatment on sow and piglet performance during the suckling period is presented in Table 2. Average daily feed intake (ADFI), BW change, and backfat change in sows from day 107 of gestation to day 21 of lactation (weaning) were similar across treatments ($P > 0.05$). Similarly, the number of piglets born alive, number of piglets at weaning per litter, survival rate of piglets, and weight of piglets at birth from day 107 of gestation to day 21 of lactation (weaning) were not influenced by sow dietary treatment ($P > 0.05$). However, the weights of piglets at weaning and ADG were significantly improved ($P < 0.05$) by the addition of 100 mg/kg L-carnitine.

Composition of colostrum and milk. The concentrations of lactose, protein, and total milk solids in colostrum and milk were not influenced ($P > 0.05$) by L-carnitine or fat types from day 107 of gestation to day 21 of lactation (weaning) (Table 3). On the other hand, adding 100 mg/kg of L-carnitine resulted in higher fat concentrations in the colostrum ($P < 0.05$) (Table 3). However, no significant interaction was found between L-carnitine level and fat type ($P > 0.05$).

Immunological variables of colostrum and milk. The concentrations of IgG and IgA in colostrum were significantly improved with the supplementation of 100 mg/kg of L-carnitine and 3.5% FO ($P < 0.05$) (Table 4). Supplementation of 100 mg/kg of L-carnitine enhanced the IgG and IgA concentration in milk in sows on day 21 ($P < 0.05$). However, no differences were found

Table 3. Effect of L-carnitine and different fat type supplementation during gestation and lactation on the composition of colostrum and milk ($n = 8$)

Item	Treatment				SEM	*P*-value		
	0 mg/kg L-carnitine diet		100 mg/kg L-carnitine diet			L-carnitine	fat type	L-carnitine × fat type
	3.5% SO	3.5% FO	3.5% SO	3.5% FO				
Colostrum (g/kg)								
Fat	42.9[b]	43.3[b]	52.5[a]	55.1[a]	1.4	< 0.001	0.500	0.602
Protein	202.0	206.3	213.8	210.5	3.7	0.298	0.952	0.618
Lactose	35.2	35.4	32.9	33.5	0.6	0.102	0.718	0.875
Total milk solid	275.1	266.5	285.9	279.2	4.9	0.245	0.442	0.928
Milk of day 14 (g/kg)								
Fat	66.5	65.7	66.3	67.9	0.7	0.537	0.803	0.449
Protein	52.3	52.0	51.4	52.8	0.6	0.979	0.676	0.535
Lactose	56.5	59.4	57.4	59.7	0.5	0.516	0.119	0.827
Total milk solids	193.9	195.6	194.1	193.8	2.5	0.889	0.907	0.865
Milk of day 21 (g/kg)								
Fat	66.5	68.1	66.8	68.3	1.5	0.941	0.648	0.988
Protein	54.2	53.5	52.3	55.7	0.7	0.913	0.343	0.162
Lactose	53.2	53.3	56.1	51.9	0.6	0.536	0.093	0.083
Total milk solids	190.1	190.9	191.6	190.2	1.9	0.935	0.948	0.810

SO = soybean oil-based diet, FO = fish oil-based diet

[a,b]means within a row without a common superscript differ significantly ($P < 0.05$)

doi: 10.17221/55/2016-CJAS

Table 4. Effect of L-carnitine and different fat type during gestation and lactation on immunological variables of colostrum and milk (n = 8)

Item	Treatment				SEM	*P*-value		
	0 mg/kg L-carnitine diet		100 mg/kg L-carnitine diet			L-carnitine	fat type	L-carnitine × fat type
	3.5% SO	3.5% FO	3.5% SO	3.5% FO				
Colostrum (g/l)								
IgG	55.29^{b}	58.12^{ab}	59.94^{a}	61.99^{a}	0.789	0.002	0.038	0.719
IgA	7.66^{b}	7.96^{ab}	8.02^{a}	8.15^{a}	0.057	0.003	0.014	0.258
IgM	3.79	3.89	3.93	4.03	0.037	0.071	0.168	0.914
Milk of day 14 (g/l)								
IgG	0.353	0.356	0.371	0.375	0.019	0.385	0.882	0.986
IgA	3.850	3.845	3.942	3.973	0.024	0.023	0.772	0.686
IgM	1.487	1.517	1.673	1.688	0.052	0.113	0.832	0.944
Milk of day 21 (g/l)								
IgG	0.814	0.831	0.870	0.894	0.012	0.010	0.315	0.867
IgA	3.752	3.875	3.952	4.062	0.048	0.047	0.208	0.944
IgM	1.822	1.917	1.865	2.017	0.038	0.361	0.125	0.708

SO = soybean oil-based diet, FO = fish oil-based diet, IgG = immunoglobulin G, IgA = immunoglobulin A, IgM = immunoglobulin M

$^{a–c}$means within a row without a common superscript differ significantly ($P < 0.05$)

based on fat type on IgG, IgA or IgM levels in milk on day 14 or on day 21 of lactation ($P > 0.05$). Furthermore, no interaction ($P > 0.05$) was found between L-carnitine and fat type supplementation on immunoglobulin concentrations in sow colostrum and milk.

Immunological variables of plasma from sows. As shown in Table 5, the concentrations of IgG

Table 5. Effect of L-carnitine and different fat type during gestation and lactation on immunological variables of plasma in sows (n = 8)

Item	Treatment				SEM	*P*-value		
	0 mg/kg L-carnitine diet		100 mg/kg L-carnitine diet			L-carnitine	fat type	L-carnitine × fat type
	3.5% SO	3.5% FO	3.5% SO	3.5% FO				
Plasma of day 0 (g/l)								
IgG	4.54^{b}	4.72^{b}	4.98^{a}	5.01^{a}	0.052	< 0.001	0.095	0.219
IgA	0.316^{c}	0.323^{bc}	0.347^{ab}	0.360^{a}	0.005	< 0.001	0.135	0.708
IgM	0.339	0.345	0.352	0.352	0.003	0.163	0.706	0.686
Plasma of day 14 (g/l)								
IgG	4.618^{b}	4.768^{b}	5.04^{a}	5.05^{a}	0.047	< 0.001	0.098	0.175
IgA	0.253^{b}	0.260^{b}	0.284^{a}	0.286^{a}	0.004	0.010	0.572	0.703
IgM	0.394	0.395	0.396	0.406	0.004	0.482	0.538	0.643
Plasma of day 21 (g/l)								
IgG	8.382^{c}	8.464^{bc}	8.88^{ab}	8.99^{a}	0.093	0.005	0.553	0.939
IgA	0.273^{b}	0.289^{b}	0.299^{a}	0.305^{a}	0.004	< 0.001	0.040	0.311
IgM	0.386	0.390	0.392	0.398	0.003	0.168	0.318	0.839

SO = soybean oil-based diet, FO = fish oil-based diet, IgG = immunoglobulin G, IgA = immunoglobulin A, IgM =immunoglobulin M

$^{a–c}$means within a row without a common superscript differ significantly ($P < 0.05$)

doi: 10.17221/55/2016-CJAS

Table 6. Effect of L-carnitine and different fat type during gestation and lactation on immunological variables of plasma in piglets (n = 12)

Item	Treatment				SEM	*P*-value		
	0 mg/kg L-carnitine diet		100 mg/kg L-carnitine diet			L-carnitine	fat type	L-carnitine × fat type
	3.5% SO	3.5% FO	3.5% SO	3.5% FO				
Plasma of day 21 (g/l)								
IgG	0.664[b]	0.752[a]	0.773[a]	0.788[a]	0.015	0.006	0.036	0.125
IgA	0.349[b]	0.357[b]	0.372[a]	0.378[a]	0.003	< 0.001	0.147	0.886
IgM	0.421	0.438	0.446	0.447	0.006	0.188	0.482	0.542

SO = soybean oil-based diet, FO = fish oil-based diet, IgG = immunoglobulin G, IgA = immunoglobulin A, IgM =immunoglobulin M

[a,b]means within a row without a common superscript differ significantly ($P < 0.05$)

and IgA in sow plasma were enhanced with the supplementation of 100 mg/kg L-carnitine on days 0, 14, and 21 ($P < 0.05$). IgA levels in the plasma of sows were increased by the addition of 3.5% FO on day 21 ($P < 0.05$). Furthermore, FO treatment showed a trend of having more IgG than SO treatment ($P < 0.1$). Additionally, no differences were found regarding IgM levels in the plasma of sows by the supplementation of L-carnitine and different fat types ($P > 0.05$). Furthermore, no interaction was found between L-carnitine level and fat type on immunoglobulin concentrations.

Immunological variables of plasma from piglets. As shown in Table 6, IgG levels in the plasma of piglets were significantly increased by the addition of L-carnitine and fat type on day 21 ($P < 0.05$). The concentrations of IgA in the piglet plasma on day 21 were improved by the addition of 100 mg/kg of L-carnitine ($P < 0.05$). Additionally, IgM levels in the piglet plasma did not differ among all treatments ($P > 0.05$). No interaction ($P > 0.05$) was found between L-carnitine level and fat type on immunoglobulin concentrations in piglet sera.

DISCUSSION

The aim of the current experiment was to examine the effect of maternal dietary supplementation with L-carnitine and FO from day 107 of gestation until weaning (day 21) on the performance of sows and piglets, colostrum and milk composition, and immunoglobulin concentrations in the colostrum of sows and in piglets.

Performance of sows and piglets. This study confirms recent studies (Ramanau et al. 2002, 2004, 2005; Birkenfeld et al. 2006) by showing that L-carnitine supplementation of sows enhances piglet growth during the suckling period and results in higher piglet weight at weaning. Our study suggests that this effect may be due to a higher milk yield and an increased transfer of energy and nutrients from the sow to the piglets with milk. The data for body weights and backfat thickness at weaning did not differ between L-carnitine-treated and control sows. However, sows that are fed *ad libitum* with L-carnitine supplementation have been shown to have no significant difference in feed intake or body weight during pregnancy (Ramanau et al. 2004, 2005), in accordance with the present study.

The present data indicate that ADG during the suckling period and average piglet weaning weight were not affected by FO-supplemented diets. Lauridsen and Danielsen (2004) observed that FO supplementation from day 108 of gestation favoured no improvement on piglet daily BW gain. In contrast, Mitre et al. (2005) reported that piglets from sows fed diets supplemented with shark liver oil from day 80 of gestation had greater weaning weight. Furthermore, Rooke et al. (2001b) reported that piglets born to dams that were fed supplemental tuna oil from day 92 of gestation were heavier than piglets from control sows. A longer period of supplementation before farrowing may be required to elicit an effect on neonatal piglet growth. Cools et al. (2011) reported that increasing FO in the sows' diet from 0 to 4%

doi: 10.17221/55/2016-CJAS

decreased piglet weaning weight and resulted in a higher pre-weaning mortality rate ($P < 0.05$). Daily supplementary cod liver oil of 50 ml to sows from day 107 of gestation until weaning did not affect weight gain or overall morbidity of piglets in a study by Taugbol et al. (1993).

Composition of colostrum and milk. Many reports have shown that the addition of fat to the diets of sows during late gestation and/or lactation increases milk production and the fat content of the colostrum and milk (Pettigrew 1981; Jackson et al. 1995; Christon et al. 1999). Similar results were observed in the present experiment; the supplementation of L-carnitine and FO increased the content of fat in the colostrum. In contrast, Birkenfeld et al. (2006) reported that colostrum in sows supplemented with L-carnitine had a higher protein concentration ($P < 0.05$) and a lower concentration of fat and lactose than milk on days 10 and 20 of lactation.

Immunological variables of colostrum and milk. Immunoglobulins in milk play an important role in the passive immunization of piglets. Many reports are in close agreement with the present study that the supplementation of L-carnitine and FO could increase concentrations of IgG and IgA in the colostrum. Studies with experimental animals indicate that diets rich in n-3 PUFA are anti-inflammatory and immunosuppressive *in vivo* (Calder 1999), and the anti-inflammatory effect has also been shown for suckling piglets of FO-fed sows (Fritsche et al. 1993). Mitre et al. (2005) observed improvements in IgG levels in colostrum by oral supply of shark-liver oil to sows during gestation and lactation ($P < 0.05$). Rooke and Bland (2004) found that sow's diets supplemented with FO could increase IgG content in colostrum ($P < 0.05$). Bontempo et al. (2004) and Rossi et al. (2004) found that the addition of conjugated linoleic acid (CLA) increased IgG levels in colostrum ($P < 0.05$). However, the reports regarding the effects of L-carnitine and FO on IgG and IgA levels are not consistent. Leonard et al. (2010) indicated that the supplementation of FO had no effect on immunoglobulin concentrations in sow milk or colostrum. Birkenfeld et al. (2006) revealed that L-carnitine supplementation did not influence the concentration of immunoglobulins in colostrum or milk in sows.

Immunological variables of sows and piglets. Many reports have either supported or opposed our results that concentrations of IgG and IgA in the plasma of sows and piglets can be increased by the addition of L-carnitine and fish oil ($P < 0.05$). Geng et al. (2007) found that serum IgG content was improved by L-carnitine supplementation ($P < 0.05$) in broilers. L-carnitine supplementation significantly improved IgG content in pigeons (Janssens et al. 2000) and broilers (Mast et al. 2000). Thangasamy et al. (2008) indicated that treatment with L-carnitine improved the concentrations of IgG and IgA in aged animals in a significant manner. One possible mechanism by which L-carnitine improves the concentrations of IgG and IgA in piglet plasma is that the piglets obtain high levels of L-carnitine from milk. The supplementation of sows' diets with L-carnitine caused a moderate increase in the L-carnitine concentrations in plasma and milk during pregnancy and lactation. Dietary L-carnitine supplementation has been demonstrated to exert an immunomodulatory effect on antigen-specific total IgA and IgG responses. A long-lasting elevated IgG response due to dietary L-carnitine supplementation may be of major practical importance for the enhancement of protective immunity due to vaccination. Therefore, piglets that obtain high levels of L-carnitine from milk and L-carnitine supplementation may exhibit elevated antigen-specific Ig responses, which may contribute to increases in immunoglobulin levels in piglets. However, L-carnitine treatment had no impact on IgM concentration or type responses. Previous studies indicated that maternal FO supplementation enriched the n-3 PUFA content of sow milk and enhanced piglet serum IgG concentrations at weaning (Rooke et al. 2003). Bontempo et al. (2004) found that the addition of CLA increased the serum IgG of sows and piglets on days 2, 10, and 20 of lactation ($P < 0.05$). Additionally, Rossi et al. (2004) observed higher serum IgG concentrations on day 21 postpartum for piglets born from sows given CLA-supplemented diets starting seven days before parturition until weaning ($P < 0.05$).

CONCLUSION

Our results demonstrate that the supplementation of L-carnitine to sows from day 107 of gestation until weaning (day 21) increased IgG and IgA concentrations in the colostrum and plasma of sows and piglets ($P < 0.05$). Furthermore, the fat

doi: 10.17221/55/2016-CJAS

concentrations in sow colostrum were enhanced by the addition of L-carnitine ($P < 0.05$). Average piglet weaning weight and ADG were also influenced by the supplementation with L-carnitine during the suckling period ($P < 0.05$). Furthermore, the average piglet weaning weight and ADG showed an increasing trend under the supplementation with 3.5% FO ($P < 0.1$), and the concentrations of IgG and IgA were significantly increased in colostrum under this treatment ($P < 0.05$). We thus conclude that L-carnitine and FO supplementation is beneficial to sows and piglets starting on day 107 of gestation to day 21 of lactation, but there is no interaction between L-carnitine and fat type on immunological variables in this study.

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Received: 2016–06–20
Accepted after corrections: 2016–11–08