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L-carnitine supplementation of sows during pregnancy improves the suckling behaviour of their offspring

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It has been shown that L-carnitine supplementation of sows increases their milk production and the postnatal growth of the suckling piglets. To test the hypothesis that this effect is due to an improved suckling behaviour of the piglets, two experiments with sows were performed. Two groups of thirteen or ten sows each (in experiments 1 and 2, respectively) were fed diets with or without supplemental L-carnitine during pregnancy (125 mg/d) and lactation (250 mg/d). After birth, the litters of all sows were standardised to equal sizes of eleven and nine piglets per litter in experiments 1 and 2, respectively. In experiment 1, the piglets of L-carnitine-supplemented sows had a higher total suckling time per day on days 3, 6 and 9, and greater weight gains during the suckling period, than the piglets of control sows ($P<0{\cdot}05$). In experiment 2, all litters were taken away from their mothers and switched to other sows. Half of the control sows and half of the L-carnitine-supplemented sows were given litters born to control sows, the other half of each group being given litters born to L-carnitine-supplemented sows. Piglets born to L-carnitine-supplemented sows had a higher total suckling time per day on day 3 and greater body weight gains during the first 14 d compared with piglets born to control sows ($P<0{\cdot}05$). This study shows that piglets born to sows supplemented with L-carnitine are able to suckle for longer, which enables them to obtain more milk and grow faster than piglets born to control sows.

L-Carnitine: Sow: Piglet: Suckling behaviour

Several studies have shown that supplementing sows with L-carnitine during pregnancy and lactation increases their reproductive performance. Sows supplemented with L-carnitine had fewer stillborn piglets, more piglets born alive and greater litter weights (Musser *et al.* 1999*b*; Eder *et al.* 2001; Ramanau *et al.* 2002, 2004, 2005). Moreover, it has been shown that litters of sows supplemented with L-carnitine gain more weight during the suckling period than do litters of control sows (Musser *et al.* 1999*b*; Eder *et al.* 2001; Ramanau *et al.* 2002, 2004, 2005).

The postnatal growth of piglets depends on their intake of energy and nutrients with the milk (Pluske & Dong, 1998). The contents of energy and nutrients, as well as the fatty acid composition of the milk, do not differ between control sows and sows supplemented with L-carnitine (Ramanau *et al.* 2004, 2005). Using the weigh–suckle–weigh method, however, we have shown that the piglets of sows supplemented with L-carnitine are able to suckle more milk from the sow than are the piglets of control sows, which may explain their higher growth rate during the suckling period (Ramanau *et al.* 2004, 2005).

The reason for the higher milk intake of piglets from sows supplemented with L-carnitine is unclear. The milk production of sows is strongly influenced by litter size, piglet weights and suckling intervals (King *et al.* 1997; Spinka *et al.* 1997; Auldist *et al.* 1998, 2000). If piglets suckle more frequently, with shorter intervals between sucklings, they will obtain more milk, thus causing the sow's milk production to rise. The hypothesis of the present study was that piglets of sows supplemented with L-carnitine would be able to suckle more frequently or for longer periods owing to an increased L-carnitine status, obtaining more milk from the sow and therefore growing faster than the piglets of control sows.

To test this hypothesis, we performed two experiments with sows. In the first experiment, sows were assigned to a control group and a group supplemented with L-carnitine during pregnancy and lactation. After delivery, litters were standardised to an identical size in order to avoid the potential effects of differences in litter size on milk production, and were suckled from their mothers during a 28 d lactation period. The second experiment was performed to clarify whether alterations in the suckling behaviour of the piglets were due to prenatal or postnatal effects of L-carnitine. In that experiment, sows were assigned to a control group and a group treated with L-carnitine. After delivery, all the litters were taken away from their mothers and switched to other sows. Half of the control sows and half of the L-carnitine-supplemented sows were given litters born to control sows, the other half of each group being given litters born to L-carnitine-supplemented sows.

If an improvement in suckling behaviour were due to prenatal effects, litters born to sows supplemented with L-carnitine should have had a higher suckling activity and have grown

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faster during the suckling period than litters born to control sows, irrespective of whether they were suckled by control sows or by sows supplemented with L-carnitine. If the improved suckling behaviour of the piglets was due to postnatal effects of L-carnitine, litters suckled by sows supplemented with L-carnitine should have had a higher suckling activity and have gained more weight during the suckling period than litters suckled by control sows, irrespective of whether they were born to control sows or to sows supplemented with L-carnitine.

Materials and methods

Animals and housing

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.

The first experiment was performed with twenty-six crossbred sows (German Landrace × Large White) in their second parity with a body weight of 179 (SE 3) kg. They were assigned to two groups, a control group and a group treated with L-carnitine, of thirteen sows each. Twenty-four hours after the weaning of their first litter, the sows received 800 IU pregnant mare serum gonadotrophin (Intergonan 6000; Intervet, Unterschleißheim, Germany) by intramuscular injection to stimulate oestrus. Seventy-two hours later they were injected with 500 IU human chorionic gonadotrophin (Ovogest 5000, Intervet). A further 26 h after that, they were artificially inseminated with sperm from Pietrain boars, a second insemination following 14 h later.

The second experiment was performed with 40 gilts (German Landrace × Large White) with a body weight of 143 (SE 1) kg. They were assigned to two groups, a control group and a group treated with L-carnitine, of twenty sows each. Their sexual cycle was blocked for 15 d by the administration of Altrenogest (Regumate; Hoechst Roussel Vet. N.V., Frankfurt, Germany). Twenty-four hours after the last dose of Regumate, they were injected with 800 IU pregnant mare serum gonadotrophin, followed 80 h later by an injection of 500 IU human chorionic gonadotrophin (Ovogest 5000; Intervet). A further 24 h after the human chorionic gonadotrophin injection, they were artificially inseminated with sperm from Pietrain boars, followed by a second injection 14 h later.

In the first experiment, nine of the thirteen sows in the control group and all thirteen sows in the L-carnitine treated group conceived. In the second experiment, thirteen of the twenty sows in the control group and sixteen of the of the twenty sows in the L-carnitine treated group conceived. Farrowing was induced on day 115 of pregnancy by intramuscular injection of prostaglandin $F_{2\alpha}$ (Cloprostenol; Medistar GmbH, Holzwickede, Germany). Within 2 d after farrowing, the litter sizes of the sows to be considered during lactation were standardised to avoid potential effects of differences in litter size on milk production and weight gains of the litters during the suckling period. In the first experiment, litters of eight randomly selected sows from each group were standardized to eleven piglets per litter.

In the second experiment, litters of ten sows from each group were standardised to nine piglets per litter within 2 d of farrowing. Sows with more than nine or eleven piglets, respectively, had the surplus piglets taken away, and sows with fewer than nine or eleven piglets were given piglets from other sows of the same group. Piglets removed from sows and piglets given to sows were selected on the basis of their body weight. The average weight of piglets of each sow after litter standardisation was matched to that before standardisation. Surplus piglets were nursed by the remaining sows of each group that were not taking part in the study.

In the second experiment, all the litters were taken away from their mothers and switched to other sows. Litters of half of the control sows or L-carnitine-treated sows, respectively, were switched to sows of the other experimental group, and litters of the other half of each group were switched to different sows of the same treatment. This resulted in four combinations in the second experiment: piglets born to control sows and suckled by different control sows; piglets born to control sows and suckled by sows supplemented with L-carnitine; piglets born to sows supplemented with L-carnitine and suckled by control sows; piglets born to sows supplemented with L-carnitine and suckled by different sows supplemented with L-carnitine.

The sows were kept in single crates until day 30 of pregnancy. From day 30 to day 110 of pregnancy, the sows were kept in groups of six to eight in pens measuring 45 m^2, which had fully slatted floors, nipple drinkers and electronic feeding stations. On day 110 of pregnancy, they were moved to the farrowing accommodation, where they were housed in single farrowing pens. Prior to farrowing, rubber mats were put down as a lying surface for the piglets. An IR heater was suspended above each rubber mat to keep the temperature for the newborn piglets at a constant 35°C. Piglets were suckled for 28 d. The climate in the dry sow accommodation and the farrowing unit was maintained at a temperature of 19 ± 2°C and at 60–80 % relative humidity by means of an air-conditioning system. A light–dark cycle (12 h light–12 h dark) was applied.

Diets and feeding

In both experiments, two commercial sow diets were used, whose composition and nutrient concentrations are shown in Table 1. The first diet ('gestation diet' SF-SATT; Deuka, Könnern, Germany) was fed during pregnancy. Two different batches of this diet were used in experiments 1 and 2, which varied slightly in their composition and nutrient concentrations. Until day 30 of pregnancy, each sow was fed 3·5 kg gestation diet individually. From day 30 to day 110 of pregnancy, when the sows were kept in groups, they had free access to the diets. The sows' daily feed intake was recorded by means of an electronic sow-feeding station (type IVOG 2FR VH; HokoFarm, Insentec B.V., Marknesse, The Netherlands). From day 110 of pregnancy to farrowing, each sow was fed 2·5 kg/d of this diet.

The second diet ('lactation diet'; Lactosan; Deuka) was fed during the lactation period. The same batches of this diet were used in experiments 1 and 2. On the day of farrowing, the sows were fed 1·5 kg of the diet, the amount then being successively increased (2 kg/d on days 1 and 2 of lactation; 4 kg/d on days 3–7 of lactation; 5·5 kg/d from days 8 to 14; 6·0 kg/d from days 15 to 25). Thereafter the sows received

Table 1. Composition of the diets used during pregnancy and lactation

	Gestation diet		Lactation diet
	Experiment 1	Experiment 2	Experiments 1 and 2
Ingredient (g/kg)			
Dried sugar beet pulp	260	260	–
Barley	150	150	150
Wheat	–	–	344
Wheat bran	380	382	170
Extracted soyabean meal	–	–	160
Extracted sunflower meal	110	140	–
Maize	–	–	80
Wheat gluten	33	–	–
Triticale	25	30	–
Soyabeans	–	–	30
Vegetable oil	2	2	27
Molasses	25	20	–
Mineral premix	10	11	24
Premix containing vitamins and amino acids	5	5	15
Nutrients			
Crude protein (g/kg)	138	147	182
Crude fibre (g/kg)	120	135	48
Crude ash (g/kg)	59	61	46
Crude fat (g/kg)	30	30	59
L-Carnitine (mg/kg)	7·4	6·5	2·5
Metabolisable energy (MJ/kg)*	9·0	8·7	12·6

* Calculated according to recommendations by Gesellschaft für Ernährungsphysiologie (1987).

5·0 kg/d until weaning on day 28. Water was provided from nipple drinker systems throughout the whole feeding period.

Supplementation of L-carnitine

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 given as tablets containing L-carnitine (62·5 mg/tablet), lactose and dextrose; Lohmann Animal Health, Cuxhaven, Germany). The tablets were administered once daily in the morning (09.00 hours) by hand. During pregnancy, each sow of the treatment group was given two tablets; during lactation, each sow was given four tablets. Amounts of L-carnitine administered to the sows during pregnancy and lactation were selected according to our recent studies (Ramanau *et al.* 2002, 2004). Control animals were given the same tablets without L-carnitine.

Data recording

Body weights (using scales with an accuracy of 100 g) of the sows were recorded on days 1 and 105 of pregnancy and on the day of weaning. Individual piglets were weighed at birth (not later than 6 h after birth) and at 7, 14, 21 and 28 d of age using scales with an accuracy of 10 g. All the sows that conceived were evaluated for number of piglets born, piglet weights and litter weights at birth.

Determination of nutrients in the diets

Concentrations of crude nutrients in the diets were analysed according to the official German VDLUFA methodology (Bassler & Buchholz, 1993). The metabolisable energy of the diet was calculated as recommended by the German nutrition society (Gesellschaft für Ernährungsphysiologie, 1987).

Analysis of L-carnitine in plasma, milk and diet

Piglets were bled by puncture of the venous plexus in the jugular fossa on day 1 (6 h postpartum) and at 14 and 28 d of age. Plasma was obtained by centrifuging the blood (1100 ***g***, 10 min, 4°C) and stored at −20°C pending analysis. On the day of birth and on day 11 of lactation, the sows were given 15 IU oxytocin (Atarost GmbH&Co, Twistringen, Germany) by intramuscular injection, and 80–100 ml milk was expressed manually from all the active teats of each sow. Milk was stored at −20°C pending analysis.

The concentrations of total carnitine in plasma, milk and diet were determined by a radiochemical method, which is based on the conversion of carnitine to [^{3}H]acetylcarnitine by carnitine-O-acetyltransferase (McGarry & Foster, 1976).

Determination of piglet suckling behaviour

In the first experiment, eight randomly selected sows from each group and their litters were filmed with a video camera (time-lapse cassette recorder: Panasonic AG-6124-E, Matsushita Electric Ind. Co. Ltd, Osaka, Japan; camera: Visicom B/W-Kamera CCD-BW2012, MHM Electronic GmbH, Lindhorst, Germany) over a 24 h period on days 3, 6 and 9 of lactation. In the second experiment, all the sows and their litters were filmed on day 3 of lactation. The video tapes were viewed with a video recorder (video recorder: Panasonic AG 7350-E; monitor: Panasonic WV-CM 1430, Matsushita).

The number of sucklings was counted, and the mean duration of one suckling act and total suckling time were measured with a stopwatch. A suckling act was deemed to

have occurred if the number of piglets nursing the udder was at least 60 % of the sow's litter size (six piglets/litter in experiment 1; five piglets/litter in experiment 2). The total suckling time/d was calculated as the sum of the individual nursing episodes. As lactation progresses, piglets' suckling behaviour changes: piglets more often tend to nose the udder individually and fall asleep there, making an accurate distinction between suckling and sleeping piglets extremely difficult or speculative. For this reason, it was no longer possible to measure the suckling time after day 9 of lactation.

Statistical analysis

All statistics were carried out using SAS software (SAS institute Inc., Cary, NC, USA). All dependent variables in the first experiment, and the dependent variables of pregnancy and litter performance in the second experiment, were analysed with a mixed linear model (procedure mixed, version 8.2; SAS Institute Inc.) that included the treatment of sows (control sow *v*. sow supplemented with L-carnitine) as a fixed effect. In the second experiment, data on lactation were evaluated by using a mixed linear model (procedure mixed, version 8.2; SAS Institute Inc.) with treatment of sow (control sow *v*. sow supplemented with L-carnitine), origin of the piglet (piglet of control sow *v*. piglet of sow supplemented with L-carnitine) and their interaction as classification factors. Results are expressed as least-square means and standard errors of the means. Means were considered significantly different for $P<0{\cdot}05$.

Results

Experiment 1: Feed intake and body weights of the sows during pregnancy and lactation, number and birth weights of piglets

Body weights on days 1 and 10, and average daily feed intake during the entire pregnancy, did not differ between the two groups of sows. Taking all pregnant sows in the experiment, values for control sows (*n* 9) and sows supplemented with L-carnitine (*n* 13) were: body weight day 1, 177 *v*. 179 (SEM 3) kg; body weight day 108, 248 *v*. 242 (SEM 5) kg; daily feed intake, 3·4 *v*. 3·4 (SEM 0·1) kg. Taking only the eight sows from each group who were studied during lactation, there was again no difference in these parameters; for control sows (*n* 8) *v*. sows supplemented with L-carnitine (*n* 8) values were: body weight day 1, 176 *v*. 181 (SEM 5) kg; body weight day 108, 246 *v*. 247 (SEM 6) kg; daily feed intake, 3·3 *v*. 3·4 (SEM 0·1) kg. Body weight at weaning and feed intake during lactation also did not differ between the two groups of sows; for control sows (*n* 8) *v*. sows supplemented with L-carnitine (*n* 8): body weight at weaning, 208 *v*. 213 (SEM 7) kg; daily feed intake, 6·5 *v*. 6·4 (SEM 0·04) kg.

Total litter size, number of piglets born alive and birth weights of the piglets and litters did not differ between control sows and sows supplemented with L-carnitine. Values for control sows (*n* 9) and sows supplemented with L-carnitine (*n* 13) were as follows: number of piglets born/litter, 11·2 *v*. 12·4 (SEM 1·0); number of piglets born alive/litter, 11·1 *v*. 12·3 (SEM 1·0); litter weight, 14·9 *v*.16·7 (SEM 1·2) kg; piglet weight, 1·37 *v*.1·38 (SEM 0·07) kg. The variation in body weights of the piglets in a litter was, however, lower in L-carnitine-supplemented sows than in control sows (the SD of piglet weights in the litters of control sows and the litters of L-carnitine-supplemented sows being 0·32 and 0·17 kg, respectively).

The sows which were considered during lactation also showed no differences in these parameters. Values for control sows (*n* 8) and sows supplemented with L-carnitine (*n* 8) were: number of piglets born/litter, 11·9 *v*.12·8 (SEM 1·0); number of piglets born alive/litter, 11·8 *v*. 12·6 (SEM 1·0); litter weight, 15·6 *v*. 17·5 (SEM 1·2) kg; piglet weight, 1·34 *v*. 1·42 (SEM 0·09) kg.

Experiment 1: Suckling behaviour and weight gains of the piglets during the suckling period

The suckling behaviour of the piglets was studied at 3, 6 and 9 d of age. On all 3 d, the number of sucklings/d was no different between piglets from the control sows and from the sows supplemented with L-carnitine (Table 2). On days 3 and 6, the average duration of one suckling was, however, significantly higher in the piglets of sows supplemented with L-carnitine than in the piglets of control sows ($P<0{\cdot}05$; Table 2). On day 9, the average duration of one suckling was marginally higher in the piglets of sows supplemented with L-carnitine than in the piglets of control sows ($P<0{\cdot}10$; Table 2). The total suckling time/d was higher in the piglets from sows supplemented with L-carnitine than in those from control sows on all 3 d ($P<0{\cdot}05$; Table 2).

Average body weights of the piglets after the standardisation of litter sizes to eleven piglets/litter did not differ between the piglets of control sows and of sows supplemented with L-carnitine (Table 2). On days 7 and 28, body weights were greater in piglets from sows supplemented with L-carnitine than in piglets from control sows ($P<0{\cdot}05$; Table 2). On days 14 and 21, the piglets of sows supplemented with L-carnitine were also slightly heavier than those of control sows, but the differences were not significant ($P>0{\cdot}05$; Table 2). The body weight gain between day 1 and day 28 was more in the piglets of sows supplemented with L-carnitine than in the piglets of control sows ($P<0{\cdot}05$).

Experiment 2: Feed intake and body weights of the sows during pregnancy and lactation, number and birth weights of piglets

The body weights on days 1 and 105, and the average daily feed intake during the entire pregnancy, did not differ between the two groups of sows. Taking all pregnant sows in the experiment, values for control sows (*n* 13) and sows supplemented with L-carnitine (*n* 16) were: body weight day 1, 144 *v*. 142 (SEM 2) kg; body weight day 105, 206 *v*. 204 (SEM 3) kg; daily feed intake, 3·0 *v*. 3·1 (SEM 0·1) kg.

Taking the ten sows of each group that were studied during lactation, there was again no difference in these parameters; for control sows (*n* 10) *v*. sows supplemented with L-carnitine (*n* 10): weight day 1, 143 *v*. 141 (SEM 2) kg; body weight day 105, 207 *v*. 205 (SEM 4) kg; daily feed intake during pregnancy, 3·1 *v*. 3·1 (SEM 0·1) kg. The average daily feed intake during lactation and weights at weaning did not differ between control sows suckling piglets born to control sows

Table 2. Suckling behaviour (number of sucklings/d, average duration of one suckling and total suckling time/d) at days 3, 6 and 9 of age, and body weights and weight gains of piglets of control sows and piglets of sows supplemented with L-carnitine (experiment 1)

(Values are least-square means)

	Piglets of control sows	Piglets of sows supplemented with L-carnitine	SEM	*P*
Suckling behaviour (*n* 8)				
Day 3				
Number of sucklings/d	43·5	44·9	1·79	0·60
Average duration of one suckling (min)	4·73[a]	5·82[b]	0·30	0·02
Total suckling time/d (h)	3·45[a]	4·36[b]	0·28	0·04
Day 6				
Number of sucklings/d	38·0	37·5	1·33	0·79
Average duration of one suckling (min)	3·27[a]	4·62[b]	0·40	0·03
Total suckling time/d (h)	2·07[a]	2·85[b]	0·22	0·03
Day 9				
Number of sucklings/d	36·8	38·3	1·47	0·48
Average duration of one suckling (min)	4·19	5·01	0·30	0·07
Total suckling time/d (h)	2·56[a]	3·17[b]	0·18	0·03
Body weight (kg) (*n* 8)				
Day 1 (birth)	1·40	1·48	0·07	0·44
Day 7	2·69[a]	3·00[b]	0·09	0·03
Day 14	4·71	5·12	0·18	0·13
Day 21	7·04	7·35	0·16	0·20
Day 28	9·14[a]	9·84[b]	0·21	0·03
Weight gain, day 1–28 (g/d)	274[a]	298[b]	8	0·05

[a,b] Mean values within a column with unlike superscript letters were significantly different ($P<0·05$).

For details of diets and procedure, see pp. 335–336.

(feed intake 4·9 (SEM 0·3) kg/d; weight at weaning 208(SEM 7) kg), control sows suckling piglets born to sows supplemented with L-carnitine (feed intake 4·8 kg/d, weight at weaning 207 kg), sows supplemented with L-carnitine suckling piglets born to control sows (feed intake 5·1 kg/d, weight at weaning 207 kg) and sows supplemented with L-carnitine suckling piglets born to sows supplemented with L-carnitine (feed intake 4·5 kg/d, weight at weaning 203 kg).

Total litter size, number of piglets born alive and birth weights of the piglets and litters did not differ between control sows and sows supplemented with L-carnitine. Taking all pregnant sows in the experiment, values for control sows (*n* 13) and sows supplemented with L-carnitine (*n* 16) were: number of piglets born/litter, 10·9 *v.* 10·9 (SEM 0·8); number of piglets born alive/litter, 10·8 *v.* 10·6 (SEM 0·8); litter weight, 14·7 *v.*13·6 (SEM 0·9) kg; piglet weight, 1·38 *v.* 1·32 (SEM 0·04) kg. The variation in body weights of piglets in a litter was similar in the L-carnitine treated sows and the control sows (the SD of piglet weights in the litters of control sows and of L-carnitine-supplemented sows being 0·14 and 0·18 kg, respectively).

Taking the ten sows of each group that were studied during lactation, there was again no difference in these parameters; for control sows (*n* 10) *v.* sows supplemented with L-carnitine (*n* 10): number of piglets born/litter, 10·3 *v.* 10·9 (SEM 0·9); number of piglets born alive/litter, 10·2 *v.* 10·4 (SEM 0·9); litter weight, 14·2 *v.* 13·9 (SEM 0·9) kg; piglet weight, 1·41 *v.* 1·36 (SEM 0·06) kg.

Experiment 2: Concentrations of free and total carnitine in the milk of the sows and plasma carnitine concentrations of piglets at birth and during the suckling period

The sows supplemented with L-carnitine had higher concentrations of total L-carnitine in their colostrum (203 *v.* 151 (SEM 15) μmol/l, $P<0·05$; *n* 10 for each group) and milk on day 7 (127 *v.* 98 (SEM 9) μmol/l, $P<0·05$; *n* 10 for each group). The concentration of free L-carnitine in the milk was relatively low and did not differ between the milk from control sows and that from L-carnitine-supplemented sows, the values in control sows *v.* sows supplemented with L-carnitine being: colostrum, 10·1 *v.* 10·5 (SEM 1·2) μmol/l; milk on day 7, 44·4 *v.* 43·1 (SEM 5·4) μmol/l.

At birth, piglets born to sows supplemented with L-carnitine had higher concentrations of total carnitine in their plasma than did piglets born to control sows ($P<0·05$, Table 3). On day 14, the plasma carnitine concentrations of piglets born to control sows and of piglets born to sows supplemented with L-carnitine were no longer different, but piglets suckled by sows supplemented with L-carnitine had higher plasma carnitine concentrations than those suckled by control sows ($P<0·05$, Table 3). On day 28, piglets born to sows supplemented with L-carnitine and suckled by sows supplemented with L-carnitine had the highest plasma carnitine concentrations, and piglets born to control sows and also suckled by control sows had the lowest. Nevertheless, ANOVA showed that the origin of the piglets and the treatment of the sow during lactation did not influence the plasma L-carnitine concentrations of piglets on day 28 (Table 3).

Experiment 2: Suckling behaviour of the piglets and weight gains of the piglets during the suckling period

The number of sucklings/d at 3 d of age was no different between litters born to control sows and litters born to sows supplemented with L-carnitine (Table 4). There was also no difference in the number of sucklings between litters suckled by control sows and litters suckled by L-carnitine-supplemented sows. The average duration of one suckling was, however, higher in litters born to sows supplemented

Table 3. L-Carnitine concentrations in plasma of piglets born to control sows and piglets born to sows supplemented with L-carnitine, suckled either by control sows or by sows supplemented with L-carnitine, on days 1, 14 and 28 of age (experiment 2)

(Values are least-square means)

			Total carnitine in plasma (μmol/l)		
Litter born to	Litter suckled by	*n*	Piglets day 1 of age	Piglets day 14 of age	Piglets day 28 of age
Control sow	Control sow	5	12·3[b]	12·1[b]	7·7[b]
Control sow	L-Carnitine-treated sow	5	14·2[a,b]	15·1[a,b]	10·3[a,b]
L-Carnitine-treated sow	Control sow	5	18·9[a,b]	10·7[b]	10·4[a,b]
L-Carnitine-treated sow	L-Carnitine-treated sow	5	23·5[a]	17·2[a]	12·3[a]
SEM			2·9	1·2	1·5
Litter born to					
Control sow		10	13·3[b]	13·6	9·0
L-Carnitine-treated sow		10	21·2[a]	13·9	11·4
SEM			2·1	0·8	1·1
Litter suckled by					
Control sow		10	15·6	11·4[b]	9·1
L-Carnitine-treated sow		10	18·9	16·2[a]	11·3
SEM			2·1	0·8	1·1
Results of ANOVA, *P*					
Origin of litter			0·02	0·80	0·13
Treatment of sow during lactation			0·28	0·001	0·15
Interaction			0·65	0·14	0·81

[a,b] Mean values within a column with unlike superscript letters were significantly different ($P<0·05$).
For details of diets and procedure, see pp. 335–336.

with L-carnitine than in litters born to control sows ($P<0·05$, Table 4). The total suckling time/d was also higher in litters from sows supplemented with L-carnitine than in litters from control sows ($P<0·05$, Table 4). Litters suckled by control sows and litters suckled by sows supplemented with L-carnitine did not differ in the average duration of one suckling and the total suckling time/d.

At birth, piglets born to control sows and those born to sows supplemented with L-carnitine did not differ in their weights (1·40 *v.* 1·36 (SEM 0·05) kg). Body weight gains between birth and day 7, and body weight gains between days 7 and 14, were greater in piglets born to sows supplemented with L-carnitine than in piglets born to control sows ($P<0·05$), irrespective of whether they were suckled by control sows or by sows supplemented with L-carnitine (Table 5). Body weights on day 14 were also significantly greater in piglets born to sows supplemented with L-carnitine than in piglets born to control sows (4·67 *v.* 4·32 (SEM 0·12) kg, $P<0·05$). Body weight gains between days 14 and 21, and between days 21 and 28, did not differ between piglets born to control sows

Table 4. Suckling behaviour (number of sucklings/d, average duration of one suckling and total suckling time/d) of piglets born to control sows and piglets born to sows supplemented with L-carnitine, suckled either by control sows or by sows supplemented with L-carnitine, at day 3 of age (experiment 2)

(Values are least-square means)

Litter born to	Litter suckled by	*n*	Number of sucklings/d	Average duration of one suckling (min)	Total suckling time/d (h)
Control sow	Control sow	5	43·6	3·7[b]	2·7[a]
Control sow	L-Carnitine-treated sow	5	45·1	3·7[b]	2·8[a,b]
L-Carnitine-treated sow	Control sow	5	43·3	4·2[a]	3·0[a,b]
L-Carnitine-treated sow	L-Carnitine-treated sow	5	44·3	4·3[a]	3·2[b]
SEM			0·9	0·2	0·2
Litter born to					
Control sow		10	44·4	3·7[b]	2·7[b]
L-Carnitine-treated sow		10	43·8	4·2[a]	3·1[a]
SEM			0·6	0·1	0·1
Litter suckled by					
Control sow		10	43·4	3·9	2·8
L-Carnitine-treated sow		10	44·7	4·0	3·0
SEM			0·6	0·1	0·1
Results of ANOVA, *P*					
Origin of litter			0·51	0·01	0·02
Treatment of sow during lactation			0·15	0·56	0·23
Interaction			0·80	0·71	0·79

[a,b] Mean values within a column with unlike superscript letters were significantly different ($P<0·05$).
For details of diets and procedure, see pp. 335–336.

Table 5. Weight gains of piglets born to control sows and piglets born to sows supplemented with L-carnitine, suckled either by control sows or by sows supplemented with L-carnitine (experiment 2)

(Values are least-square means)

			Body weight gain (g/d)				
Litter born to	Litter suckled by	*n*	Day 1–7	Day 7–14	Day 14–21	Day 21–28	Day 1–28
Control sow	Control sow	5	164[b]	237[b]	263	322	246
Control sow	L-Carnitine-treated sow	5	175[ab]	256[a,b]	290	320	260
L-Carnitine-treated sow	Control sow	5	189[ab]	292[a]	254	327	266
L-Carnitine-treated sow	L-Carnitine-treated sow	5	191[a]	274[a,b]	292	329	271
SEM			9	18	19	22	11
Litter born to							
Control sow		10	170[b]	246[b]	277	321	253
L-Carnitine-treated sow		10	190[a]	283[a]	273	328	269
SEM			6	13	13	16	8
Litter suckled by							
Control sow		10	177	265	259	325	256
L-Carnitine-treated sow		10	183	265	291	325	266
SEM			6	13	13	16	8
Results of ANOVA, *P*							
Origin of litter			0·04	0·04	0·85	0·74	0·19
Treatment of sow during lactation			0·48	0·98	0·10	0·99	0·38
Interaction			0·22	0·31	0·79	0·93	0·71

[a,b] Mean values within a column with unlike superscript letters were significantly different ($P<0·05$).
For details of diets and procedure, see pp. 335–336.

and those born to sows supplemented with L-carnitine (Table 5). The weight gain during the entire suckling period (birth to day 28) did not differ between piglets born to control sows and those born to sows supplemented with L-carnitine (Table 5). Body weights on day 28 did not differ between piglets born to sows supplemented with L-carnitine and those born to control sows (8·88 *v.* 8·50 (SEM 0·23) kg, $P>0·05$). Litters suckled by sows supplemented with L-carnitine did not differ in their weight gains from those suckled by control sows during the entire suckling period (Table 5).

Discussion

In this study, sows were supplemented with L-carnitine during pregnancy and lactation. In both experiments, L-carnitine supplementation of the sows did not increase the weights of the litters or of individual piglets at birth. This is in disagreement with recent studies that have demonstrated, in large groups of sows, that L-carnitine supplementation significantly increased the weights of litters and of individual piglets (Musser *et al.* 1999*b*; Eder *et al.* 2001; Ramanau *et al.* 2002). We are aware that, because of the small number of sows used, the experiments presented here are not suitable to study the effects of L-carnitine on litter parameters at birth. Interestingly, in both experiments, more sows conceived in the L-carnitine group than in the control group. This finding agrees with results of a recent study that also looked at a small number of sows (Birkenfeld *et al.* 2006), suggesting that L-carnitine supplementation could improve the pregnancy rate of sows. However, no study with a larger number of sows has been performed that shows a beneficial effect of L-carnitine supplementation on pregnancy rate.

In the first experiment of the present study, piglets from sows supplemented with L-carnitine had greater body weight gains during the 28 d suckling period than did piglets from control sows. This finding agrees with our recent studies (Eder *et al.* 2001; Ramanau *et al.* 2002, 2004, 2005). Moreover, the first experiment demonstrates that the piglets of sows supplemented with L-carnitine are able to suckle for a longer time/d at 3, 6, and 9 days of age compared with the piglets of control sows.

The second experiment was designed to find out whether the beneficial effects of L-carnitine supplementation of sows on the suckling behaviour and growth of the piglets during the suckling period were induced during the piglets' prenatal or postnatal phase. We observed that piglets born to sows supplemented with L-carnitine were able to suckle for longer on day 3 and grew faster during the first 14 d of the suckling period than did piglets born to control sows, irrespective of whether they were suckled by control sows or by sows supplemented with L-carnitine. This observation demonstrates that the effects of L-carnitine supplementation during pregnancy were responsible for the higher postnatal growth of the piglets, and that L-carnitine supplementation of lactating sows did not influence the growth of the suckling piglets.

It has been shown that sows exposed to increased suckling demand, e.g. by nursing heavier piglets or nursing piglets more frequently, produce more milk (King *et al.* 1997; Auldist *et al.* 2000). More prolonged suckling by the piglets may have imposed a greater suckling demand on the sow, which may in turn have stimulated the sow's milk production. We recently observed that the piglets of sows supplemented with L-carnitine are able to obtain more milk from the sow than are the piglets of control sows (Ramanau *et al.* 2004, 2005). The present study shows that this effect is due to increased suckling activity by piglets born to sows supplemented with L-carnitine. The higher milk intake of the piglets as a result of increased suckling activity explains their higher growth rate during the suckling period.

We were unable, for technical reasons, to study the suckling behaviour of the piglets after day 9. As the piglets of sows supplemented with L-carnitine tended to have higher growth

rates than the piglets of control sows, even in the last week of the suckling period, we assume that the piglets in those litters had a more favourable suckling behaviour and a higher milk intake than the piglets of control sows after day 9 as well. It has been shown that energy and nutrient contents, as well as the fatty acid composition of the milk, do not differ between sows supplemented with L-carnitine and control sows (Ramanau *et al.* 2004, 2005). Milk composition might therefore not play a role with regard to differences in growth rate between piglets from control sows and from sows supplemented with L-carnitine. We cannot rule out the idea that the piglets of sows supplemented with L-carnitine might be suckled not only for a longer time each day but also with more vigour than the piglets of control sows. This hypothesis could not, however be tested in this study.

The finding that piglets suckled by control sows did not differ in body weight gain from piglets suckled by sows supplemented with L-carnitine demonstrates that L-carnitine supplementation did not influence the milk yield of the sow. It has been shown that the size and the milk yield of the mammary gland increases with an increasing number of fetuses. This has been linked to a greater placental lactogen level (Forsyth, 1986; Forsyth & Wallis, 2002). In a recent study, sows supplemented with L-carnitine had a significantly higher number of newborn piglets than control sows (Ramanau *et al.* 2004). The increased number of piglets could have led to increased placental lactogen levels, which could in turn have led to increased mammary gland sizes; this may have contributed to the increased milk yield observed in the sows supplemented with L-carnitine in that study. In the present study, L-carnitine supplementation did not influence the number of piglets in both experiments and probably did not influence the release of placental lactogen and the development of the mammary gland. This matches with the finding that L-carnitine supplementation did not influence the milk yield of the sows.

The present study shows that L-carnitine supplementation during lactation does not influence the suckling behaviour of the piglets and their growth during the suckling period. This observation agrees with results of Musser *et al.* (1999*a*,*b*), who studied the effects of L-carnitine supplementation during pregnancy and lactation separately. These authors showed that L-carnitine supplementation of the sows during pregnancy increased litter weight gains during the suckling period, whereas L-carnitine supplementation during lactation alone did not. There was some disagreement between the two experiments in that piglets born to sows supplemented with L-carnitine in the first experiment showed higher body weight gains during the entire 28 d suckling period, whereas in the second experiment they had higher body weight gains compared with the piglets of control sows only during the first 14 d. There could be several reasons for this discrepancy as the experimental conditions were not identical in the two experiments. Nevertheless, data from both experiments show that the L-carnitine supplementation of sows during gestation increases the weight gains of their litters during the suckling period, regardless of whether or not the sows received L-carnitine during lactation.

The reason for the increased suckling activity observed in piglets born to sows supplemented with L-carnitine is unclear. As the piglets of sows supplemented with L-carnitine did not differ from those of control sows in their initial body weights, and as litters were standardised to an identical number of piglets, the possibility that differences in litter sizes or piglet weights could play a role in influencing suckling behaviour and postnatal growth rates can be ruled out. It could be that the improved L-carnitine status at birth, as assessed by higher plasma L-carnitine concentrations, increased the suckling activity of the piglets from sows supplemented with L-carnitine.

Immediately after birth, L-carnitine plays an important role in energy production. During the intrauterine phase, the fetal supply of amino acids, glucose, minerals and fatty acids from the mother via the placenta is essential for fetal development. The rate of fatty acid oxidation in the fetus is low (Novak *et al.* 1981). Immediately after birth, however, the oxidation of fatty acids becomes important because of the discontinuation of the glucose supply and the rapid exhaustion of glycogen stores (Warshaw & Curry, 1980). Sufficient concentrations of L-carnitine in the tissues are required for the utilisation of fatty acids for energy production. L-Carnitine is required for both the release of fatty acids from adipose tissue and fatty acid utilisation (Hahn, 1982; Novak *et al.* 1975*a*,*b*). We suspect that the piglets of sows supplemented with L-carnitine were able to switch on fatty acid oxidation faster than the piglets of control sows. Greater fatty acid oxidation leads to increased energy and heat production on the part of the piglets, which might in turn have increased their suckling persistence during the first few days after birth.

However, L-carnitine status alone cannot explain the differences in suckling behaviour and body weight gain between piglets born to sows supplemented with L-carnitine and those born to control sows. If L-carnitine status alone had been responsible for suckling behaviour and growth during the suckling period, piglets suckled by sows treated with L-carnitine would have grown faster than piglets suckled by control sows, at least after the second week, because they had higher plasma L-carnitine concentrations on day 14 than piglets suckled by control sows. Yet the weight gains of the litters did not differ between piglets suckled by sows supplemented with L-carnitine and those suckled by control sows.

Musser *et al.* (1999*b*) suggested that the L-carnitine supplementation of sows increases the intrauterine nutrition and development of the fetuses. These authors also showed that piglets born to sows supplemented with L-carnitine had more muscle fibres, a greater loin depth, a higher percentage of lean and less backfat than the piglets of control sows, which might be due to higher maternal plasma concentrations of insulin-like growth factor-1 (Musser *et al.* 2000, 2001). It is conceivable that improved fetal development as a result of maternal supplementation with L-carnitine could have led to increased piglet vitality at birth, which might have been associated with increased persistence of suckling. This suggestion remains speculative, however, because we did not measure parameters of piglet vitality.

It is known that the endogenous synthesis of carnitine is extremely low in the fetus and during the first week of life, increasing thereafter (Borum, 1981; Baltzell *et al.* 1987; Coffey *et al.* 1991). Higher plasma L-carnitine concentrations at birth observed in piglets born to sows supplemented with L-carnitine might be due to an increased transplacental supply of L-carnitine to the fetuses. It has previously been shown that supplementing sows with L-carnitine increases

their plasma L-carnitine concentration (Musser *et al.* 1999*b*; Ramanau *et al.* 2004, 2005). As L-carnitine can cross the placenta, increased maternal plasma L-carnitine concentrations may lead to higher fetal plasma carnitine concentrations (Lahjouji *et al.* 2004; Grube *et al.* 2005). Higher plasma carnitine concentrations on day 14 in piglets suckled by sows supplemented with L-carnitine compared with piglets suckled by control sows might be due to a higher L-carnitine intake with the milk. The finding that the milk of sows supplemented with L-carnitine contains more L-carnitine than the milk of control sows agrees with the results of recent studies (Ramanau *et al.* 2004, 2005). Interestingly, plasma L-carnitine concentrations on day 28 were no longer different between piglets suckled by sows supplemented with L-carnitine and piglets suckled by control sows.

In conclusion, this study shows that piglets born to sows supplemented with L-carnitine are able to suckle for longer in the early suckling period, obtain more milk and grow faster during the first 14 d of life than piglets born to control sows. It has also been shown that this effect is due to supplementation of the sows with L-carnitine during gestation. The practical implication of this study is that L-carnitine must be administered to sows during gestation to obtain beneficial effects on the growth of their litters during the suckling period.

References

Auldist DE, Carlson D, Morrish L, Wakeford CM & King RH (2000) The influence of suckling interval on milk production of sows. *J Anim Sci* **78**, 2026–2031.

Auldist DE, Morrish L, Eason P & King RH (1998) The influence of litter size on milk production of sows. *Anim Sci* **67**, 333–337.

Baltzell JK, Bazer FW, Miguel SG & Borum PR (1987) The neonatal piglet as a model for human neonatal carnitine metabolism. *J Nutr* **117**, 754–757.

Bassler R & Buchholz H (1993) *Methodenbuch Band III. Die chemische Untersuchung von Futtermitteln, 3. Ergänzungslieferung*. Darmstadt: VDLUFA-Verlag.

Birkenfeld C, Doberenz J, Kluge H, Eder K (2006) Effect of L-carnitine supplementation of sows on L-carnitine status, body composition and concentrations of lipids in liver and plasma of their piglets at birth and during the suckling period. *Anim Feed Sci Technol* (Epublication ahead of print version)

Borum PR (1981) Possible carnitine requirement of the newborn and the effect of genetic disease on the carnitine requirement. *Nutr Rev* **39**, 385–390.

Coffey TM, Shireman RB, Herman DL & Jons EE (1991) Carnitine status and lipid utilization in neonatal piglets fed diets low in carnitine. *J Nutr* **121**, 1047–1053.

Eder K, Ramanau A & Kluge H (2001) Effect of L-carnitine supplementation on performance parameters in gilts and sows. *J Anim Physiol Anim Nutr* **85**, 73–80.

Forsyth IA (1986) Variation among species in the endocrine control of mammary growth and function: the roles of prolactin, growth hormone, and placental lactogen. *J Dairy Sci* **69**, 886–903.

Forsyth IA & Wallis M (2002) Growth hormone and prolactin-molecular and functional evolution. *J Mamm Gland Biol Neopl* **7**, 291–312.

Gesellschaft für Ernährungsphysiologie (Ausschuß für Bedarfsnormen) (1987) *Energie- und Nährstoffbedarf landwirtschaftlicher Nutztiere, Nr. 4 Schweine*, pp. 30–43. Frankfurt/Main: DLG-Verlag.

Grube M, Schwabedissen HM, Draber K, Prager D, Moritz KU, Linnemann K, Fusch C, Jedlitschky G & Kroemer HK (2005) Expression, localization, and function of the carnitine transporter octn2 (slc22a5) in human placenta. *Drug Metabol Dispos* **33**, 31–37.

Hahn P (1982) Development of lipid metabolism. *Annu Rev Nutr* **2**, 91–111.

King RH, Mullan BP, Dunshea FR & Dove H (1997) The influence of piglet body weight on milk production of sows. *Livest Prod Sci* **47**, 169–174.

Lahjouji K, Elimrani I, Lafond J, Leduc L, Qureshi IA & Mitchell GA (2004) L-carnitine transport in human placental brush-border membranes is mediated by the sodium-dependent organic cation transporter OCTN2. *Am J Physiol Cell Physiol* **287**, C263–C269.

McGarry JD & Foster DW (1976) An improved and simplified radioisotopic assay for the determination of free and esterified carnitine. *J Lip Res* **17**, 277–281.

Musser RE, Dritz SS, Goodband RD, Tokach MD, Davis MD, Nelssen JL, Owen KQ, Hanni S, Bauman JS & Heintz M (2000) Added L-carnitine in sow gestation diet improves carcass characteristics of the offspring. *J Anim Sci* **78**, Suppl. 2, 30.

Musser RE, Goodband RD, Owen KQ, Davis MD, Tokach MD, Dritz SS & Nelssen JL (2001) Determining the effect of increasing L-carnitine additions on sow performance and muscle fiber development of the offspring. *J Anim Sci* **79**, Suppl. 2, 65.

Musser RE, Goodband RD, Tokach MD, Owen KQ, Nelssen JL, Blum SA, Campbell RG, Smits R, Dritz SS & Civis CA (1999*a*) Effects of L-carnitine fed during lactation on sow and litter performance. *J Anim Sci* **77**, 3296–3303.

Musser RE, Goodband RD, Tokach MD, Owen KQ, Nelssen JL, Blum SA, Dritz SS & Civis CA (1999*b*) Effects of L-carnitine fed during gestation and lactation on sow and litter performance. *J Anim Sci* **77**, 3289–3295.

Novak M, Monkus EF, Chung D & Buch M (1981) Carnitine in the perinatal metabolism of lipids. I. Relationship between maternal and fetal plasma levels of carnitine and acylcarnitines. *Pediatrica* **67**, 95–100.

Novak M, Penn-Walker D, Hahn P & Monkus EF (1975*a*) Effect of carnitine on lipolysis in subcutaneous adipose tissue of newborns. *Biol Neonate* **25**, 84–94.

Novak M, Penn-Walker D & Monkus EF (1975*b*) Oxidation of fatty acids by mitochondria obtained from newborn subcutaneous (white) adipose tissue. *Biol Neonate* **25**, 95–107.

Pluske JR & Dong GZ (1998) Factors influencing the utilization of colostrums and milk. In *The Lactating Sow*, pp. 45–70 [MWA Verstegen, PJ Moughan and JW Schrama, editors]. Wageningen, The Netherlands: Wageningen Pers.

Ramanau A, Kluge H & Eder K (2005) Effects of L-carnitine supplementation on milk production, litter gains and backfat thickness in sows with a low energy and protein intake during lactation. *Br J Nutr* **93**, 717–721.

Ramanau A, Kluge H, Spilke J & Eder K (2002) Reproductive performance of sows supplemented with dietary L-carnitine over three reproductive cycles. *Arch Anim Nutr* **56**, 287–296.

Ramanau A, Kluge H, Spilke J & Eder K (2004) Supplementation of sows with L-carnitine during pregnancy and lactation improves growth of the piglets during the suckling period through increased milk production. *J Nutr* **134**, 86–92.

Spinka M, Illmann G, Algers B & Stetkova Z (1997) The role of nursing frequency in milk production in domestic pigs. *J Anim Sci* **75**, 1223–1228.

Warshaw JB & Curry E (1980) Comparison of serum carnitine and ketone body concentrations in breast- and in formula-fed newborn infants. *J Pediatr* **97**, 122–125.