Nutrient Requirements

Supplementation of Sows with L-Carnitine during Pregnancy and Lactation Improves Growth of the Piglets during the Suckling Period Through Increased Milk Production

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ABSTRACT Recent studies showed that piglets of sows fed diets supplemented with L-carnitine grow faster during the suckling period than piglets of control sows fed diets without L-carnitine. This study was undertaken to investigate the effect of L-carnitine supplementation in sows on milk production and milk constituents. An experiment was performed in which two groups of 20 gilts each were fed diets with or without supplemental L-carnitine during pregnancy (0 vs. 125 mg L-carnitine daily/sow) and lactation (0 vs. 250 mg L-carnitine daily/sow). The experiment was continued over two reproductive cycles. L-carnitine–treated sows had larger litters ($P < 0.01$) and higher litter weights ($P < 0.05$) than control sows. Piglets of L-carnitine–treated sows had lower birth weights ($P < 0.05$) but grew faster during the suckling period ($P < 0.01$) and were heavier ($P < 0.05$) at weaning than piglets of control sows. L-Carnitine–treated sows had higher milk yields on d 11 and 18 of lactation than control sows ($P < 0.05$). Milk of L-carnitine–treated sows had higher concentrations of total and free carnitine than milk of control sows ($P < 0.001$); concentrations of fat, protein and lactose and the amounts of gross energy in the milk did not differ between the two groups of sows. The amounts of protein ($P < 0.05$) and lactose ($P < 0.05$) were higher in L-carnitine–treated sows than in control sows; the amount of energy secreted with the milk tended to be higher in carnitine-treated sows than in control sows ($P < 0.10$). The study suggests that piglets of carnitine-treated sows grow faster during the suckling period than those of control sows because they ingest more nutrients and energy with the milk. J. Nutr. 134: 86–92, 2004.

KEY WORDS: • *L-carnitine* • *sows* • *piglets* • *milk*

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Recent studies showed that supplementing sow diets with L-carnitine during pregnancy and lactation increases birth weights of piglets (1–3). Moreover, piglets of sows fed diets supplemented with L-carnitine grew faster during the suckling period than piglets of control sows (2,3). The reasons for these effects are largely unknown. The growth of piglets after birth is determined primarily by the supply of nutrients with the milk, which is their only source of food during the first few days of life (4). We therefore suspect that faster growth of piglets from sows supplemented with L-carnitine during suckling might be due to increased milk production or higher nutrient levels in the milk. This study was designed to investigate the effect of dietary L-carnitine supplementation of sows on milk production and concentrations of various nutrients in the milk. Milk production depends on the sow's nutritional status (5) but can also be affected by the suckling behavior of her piglets. Piglets suckling more frequently stimulate increased milk secretion and consequently have a higher total milk intake (6,7). To determine whether dietary L-carnitine supplementation of sows influences the suckling behavior of piglets, we measured the number of sucklings, the intervals between sucklings and the total time spent suckling in a day. Because newborn piglets can synthesize L-carnitine only to a small extent, the milk is an important source of L-carnitine. Therefore, we also determined the concentrations of L-carnitine in the milk.

MATERIALS AND METHODS

Animals. Crossbred gilts (German land race × Large white; $n = 40$) with a mean (±SEM) body weight of 144 ± 2 kg, acquired from a local breeder, were assigned to two groups of 20 pigs each. Their sexual cycle was synchronized by oral administration of 20 mg Altrenogest/d (Regumate, Hoechst Roussel, Frankfurt, Germany). The sows were artificially inseminated with sperm from Pietrain boars. Sows who failed to conceive were removed from the experiment. After weaning, the trial continued for a second reproductive cycle.

Housing. The sows were kept in single crates until d 30 of pregnancy. From d 30 to 110 of pregnancy, the sows were kept in groups of eight in pens measuring 45 m^2 that had fully slatted floors, nipple drinkers and electronic feeding stations. On d 110 of pregnancy, they were moved to the farrowing accommodation where they were housed in single farrowing pens. Before farrowing rubber mats were put down as a surface for the piglets to lie on. An infrared heater

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was suspended above each rubber mat to keep the temperature for the newborn piglets at a constant 35°C. The climate in the dry sow accommodation and the farrowing unit was maintained at a temperature of 19 ± 2°C and 60–80% relative humidity by means of an air conditioning system. A light:dark cycle (12-h light:12-h dark) was applied. All animal procedures described followed established guidelines for the care and handling of laboratory animals and were approved by the regional council of Saxony-Anhalt.

Diets and feeding. Two commercial sow diets were used. The first diet, fed from the start of the experiment until d 110 of pregnancy ("gestation diet," Turbo Sauenfutter Soft pell, Kraftfutterwerk Niederpöllnitz, Niederpöllnitz, Germany), consisted of (g/kg diet): wheat bran (300), alfalfa meal (250), triticale (138), molassed dried sugar beet pulp (120), barley (77), peas (20), extracted sunflower meal (50), rapeseed cake (13), molasses (20) and premix including minerals, vitamins and L-lysine (12). The second diet, fed from d 111 of pregnancy until weaning ("lactation diet," Porfinal, Deuka, Düsseldorf, Germany) consisted of (g/kg diet): wheat (322), barley (220), wheat bran (180), soy bean meal (140), peas (50), wheat gluten (30), extracted soy bean oil (24) and premix including minerals and vitamins (34). Concentrations of nutrients in the diets are shown in **Table 1**. The gestation and lactation diets contained 16 and 4 mg L-carnitine/kg, respectively. From the beginning of the experiment until d 30 of pregnancy the sows were offered 3.0 kg of gestation diet/d; from d 30 to 110 the diet was consumed ad libitum. From d 110 to farrowing each sow was fed 2.5 kg of the lactation diet. On the day of farrowing, the sows were fed 1.5 kg, which was then successively increased (3 kg/d on d 1 and 2 of lactation; 4.5 kg/d on d 3 and 4 of lactation; ad libitum consumption from d 5 of lactation to weaning). From weaning until the second insemination, the sows were fed 2.5 kg gestation diet/d. Sows in the treatment group were supplemented with 125 mg L-carnitine/d during pregnancy and 250 mg L-carnitine/d during lactation. L-Carnitine was supplied as tablets containing L-carnitine (125 mg/tablet, supplied by Lohmann Animal Health, Cuxhaven, Germany), lactose and dextrose. During pregnancy, the tablets were administered once daily; during lactation, tablets were administered twice daily, at 0900 and 1600 h. Control pigs were given the same tablets without L-carnitine. Water was provided by nipple drinking systems. The piglets were offered a creep feed (Deuka Primo Wean, Deuka) from d 19 of lactation until weaning. The creep feed contained (per kg): 15.6 MJ metabolizable energy, 200 g crude protein, 85 g crude fat, 25 g crude fiber and 60 g crude ash; the carnitine concentration was <5 mg/kg.

Data collection. The daily diet intake of the sows from d 30 to 110 of pregnancy was recorded by means of an electronic sow feeding station (Type IVOG 2FR VH, HohoFarm, Insentec BV). The sows were weighed on d 1, 85 and 110 of pregnancy in the morning before feeding using scales with an accuracy of ± 100 g. Backfat thickness was determined by ultrasound on d 1 and 110 of pregnancy and after weaning. The number of piglets born (total, number born alive and number stillborn) was recorded. Individual piglets were weighed at birth (not later than 6 h after birth), at d 12 and 19, and at weaning using scales with an accuracy of ± 10 g. The creep feed intake of piglets was recorded daily by determining the amount that was left after 24 h.

TABLE 1

Concentrations of nutrients in the basal experimental diets used during pregnancy and lactation

Diet	Pregnancy diet	Lactation diet
Metabolizable energy, *MJ/kg*	9.6	13.1
Crude protein, *g/kg*	150	178
Crude fat, *g/kg*	30	61
Crude fiber, *g/kg*	114	48
Crude ash, *g/kg*	62	58
L-Lysine, *g/kg*	7.0	9.5
L-Carnitine, *mg/kg*	16.2	3.8

Determination of milk output. Milk output was determined on d 11 and 18 of lactation in 13 of the 16 sows of each group in the first lactation and in the 10 of the 13 sows of each group in the second lactation. To eliminate the effect of litter size on milk production, the litter size of these sows was standardized to 10 piglets/litter within 2 d of farrowing. Piglets were removed from sows having >10 piglets and placed with sows of the same group having <10 piglets. Piglets taken away from sows as well as piglets added to sows were selected on the basis of their body weights. It was intended to adjust the average weights of piglets of each individual sow after litter standardization to those before litter standardization. Surplus piglets were nursed by the remaining three sows of each group that were not being used for milk output determination. Piglets that dropped out before d 18 of lactation were immediately replaced by equivalent piglets with similar body weights that had previously been nursed by the remaining control or treated sows. The milk output was measured by the "weigh-suckle-weigh" method (8). On the day of the milk recording procedure, the piglets were separated from the sow by means of a barrier from 0600 to 1600 h and allowed supervised access to the sow only at 1-h intervals for the duration of suckling. The first two weighings (0700 and 0800 h) were done to allow sow and piglets to become accustomed to the procedure; the calculation of the daily milk production was based on the last seven measurements. To minimize losses through feces and urine, the piglets were weighed rapidly; the accuracy of the scales was ±1 g.

Analysis of milk constituents. On d 11 of the lactation, after termination of milk output determination, the sows were given 15 IU oxytocin (Atarost, Twistringen, Germany) by i.m. injection; 80–100 mL of milk was expressed manually from all active teats of each sow. The concentration of lactose in the milk was determined using an enzymatic kit reagent from Boehringer (Mannheim, Germany, Cat-No. 0176303); the concentration of protein in the milk was determined using the Kjehldahl method of the IDF-ISO-AOAC (9); the concentration of fat in the milk was determined by ether extraction (9). The energy content of the milk was calculated from the concentrations of protein, fat and lactose; the following energy concentrations were used: lactose, 16.4 kJ/g; fat, 38.9 kJ/g; protein, 23.8 kJ/g. Amounts of fat, protein, lactose and energy secreted with the milk on d 11 of lactation were calculated by multiplying the daily milk yield by the concentrations of these nutrients or energy, respectively, in the milk. The fatty acid composition of the milk fat was determined by extracting lipids with hexane-isopropanol (3:2, v/v) (10) and transmethylation by means of trimethyl sulfonium hydroxide (11). The resulting FAME were separated by capillary GC (12). The concentrations of total carnitine in the diets and of total, free and esterified carnitine in the milk were determined by a radiochemical method, which is based on the conversion of carnitine into [^{3}H]acetylcarnitine by carnitine-O-acetyltransferase (13).

Determination of piglet suckling times. On d 3 of the second lactation, four sows from each of the two groups and their litters were filmed over a 24-h period with a video camera. The videotapes were viewed. The number of sucklings was counted and their mean duration and the total suckling time measured with a stop-watch.

Statistics. The statistical analysis of the data was performed with the SAS package (procedure mixed, version 8.2, SAS Institute, Cary, NC). A mixed linear model with three fixed effects, two random effects and, depending on the trait under investigation, one covariable was used. Treatment (control, L-carnitine), reproductive cycle and the interaction between these factors were included as fixed effects. Because the same sows were used over two reproductive cycles the observations within one sow were repeated measurements. Thus, in addition to the random error effect, a random sow effect was included. Body weights of the piglets at birth were additionally analyzed with litter size as a covariable. For estimation of the variance of the random effects, the restricted maximum likelihood (REML) method was used (14). The standard errors of the estimated fixed effects and their linear combination to least-square means (LS means) as well as the df for estimates and hypothesis tests, respectively, were calculated according to Kenward and Roger (15). Values in the text are LS mean ± SE. Differences were considered significant if $P < 0.05$.

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RESULTS

Number of pregnant sows. In the first cycle, 16 of the 20 sows in each group conceived; in the second cycle, 13 of the 16 sows in each group conceived.

Diet intake, body weights of the sows and backfat thickness. Diet intakes of the sows from d 1 to 110 of pregnancy and during lactation were higher in the second than in the first cycle (**Table 2**). L-Carnitine supplementation did not influence diet intake from d 1 to 110 of pregnancy but did increase diet intake during lactation. Body weights of the sows on d 1, 85 and 110 of pregnancy and at weaning were higher in the second cycle than in the first cycle; L-carnitine supplementation did not affect the sows' body weights. Backfat thickness was also unaffected by L-carnitine supplementation. However, backfat thickness of the sows on d 110 of pregnancy and at weaning was significantly higher in the second cycle than in the first cycle.

Number and birth weights of piglets. Total litter size and the number of piglets born alive did not differ between the first and the second cycle, but piglet and litter weights were significantly higher in the second cycle than in the first (**Table 3**).

In both cycles, sows treated with L-carnitine produced larger litters overall and more live-born piglets than the control sows. Piglets of sows treated with L-carnitine had lower actual body weights than those of control sows. Body weights of piglets adjusted for litter sizes by covariate analysis did not differ between piglets of control sows and those of sows treated with L-carnitine. In the first cycle, they were 1.46 ± 0.05 and 1.44 ± 0.05 kg for piglets of controls sows and those of sows treated with L-carnitine, respectively; in the second cycle they were 1.65 ± 0.05 and 1.62 ± 0.05 kg, respectively. Litters from sows treated with L-carnitine were significantly heavier than those of the control sows in both cycles.

Creep feed intake of piglets. Creep feed intake did not differ in piglets of control sows and piglets of sows treated with L-carnitine. Piglets of control sows and sows treated with L-carnitine, born in the first reproductive cycle consumed 172 ± 5 and 178 ± 7 g creep feed, respectively, from d 19 to weaning on d 25 ($n = 13$); piglets of control sows and sows treated with L-carnitine, born in the second cycle consumed 528 ± 16 and 504 ± 14 g creep feed, respectively, from d 19 to weaning on d 30 ($n = 10$).

Weight gains of piglets during suckling. Piglets born in the second reproductive cycle grew faster during the suckling period than piglets born in the first cycle (**Table 4**).

After standardization of litter sizes to 10 piglets/litter, piglets weights were similar to those before standardization. At the beginning of the suckling period (d 1) the body weights of piglets from the sows treated with L-carnitine tended to be lighter than those of control sows ($P < 0.10$). In the intervals from d 1 to 12 and from d 12 to 19 of suckling, piglets of sows treated with L-carnitine grew faster than piglets of control sows; in the interval from d 19 to weaning, daily body weight gains of the piglets of both groups of sows did not differ. Daily body weight gains over the entire suckling period were also higher in piglets of sows supplemented with L-carnitine than in piglets of control sows, in both cycles. At d 12, body weights of piglets from sows treated with L-carnitine tended to be higher than those of piglets from control sows ($P < 0.15$); at d 19 and at weaning, piglets from sows treated with L-carnitine were heavier than those of control sows.

Milk production, milk constituents and amounts of nutrients secreted in the milk. Sows produced more milk in the

TABLE 2

The effect of L-carnitine supplementation on diet intake, body weights and backfat thickness of sows during the first and second reproductive cycles[1]

	First		Second		Results of *F*-test, *P*		
Cycle treatment	Control	+L-carnitine	Control	+L-carnitine	Treatment	Cycle	Treatment × cycle
n	16	16	13	13			
			kg/d				
Diet intake							
d 1–110 of pregnancy	3.2 ± 0.1	3.2 ± 0.1	3.3 ± 0.1	3.5 ± 0.1	NS[2]	<0.05	NS
Lactation	4.3 ± 0.2	4.6 ± 0.2	5.5 ± 0.2	6.1 ± 0.2	<0.01	<0.001	NS
			kg				
Body weight							
d 1 of pregnancy	145 ± 3	144 ± 3	172 ± 3	172 ± 3	NS	<0.0001	NS
d 85 of pregnancy	196 ± 4	196 ± 4	238 ± 4	240 ± 4	NS	<0.0001	NS
d 110 of pregnancy	220 ± 4	222 ± 4	262 ± 4	266 ± 4	NS	<0.0001	NS
Weaning	171 ± 5	166 ± 5	207 ± 5	210 ± 5	NS	<0.0001	NS
			mm				
Backfat thickness							
d 1 of pregnancy	16.4 ± 0.6	16.6 ± 0.6	16.8 ± 0.7	15.8 ± 0.7	NS	NS	NS
d 110 of pregnancy	19.3 ± 0.8	18.9 ± 0.7	23.9 ± 0.8	23.5 ± 0.8	NS	<0.0001	NS
Weaning	16.8 ± 0.8	15.6 ± 0.7	17.7 ± 0.8	17.2 ± 0.8	NS	<0.05	NS

[1] Values are LS means ± SE.
[2] NS, nonsignificant ($P > 0.05$).

TABLE 3

The effect of L-carnitine supplementation in sows on the number of piglets and weights of piglets and litters at birth in the first and second reproductive cycles[1]

	First		Second		Results of *F*-test, *P*		
Cycle treatment	Control	+L-carnitine	Control	+L-carnitine	Treatment	Cycle	Treatment × cycle
n	13	13	10	13			
Piglets born, *n*	10.2 ± 0.8	12.9 ± 0.7	10.8 ± 0.9	13.5 ± 0.9	<0.01	NS[2]	NS
Piglets born alive, *n*	9.6 ± 0.8	12.4 ± 0.8	10.3 ± 0.9	13.1 ± 0.9	<0.01	NS	NS
Weights of piglets at birth, *kg*	1.54 ± 0.06	1.39 ± 0.06	1.70 ± 0.07	1.53 ± 0.07	<0.05	<0.01	NS
Weights of litters at birth, *kg*	14.2 ± 1.0	16.8 ± 0.9	17.3 ± 1.1	19.6 ± 1.1	<0.05	<0.01	NS

[1] Values are LS means ± SE.
[2] NS, nonsignificant ($P > 0.05$).

second cycle than in the first cycle, on both d 11 and 18 of lactation (**Table 5**). Sows supplemented with L-carnitine produced more milk on d 11 and 18 of lactation than control sows. This effect was evident in both lactations.

The concentrations of protein and lactose and the amount of gross energy in the milk were higher in the second lactation than in the first; the concentration of fat in the milk did not differ between the lactations. The concentrations of fat, protein and lactose and the amount of gross energy in the milk did not differ between sows supplemented with L-carnitine and control sows. Amounts of nutrients and energy secreted with the milk on d 11 of lactation were higher in the second cycle than in the first. In both lactations, sows supplemented with L-carnitine secreted more protein and lactose daily with the milk than control sows. The secretion of fat with the milk did not differ between the two groups of sows. The amount of gross energy secreted with the milk tended to be higher in sows supplemented with L-carnitine than in control sows ($P < 0.10$).

Fatty acid composition of milk total lipids. The fatty acid composition of total lipids, measured in the milk on d 11 of the second lactation, did not differ between the two groups of sows (data not shown). Palmitic acid (29.2 ± 0.7 g/100 g total fatty acids), oleic acid (33.9 ± 1.2 g/100 g total fatty acids) and linoleic acid (13.9 ± 0.3 g/100 total fatty acids, $n = 26$) made up the quantitatively largest amounts of fatty acids in the milk. The amounts of total saturated, monounsaturated and polyunsaturated fatty acids were 39.5 ± 0.9, 42.9 ± 0.9 and 17.2 ± 0.3 g/100 g total fatty acids, respectively, in the milk of control sows and 39.8 ± 0.6, 42.3 ± 2.4 and 17.5 ± 0.3 g/100 g total fatty acids, respectively, in the milk of sows treated with L-carnitine ($n = 13$).

Carnitine concentration in milk. The milk of sows in the first lactation had higher concentrations of total and free carnitine than in the second lactation; the concentration of esterified carnitine in the milk did not differ between the first and the second lactations (**Table 6**). The milk of sows treated with L-carnitine had higher concentrations of total and free carnitine; the concentration of esterified carnitine in the milk did not differ between the two groups of sows.

Suckling behavior of piglets. There was no difference between piglets from control sows and sows treated with L-

TABLE 4

The effect of L-carnitine supplementation in sows on weight gains of piglets during the suckling period in the first and the second reproductive cycles[1]

	First		Second		Results of *F*-test, *P*		
Cycle treatment	Control	+L-carnitine	Control	+L-carnitine	Treatment	Cycle	Treatment × cycle
n	13	13	10	10			
			kg				
Body weight							
d 1	1.49 ± 0.06	1.34 ± 0.06	1.67 ± 0.07	1.52 ± 0.07	NS[2]	<0.05	NS
d 12	3.66 ± 0.14	3.90 ± 0.14	4.19 ± 0.22	4.27 ± 0.22	NS	<0.05	NS
d 19	5.54 ± 0.22	5.85 ± 0.22	6.37 ± 0.26	6.68 ± 0.26	<0.05	<0.001	NS
Weaning[3]	7.60 ± 0.21	8.11 ± 0.21	10.81 ± 0.24	11.43 ± 0.24	<0.05	<0.001	NS
Body weight gain during suckling							
d 1 to 12	1.98 ± 0.10	2.32 ± 0.10	2.27 ± 0.12	2.53 ± 0.12	<0.01	<0.05	NS
d 12 to 19	1.61 ± 0.05	1.67 ± 0.05	1.87 ± 0.07	2.06 ± 0.07	<0.05	<0.001	NS
d 19 to weaning	2.52 ± 0.08	2.78 ± 0.08	5.00 ± 0.15	5.33 ± 0.15	NS	<0.001	NS
d 1 to weaning	6.11 ± 0.21	6.77 ± 0.21	9.14 ± 0.24	9.92 ± 0.24	<0.01	<0.001	NS

[1] Values are LS means ± SE.
[2] NS, nonsignificant ($P > 0.05$).
[3] Piglets of the first cycle were suckled for 25 d; piglets of the second cycle were suckled for 30 d.

TABLE 5

The effect of L-carnitine supplementation in sows on their milk production at d 11 and 18 and amounts of nutrients secreted with milk at d 11 of lactation of the first and second cycles[1]

	First		Second		Results of *F*-test, *P*		
Cycle treatment	Control	+L-carnitine	Control	+L-carnitine	Treatment	Cycle	Treatment × cycle
n	13	13	10	10			
			kg/d				
Milk production[2]							
d 11	4.64 ± 0.43	5.53 ± 0.43	7.74 ± 0.50	9.17 ± 0.50	<0.05	<0.001	NS[3]
d 18	5.64 ± 0.39	7.04 ± 0.39	9.91 ± 0.45	10.64 ± 0.45	<0.05	<0.001	NS
			g/kg				
Nutrients in the milk							
Fat	81 ± 4	83 ± 4	89 ± 4	82 ± 4	NS	NS	NS
Protein	44 ± 1	43 ± 1	50 ± 1	48 ± 1	NS	<0.001	NS
Lactose	51 ± 1	53 ± 1	55 ± 1	54 ± 1	NS	<0.001	NS
Gross energy, *MJ/kg*	5.01 ± 0.13	5.08 ± 0.13	5.54 ± 0.15	5.22 ± 0.15	NS	<0.05	NS
			g/d				
Nutrients secreted with milk (d 11)							
Fat	375 ± 43	458 ± 43	689 ± 49	758 ± 49	NS	<0.001	NS
Protein	203 ± 19	236 ± 19	384 ± 22	443 ± 22	<0.05	<0.001	NS
Lactose	239 ± 24	293 ± 24	426 ± 27	497 ± 27	<0.05	<0.001	NS
Gross energy, *MJ/d*	23.3 ± 2.4	28.1 ± 2.4	42.8 ± 2.8	48.0 ± 2.8	<0.10	<0.001	NS

1 Values are LS means ± SE.
2 Each sow nursed 10 piglets.
3 NS, nonsignificant ($P > 0.05$).

carnitine in the number of sucklings per day, the average duration of suckling or the total time spent suckling in a day. The number of sucklings/d for piglets of control sows and those of sows treated with L-carnitine was 36.8 ± 1.5 and 32.8 ± 2.2, respectively. The duration of suckling was 5.84 ± 0.70 and 6.87 ± 0.65 min. respectively, and the total time spent suckling was 217 ± 34 and 224 ± 24 min/d, respectively (*n* = 4/group of sows).

DISCUSSION

This study was undertaken to investigate the effects of L-carnitine supplementation in sows during pregnancy and lactation on milk production and milk constituents. An experiment was performed over two reproductive cycles. It was not surprising that the sows were heavier and had higher diet intakes, higher litter weights and higher milk production in the second cycle than in the first cycle. Differences in body weights, feed intake capacity, litter weights and milk production between first parity sows and multiparous sows are well documented in the literature (16). Milk production of sows depends largely on the number of nursing piglets. The milk production of the sows and body weight gains of the suckling piglets during the first and second lactation observed in this study are in close agreement with data reported in the litera-

TABLE 6

The effect of L-carnitine supplementation in sows on the concentration of total, free and esterified carnitine in the milk on d 11 of lactation in the first and the second reproductive cycles[1]

	First		Second		Results of *F*-test, *P*		
Cycle treatment	Control	+L-carnitine	Control	+L-carnitine	Treatment	Cycle	Treatment × cycle
n	13	13	10	10			
			μmol/L				
Carnitine							
Free	41 ± 7	69 ± 6	26 ± 2	36 ± 1	<0.001	<0.001	NS[2]
Esterified	33 ± 6	40 ± 8	36 ± 2	39 ± 3	NS	NS	NS
Total	74 ± 12	109 ± 10	62 ± 3	75 ± 3	<0.001	<0.05	NS

1 Values are LS means ± SE.
2 NS, nonsignificant ($P > 0.05$).

ture for sows nursing 10 piglets (17). The milk composition, i.e., the concentrations of protein, fat and lactose in the milk of the sows, also is consistent with literature data (18).

Our work confirms recent studies (1–3) showing that supplementation of sows' diets with L-carnitine increases reproductive performance. Recent studies reported increased piglet and litter weights at birth in sows fed diets supplemented with L-carnitine (1–3). An increase in the number of piglets born to sows fed L-carnitine–supplemented diets during pregnancy has not yet been observed. However, Musser et al. (19) found that dietary L-carnitine supplementation during lactation increased the number of piglets in the subsequent litter. These observations suggest that dietary L-carnitine either increases the ovulation rate or reduces embryonal mortality in sows. A previous study by Musser et al. (1) showed that dietary L-carnitine increases the concentrations of insulin and insulin-like growth factor-1 in the blood of sows during pregnancy. Because insulin influences ovarian function, follicle development and ovulation rate (20), a relationship may exist among L-carnitine, insulin and ovulation rate. Further studies are required to clarify the effects of L-carnitine on ovarian function, ovulation rate and embryonal mortality in sows. The effect of L-carnitine treatment on the number of piglets born in this study was much larger than one would normally expect. Further studies with a much higher number of sows are required to confirm the effects of L-carnitine on the number of piglets born.

As in previous studies (1–3), piglets of sows supplemented with L-carnitine grew faster during the suckling period than piglets of control sows. Our study suggests that this effect might be due to a higher milk yield and an increased transfer of energy and nutrients from the sow to the piglets with the milk. The main action of L-carnitine in mammals is to transfer long-chain fatty acids through the inner membrane of mitochondria where β-oxidation occurs (21). However, neither the fat content of the milk nor the fatty acid composition of milk total lipids was affected by dietary L-carnitine. We therefore assume that L-carnitine did not influence the fatty acid metabolism in the mammary gland. Newborn or weanling pigs can synthesize L-carnitine only to a small extent (22,23). An increased concentration of carnitine in the milk of sows treated with L-carnitine could therefore induce more efficient energy utilization in suckling piglets. In weaned piglets, dietary L-carnitine supplementation slightly increased the gain/feed ratio (24) and improved nitrogen retention (25).

Another finding of this study is that dietary L-carnitine increased the secretion of lactose and protein with milk. This supports the concept that both carbohydrate and protein metabolism of pigs may be altered by dietary L-carnitine. Owen et al. (26) observed altered metabolism in growing pigs fed L-carnitine. These researchers observed increased flux through pyruvate carboxylase and decreased flux through branched-chain α-keto acid dehydrogenase in liver mitochondria with increasing dietary L-carnitine. These metabolic changes favor gluconeogenesis and reduced oxidation of BCAA that could provide substrate for milk lactose and protein synthesis.

Milk production of sows is influenced by their nutritional status, in particular the energy supply during lactation (5). The increased milk production of sows treated with L-carnitine could therefore be due to the higher diet intake of these sows compared with control sows. In weaned piglets and growing-finishing pigs, dietary L-carnitine enhanced the oxidation of fatty acids from adipose tissue and the accretion of body protein, leading to a higher ratio of body protein to adipose tissue (25–27). The data for body weights and backfat thickness at weaning, which did not differ between L-carnitine treated and control sows, do not suggest enhanced mobilization of adipose tissue by supplemental L-carnitine for milk synthesis. The additional energy required for increased milk production in sows treated with L-carnitine might therefore have been supplied primarily by the diet.

Milk production of sows is also strongly influenced by litter size, piglet weights and suckling intervals (6,7,17,28). If piglets suckle more frequently, they will obtain more milk, thus causing milk production to rise. To study the suckling behavior of the piglets, we filmed four litters of each group of sows over a 24-h period. In this small number of litters, no differences in suckling behavior were observed between the two groups of piglets in terms of the number of sucklings and the total time spent suckling in a day. Litter size did not play a role in the different milk yields of carnitine-treated and control sows because the number of piglets was standardized after birth. It is remarkable that piglets of sows supplemented with L-carnitine gained more body weight during the suckling period although they were initially lighter than piglets of control sows. Normally, piglets that are heavier at birth grow faster during the suckling period because they are able to massage the teats more strongly and therefore obtain more milk at each suckling (28). What we suspect is that piglets of sows supplemented with L-carnitine were more vigorous and despite their lower initial body weights, they were able to stimulate a greater milk flow in the sows than piglets of control sows.

In conclusion, this study confirms that dietary L-carnitine improves the reproductive performance of sows. It also shows that higher growth rates of piglets from sows treated with L-carnitine during the suckling period compared with piglets from control sows are due to an increased supply of nutrients in the milk.

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