Available online at www.sciencedirect.com
ScienceDirect
Livestock Science 116 (2008) 63–69
LIVESTOCK SCIENCE
www.elsevier.com/locate/livsci

Additive effects of L-carnitine and chromium picolinate on sow reproductive performance☆

D.E. Real [a], J.L. Nelssen [a], M.D Tokach [a], R.D Goodband [a,*], S.S. Dritz [a,1], J.C. Woodworth [a], K.Q. Owen [b]

[a] *Department of Animal Sciences and Industry, Kansas State University, Manhattan, 66506-0201, United States*
[b] *Lonza, Inc., Allendale, NJ 0741, United States*

Received 18 January 2007; received in revised form 30 July 2007; accepted 21 August 2007

Abstract

A total of 599 sows were used to determine the effects of added L-carnitine with or without chromium picolinate on reproductive performance. Experimental treatments were arranged in a 2×2 factorial with main effects of added L-carnitine and chromium picolinate. Starting on the first day of breeding, sows were provided a daily top dress containing the carnitine with or without chromium along with the standard gestation or lactation diet. The top dress was formulated to provide 90 mg/d and 250 mg/d of L-carnitine in gestation and lactation, respectively. Chromium from chromium picolinate was provided at 360 μg/d and 1000 μg/d during gestation and lactation, respectively. These inclusions were calculated to provide 50 mg/kg of carnitine and 200 μg/kg of chromium when sows were fed 1.8 kg/d of the gestation diet and an estimated 5.0 kg/d of the lactation diet (actual lactation feed intake was not recorded). Dietary treatments were administered daily through the initial gestation and lactation (parity 1), and a second gestation period (parity 2). At farrowing all pigs were cross-fostered across dietary treatments. During the first parity, there was a carnitine×chromium interaction ($P<0.01$) for first service farrowing rate. Added dietary chromium increased ($P<0.01$) first service farrowing rate, but there was no further increase when carnitine was added. No differences ($P>0.05$) were observed in number of pigs born alive, stillborn, mummies, or total born in the first or second parity. Added dietary L-carnitine decreased ($P<0.05$) wean to estrus interval, and tended to increase ($P<0.08$) the number of sows in estrus by d 7. In the second parity, supplementing both carnitine and chromium tended to improve (carnitine×chromium interaction, $P<0.08$) farrowing rate. Based on all sows that started on test, for the two-parity period both added carnitine and chromium increased ($P<0.01$) the number of pigs born and born alive. These results show that carnitine and chromium supplementation additively increased farrowing rate and thus total number born alive over two parities.

Keywords: Carnitine; Chromium; Farrowing rate; Fecundity; Sows

1. Introduction

Carnitine is a water soluble, vitamin-like compound that functions to transport fatty acids across the mitochondria membrane where they undergo β-oxidation to produce energy. Previous research has shown that

☆ Contribution no. 02-206-J from the Kansas Agric. Exp. Sta., Manhattan 66506.

* Corresponding author. 242 Weber Hall. Tel.: +1 785 532 1228; fax: +1 785 532 7059.
E-mail address: Goodband@KSU.edu (R.D. Goodband).
[1] Food Animal Health and Management Center, College of Veterinary Medicine, Kansas State University.

1871-1413/$ - see front matter © 2007 Elsevier B.V. All rights reserved.
doi:10.1016/j.livsci.2007.08.009

carnitine is effective in decreasing lipid accretion rate (Owen et al., 1996). However, carnitine may play a greater role in metabolism than just fatty acid transport (Owen et al., 2001). Recent studies have observed that dietary L-carnitine fed during gestation and lactation increased the number of pigs born live (Musser et al., 1999b), number of pigs weaned (Eder et al., 2001), and litter weight gain (Ramanau et al., 2004).

Chromium is a trace mineral that is actively involved in the metabolism of carbohydrates, lipids, proteins, and nucleic acids in the body. Chromium potentiates insulin action resulting in increased cellular uptake of glucose and improved intracellular carbohydrate and lipid metabolism. Studies have shown that feeding chromium in gestation and lactation increased number of piglets born alive (Lindemann et al., 1995b; Hagen et al., 2000). Because both of these nutrients influence sow reproductive performance, the objective of this study was to compare carnitine and chromium on sow reproductive performance. In addition, a second objective was to determine if the responses to carnitine and chromium were additive.

2. Materials and methods

2.1. Animals and housing

Sows ($n=599$ PIC Line C22, Franklin, KY, USA) were used on a commercial 1500-sow, farrow-to-wean operation in central Kansas. The experiment began in January and ended in November. Average parity at the start of the study was 4.5± 2.9. Historically, the farm average farrowing rate was approximately 88–90% (lower during the summer) with 10 piglets born alive and 9 weaned. Sow last rib fat depth averaged approximately 17 mm (personal communication from the farm manager) and body condition score was taken into account during randomization to dietary treatment. The sows were followed over two consecutive parities. The farm followed animal care guidelines set forth by FASS (1999). Sows were housed in crates (0.61×2.13 m) in a double curtain sided barn during gestation. Dietary treatments were randomly assigned to sows on the first day of breeding. Dietary treatments were not provided at this time to pregnant or lactating sows (i.e., the whole farm was not put on test, just sows bred on or after the first day of breeding the week the trial was begun). Sows later found to have a previous lactation length less than 10 d were deleted from the data set. Only sows bred immediately after weaning were used (i.e., those bred, detected open, then rebred during the experimental period were deleted). This is referred to as first service farrowing rate. On approximately d 112 of gestation, sows were moved to farrowing crates (0.61×2.13 m for sows, 0.89×2.13 m additionally for pigs) in an environmentally controlled room for parturition. Pigs were weaned after approximately 15 d of lactation and sows were returned to gestation crates to be rebred for parity 2. Each sow remained on the same treatment through the first gestation and lactation (parity 1) and through a second gestation period (parity 2). Sows were not fed dietary treatments during the second lactation period.

Pregnant sows were fed a common grain sorghum–soybean meal-based diet formulated to contain 6.5 g/kg lysine, 8.3 g/kg Ca, and 7.6 g/kg P (Table 1). In lactation, all sows were fed a grain sorghum–soybean meal-based diet formulated to contain 11 g/kg lysine, 9 g/kg Ca, and 8 g/kg P. Dietary treatments were provided via a maize-based top dress fed at 30 g/d (Table 1). The top dress was formulated to provide 90 mg/d and 250 mg/d of L-carnitine in gestation and lactation, respectively. Chromium from chromium picolinate was provided at 360 μg/d and 1000 μg/d during gestation and lactation, respectively. These inclusions were calculated to provide 50 mg/kg of added L-carnitine and 200 μg/kg of added chromium when sows were fed 1.8 kg/d of the gestation diet and 5.0 kg/d of the lactation diet. The inclusion rate for L-carnitine was based on data by Musser et al. (1999a,b) and that for chromium by Hagen et al. (2000). Sows were fed 1.8 kg/d in gestation and ad libitum during lactation. Sow lactation feed intake was not recorded because of the large

Table 1
Diet composition[a]

Ingredient, g/kg	Gestation[b]	Lactation[c]
Diet		
Grain sorghum	801.7	641.0
Soybean meal (46.5%)	156.8	317.5
Monocalcium Phosphate, 21% P	20.0	19.0
Limestone	10.0	11.0
Salt	5.0	5.0
Vitamin and trace mineral premix[d]	6.5	6.5
Top dress[e]		
Maize[f]	990	990
Maize cobs[g]	10	10

[a] All sows fed similar basal diet.
[b] Sows were fed 1.8 kg/d gestation diet; (6.5 g/kg lysine, 8.3 g/kg Ca, and 7.6 g/kg P).
[c] Sows were allowed ad libitum consumption of the lactation diet; (11.0 g/kg lysine, 9.0 g/kg Ca, and 8.0 g/kg P).
[d] Provided 11,000 IU vitamin A (retinyl acetate), 1650 IU vitamin D_3, 44 IU vitamin E (DL alpha tocophorol), 4.4 mg menadione (menadione dimethylpryimidinol bisulfate), 44 μg vitamin B_{12} (cyanocobalamine), 9.9 mg riboflavin, 33 mg pantothenic acid (D-calcium pantothenate), 55 mg niacin (niacinamide), 165 mg zinc (oxide), 165 mg iron (sulfate), 40 mg manganese (oxide), 16.5 mg copper (sulfate), 297 μg iodine (Ca iodate), 297 μg selenium (Na selenite), 550 mg choline (choline chloride), 220 μg biotin, 1.65 mg folic acid, and 15 mg pyridoxine (pyridoxine HCl) per kg of diet.
[e] Fed to sows 30 g/d with the daily feed allotment.
[f] L-carnitine and/or chromium picolinate replaced maize to achieve dietary supplementation of 90 mg/d of carnitine and 360 μg/d of chromium in gestation, 250 mg/d of carnitine and 1000 μg/d of chromium in lactation.
[g] Colored maize cobs were added to distinguish treatments.

number of sows on test. The top dress was color coded by treatment to assure proper distribution of experimental treatments. The control top dress was 100% maize (yellow) and the top dress for each of the other treatments had 10 mg/kg colored maize cobs (red, blue, or green) for the treatments containing carnitine, chromium, or both. In gestation, the top dress was added to the feed box between meals in order to be dropped into the individual feeder with the rest of the daily feed allocation. It was observed that the gestation feed allowance was consumed within the 15 min after feeding. In lactation, the top dress was provided with the morning feeding. Although sows were fed ad libitum during lactation, the morning feeding was restricted so that the meal was consumed within 15 min.

At farrowing, the total number of pigs born, born alive, stillborn, and born mummified were recorded. After these were recorded, pigs were cross-fostered across dietary treatment to equalize the number of pigs per sow. Because of this equalization we did not analyze number of pigs weaned. With the relatively large number of sows farrowing each week (50 to 60), we anticipated cross-fostering to result in equalization of litter size across treatments, thus minimizing any potential impact of initial litter size differentially affecting subsequent reproductive performance. Sows were rebred after weaning and remained on the same treatment until farrowing a second litter. If a sow did not return to estrus within 18 days, she was removed from the experiment (Table 2) because sows that have been allowed to skip at least one estrus cycle before breeding after weaning have been shown to have improved reproductive performance (Leman, 1992). Sows that were bred at the start of the study, but later were found open, were removed from test when estrus was detected. Procedures and data collection were identical for the second gestation and lactation period. However, dietary treatments were not administered during the second lactation period.

The total number of pigs born, born alive, stillborn, or mummified were summed over both parities for each sow. Calculations were made to determine the total number of pigs born, born alive, as stillborns, or as mummies per sow for the two parities. Total number of pigs were calculated using only sows that initially farrowed, then completed the second parity, as well as calculated from all the sows that were actually started on test.

2.2. Statistical analysis

Experimental treatments were arranged in a 2×2 factorial with main effects of added L-carnitine and chromium picolinate. The effects of L-carnitine, chromium picolinate and their interactions were tested. Data were analyzed using the MIXED procedure of SAS (SAS Inst. Inc., Cary, NC). Sow was the experimental unit for the analysis with parity and previous lactation length used as a covariate for total number of pigs born, born alive, stillborn, or born mummified. The distribution of values for wean to estrus interval was skewed to the right. In order to more closely approximate a normal distribution the data for wean to estrus interval was transformed using an inverse of the value for analysis. A chi-square statistic was calculated to determine differences among treatments when analyzing percentage in estrus and farrowing rate. Response criteria with a P-value of 0.05 or less were considered a significant difference and those with a P-value on 0.10 to 0.06 were considered trends.

3. Results

In parity 1, a carnitine×chromium interaction ($P<0.01$) was observed for first service farrowing rate (Table 3). Added dietary chromium improved ($P<0.01$) first service farrowing rate, but there was no further benefit from adding carnitine to the diet. There were no differences ($P>0.10$) in total number of pigs born, born alive, or born mummified. However, sows fed added chromium tended to have increased ($P<0.07$) number of stillborn pigs/litter. Adding dietary carnitine improved ($P<0.05$) wean to estrus interval and tended to increase ($P<0.08$) the number of sows in estrus by d 7.

Table 2
Reasons and numbers of sows that failed to farrow or were removed from test

Reason	Treatment			
	Control	Carnitine[a]	Chromium[b]	Both[a, b]
Parity 1				
Failure to farrow after determined pregnant on d 25 after breeding	25	12	7	12
Parity 2				
Culled for lameness or poor health	6	4	3	1
Returned to estrus after d 18 post weaning	9	8	8	7
Failure to conceive after breeding	11	12	14	7
Failure to farrow after determined pregnant on d 25 after breeding	10	12	11	5

[a] The top dress was formulated to provide 90 mg/d and 250 mg/d of L-carnitine in gestation and lactation, respectively.
[b] The top dress was formulated to provide 360 μg/d and 1000 μg/d of chromium from chromium picolinate during gestation and lactation, respectively.

Table 3
Effects of L-carnitine and chromium picolinate on reproductive performance (first parity)[a]

Item	Treatment				SEM	Probabilities, $P <$		
	Control	Carnitine[b]	Chromium[c]	Both[b, c]		Carnitine	Chromium	Interaction
No. of sows								
Started on test	148	150	147	154				
Farrowed	123	138	140	142				
First service farrowing rate, %[d, e]	82.9	91.9	95.5	92.2	2.38	0.22	0.01	0.01
No. of pigs								
Total born[d]	11.3	11.5	11.5	11.6	0.28	0.62	0.57	0.90
Born alive[d]	10.0	10.2	9.8	10.2	0.25	0.32	0.63	0.71
Stillborn[d]	0.95	0.98	1.26	1.13	0.120	0.68	0.07	0.52
Mummies[d]	0.34	0.26	0.39	0.34	0.060	0.26	0.29	0.77
Wean to estrus interval[f, g]	4.9	4.6	4.7	4.5	0.15	0.05	0.23	0.75
Sows in estrus by d 7, %[d, e]	84.8	88.6	86.7	92.3	2.88	0.08	0.31	0.73
Sows in estrus by d 18, %[d, e]	88.1	91.5	91.7	94.4	2.49	0.20	0.17	0.89

[a] Initially 599 sows bred.
[b] The top dress was formulated to provide 90 mg/d and 250 mg/d of L-carnitine in gestation and lactation, respectively.
[c] The top dress was formulated to provide 360 μg/d and 1000 μg/d of chromium from chromium picolinate during gestation and lactation, respectively.
[d] Parity was used as a covariate.
[e] *P*-values from chi-square statistic.
[f] Wean to estrus interval analyzed as inverse of means.
[g] Previous lactation length used as a covariate.

In parity 2, feeding additional dietary carnitine and chromium tended to improve (carnitine × chromium interaction $P<0.08$) first service farrowing rate of sows compared to sows fed the control diet, or carnitine or chromium separately (Table 4). In parity 2, there were no differences ($P>0.19$) among treatments for total number of pigs born, born alive, stillborn, or born mummified. There were also no differences ($P>0.14$)

Table 4
Effects of L-carnitine and chromium picolinate on reproductive performance (second parity)[a]

Item	Treatment				SEM	Probabilities, $P <$		
	Control	Carnitine[b]	Chromium[c]	Both[b, c]		Carnitine	Chromium	Interaction
Started on test	123	138	140	142				
Bred by d 18	108	126	129	134				
Farrowed	87	102	104	122				
First service farrowing rate, %[d, e]	80.7	81.0	80.5	91.1	3.55	0.07	0.20	0.08
Percentage of weaned parity 1 sows that farrowed parity 2[d, e]	70.7	73.9	74.3	85.9	3.84	0.04	0.03	0.24
No. of pigs								
Total born[d]	11.1	11.3	11.0	11.3	0.34	0.57	0.90	0.78
Born alive[d]	9.7	9.9	9.5	9.8	0.30	0.60	0.65	0.86
Stillborn[d]	1.02	1.02	1.09	1.31	0.140	0.43	0.19	0.45
Mummies[d]	0.35	0.33	0.40	0.25	0.065	0.22	0.88	0.29
Second parity								
Wean to estrus interval[f, g]	4.6	4.7	4.6	4.8	0.12	0.14	0.94	0.46
% in estrus by d 7[d, e]	80.3	76.9	81.0	75.0	4.32	0.23	0.88	0.75
% in estrus by d 18[d, e]	80.3	80.8	82.9	75.9	4.17	0.40	0.77	0.32

[a] Five hundred and forty three sows bred out of 599 sows initially bred in parity one.
[b] The top dress was formulated to provide 90 mg/d and 250 mg/d of L-carnitine in gestation and lactation, respectively.
[c] The top dress was formulated to provide 360 μg/d and 1000 μg/d of chromium from chromium picolinate during gestation and lactation, respectively.
[d] Parity was used as a covariate.
[e] *P*-values from chi-square statistic.
[f] Wean to estrus interval analyzed as inverse of means.
[g] Previous lactation length used as a covariate.

Table 5
Effects of L-carnitine and chromium picolinate on reproductive performance (first and second parity combined)[a]

Item	Treatment				SEM	Probabilities, $P <$		
	Control	Carnitine[b]	Chromium[c]	Both[b, c]		Carnitine	Chromium	Interaction
Total pigs per sow for sows that completed parity one								
Total born[d, e]	19.4	19.8	19.5	21.2	0.56	0.04	0.15	0.25
Born alive[d, e]	17.1	17.9	16.8	18.4	0.53	0.04	0.60	0.23
Still born[d]	1.7	1.7	2.1	2.3	0.19	0.46	0.01	0.66
Mummies[d]	0.6	0.5	0.7	0.6	0.08	0.17	0.43	0.85
Total pigs per sow of all sows started on test for two parities								
Total born[d, e]	15.8	18.5	18.8	19.7	0.70	0.01	0.003	0.25
Born alive[d, e]	13.9	16.3	16.2	17.0	0.63	0.01	0.02	0.23
Stillborn[d]	1.4	1.6	2.0	2.1	0.17	0.35	0.002	0.94
Mummies[d]	0.5	0.5	0.7	0.5	0.71	0.27	0.16	0.42

[a] Initially 599 sows bred.
[b] The top dress was formulated to provide 90 mg/d and 250 mg/d of L-carnitine in gestation and lactation, respectively.
[c] The top dress was formulated to provide 360 μg/d and 1000 μg/d of chromium from chromium picolinate during gestation and lactation, respectively.
[d] Parity was used as a covariate.
[e] Week of farrowing used as a covariate.

among treatments for wean to estrus interval or percentage of sows returning to estrus by d 7 or 18.

When calculating the total number of pigs born, born alive, stillborn, and born mummified over the entire trial for those sows that farrowed in parity one ($n=123$, 138, 140, and 142, for control, added carnitine, added chromium, and both, respectively), this resulted in sows fed added carnitine having more ($P<0.04$) total pigs, and pigs born alive, and sows fed added chromium having more ($P<0.01$) stillborn pigs (Table 5). When calculating the total number of pigs born, born alive, stillborn, and born mummified using all the sows that were started on test ($n=147$ to 154 sows per treatment), total pigs and pigs born alive were increased ($P<0.02$) for sows fed added carnitine and/or chromium. The number of pigs stillborn was increased ($P<0.02$) in sows fed added chromium. No carnitine × chromium interactions ($P>0.10$) were observed for these response criteria.

4. Discussion

In parity 1, all sows were bred during the winter months and in parity 2 all sows were bred during the summer months. However, within parity, an equal number of sows were bred each week in order to avoid any confounding effect of environmental temperature. In parity 1, a high number of control sows failed to farrow after they were determined pregnant on d 25 of gestation (Table 2). This indicates that they conceived but failed to maintain their pregnancy. This resulted in a lower farrowing rate compared with sows fed carnitine, chromium, or both. We have no explanation for what appears to be a higher than average number of control sows determined not pregnant after d 25; however, any season, health, or management influences would have been spread across all treatment groups. The improved farrowing rate of sows fed chromium is similar to results of Campbell (1996) who also observed improvements in farrowing rate in sows fed chromium.

In general, farrowing rates were higher in parity 1 than in parity 2, with the exception of those sows fed both carnitine and chromium in parity 2. Despite a lower average farrowing rate in parity 2, the response to carnitine and chromium appears to be additive. This is the result of fewer sows (approximately 50% less, Table 2) that failed to conceive and failed to farrow after confirmed pregnant on d 25. The differences in farrowing rate between parity 1 and 2 could be attributed to differences in season and parity (Hurtgen et al., 1980).

Because there were no carnitine × chromium interactions for the percentage of sows weaned in parity 1 that farrowed in parity 2, or in the total number of pigs for all sows started on test for the two parities, these two nutrients may be working via different mechanisms to improve reproductive performance.

Although we did not measure plasma metabolite criteria in our study, data of Woodworth et al. (in press) supports the concept of different mechanisms. In their study chromium appeared to influence glucose and insulin concentrations immediately after feeding, whereas carnitine appeared to influence NEFA concentrations 6 to 24 h after feeding as well as IGF-1 concentrations. In addition, feeding L-carnitine, but not chromium tripicolinate elevated the concentration of circulating

leptin in gestating sows (Woodworth et al., 2004). The elevated leptin concentrations suggest that feeding carnitine will influence the biochemical pathways involved in energy metabolism.

Musser et al. (1999a) fed sows 50 mg/kg of carnitine during lactation and reported minimal differences in farrowing rate, or in total number of pigs born or born alive in three different experiments. Similar results have been observed in more recent studies (Ramanau et al., 2004). Musser et al. (1999b) reported that adding L-carnitine to gestating sow diets had no effect on farrowing rate, but showed an increase in number of pigs born alive in the subsequent parity. The authors also reported no differences in wean to estrus intervals. We have no explanation for why their results differed from the responses observed in our experiments; however, this is not atypical among studies evaluating the response to various nutrients in gestation and lactation diets. For example, Eder et al. (2001) and Ramanau et al. (2002) observed no change in litter size, but increased sow weight gain in gestation and increased pig weight at weaning in sows fed L-carnitine in gestation and lactation. Lindemann et al. (1995b) and Hagen et al. (2000) reported increases in number of pigs born alive with no effects on farrowing rate when adding 200 μg/kg of chromium whereas Campbell (1996) observed only improvements in farrowing rate.

Differences in feed intake during lactation could contribute to changes in reproductive performance. In our study we did not record lactation feed intake because of the large number of sows on test; however, previous studies have shown neither chromium nor L-carnitine to affect lactation feed intake (Lindemann et al., 1995b; Musser et al., 1999a,b). A second possible variable we did not record that could contribute to the interpretation of our results is the effects of litter size on subsequent reproductive performance. Sows nursing large litters may catabolize more body lipid and protein than those nursing small litters, and therefore may have poorer reproductive performance in the subsequent farrowing. In our study we decided to equalize litter size across dietary treatments. With the large number of sows farrowing each week (50 to 60) we anticipated cross-fostering to result in equalization of litter size across treatments, thus minimizing any potential impact of initial litter size differentially affecting subsequent reproductive performance. Overall average number of pigs weaned was 8.84 and 9.03 pigs in parities 1 and 2, respectively.

Musser et al. (1999b) and Ramanau et al. (2004) observed that adding carnitine to the gestation diet improved nutrient utilization. This has also been shown in nursery (Real et al., 2001; Rincker et al., 2003) and grow-finishing pigs (Owen et al., 1993). Owen et al. (1996) reported decreases in daily fat accretion when adding dietary carnitine, potentially by increasing β-oxidation of fatty acids. Gestating sows are generally fed diets that contain low amounts of fat once a day. After all nutrients from the digestive tract have been absorbed, added carnitine could improve the utilization of lipids from body stores, leaving glucose needed for fetal growth. Additionally, increasing the energy density of the diet has been associated with improvements in ovulation rate (Flowers et al., 1989). Therefore, additional dietary carnitine could improve ovulation rate by improving the energy status of the sow.

Several studies have investigated chromium supplementation in sow diets. Lindemann et al. (1995b) and Hagen et al. (2000) reported increases in number of pigs born alive with no effects on farrowing rate when adding 200 μg/kg of chromium. Lindemann et al. (1995b) reported this increase in sows over two parities and also reported increases in total number of pigs born, and gestational weight gain. In a follow up study, Lindemann et al. (1995a) reported no improvements in number of pigs born or born alive. Similarly, our study showed no improvements in number born alive, but we did find increases in farrowing rate and tendencies to increase number of stillborn pigs per litter. Campbell (1996) reported improvements in farrowing rate in two experiments, but not in a third trial. These different responses were attributed to differences in inherent fertility of the herds, as control sows in the third experiment had reproductive performance similar to that of supplemented sows in the first two experiments.

5. Conclusion

Supplementing gestation and lactation diets with added L-carnitine and chromium had minimal effects on number of pigs born alive per litter; however, the improvement in farrowing rate observed during both parities resulted in greater overall number of pigs born. These data suggest that improvements in reproductive performance from the two nutrients may be additive. Additional research is needed to verify the biological mechanisms L-carnitine and chromium improve sow productivity.

References

Campbell, R.G., 1996. The effects of chromium picolinate on the fertility and fecundity of sows under commercial conditions. Proc. 16th Annual Prince Feed Ingredient Conf., Quincy, IL, pp. 33–38.

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.

FASS, 1999. Guide for the care and use of agricultural animals in agricultural research and teaching. 1st rev. ed. Fed. Anim. Sci. Soc, Savoy, IL.

Flowers, B., Martin, M.J., Cantley, T.C., Day, B.N., 1989. Endocrine changes associated with a dietary-induced increase in ovulation rate (flushing) in gilts. J. Anim. Sci. 67, 771–778.

Hagen, C.D., Lindemann, M.D., Purser, K.W., 2000. Effect of dietary chromium tripicolinate on productivity of sows under commercial conditions. Swine Health Prod. 8, 59–63.

Hurtgen, J.P., Leman, A.D., Crabo, B., 1980. Seasonal influence on estrous activity in sows and gilts. J. Am. Vet. Med. Assoc. 176, 119–123.

Leman, A.D., 1992. Optimizing farrowing rate and litter size and minimizing nonproductive sow days. Veterinary Clinics of North America: Food Animal Practice, 8, pp. 609–621.

Lindemann, M.D., Harper, A.F., Kornegay, E.T., 1995a. Further assessment of the effects of the supplementation of chromium from chromium picolinate on fecundity in swine. J. Anim. Sci. 73 (Suppl. 1), 185 (Abstr.).

Lindemann, M.D., Wood, C.M., Harper, A.F., Kornegay, E.T., Anderson, R.A., 1995b. Dietary chromium picolinate additions improve gain:feed and carcass characteristics in growing–finishing pigs and increase litter size in reproducing sows. J. Anim. Sci. 73, 457–465.

Musser, R.E., Goodband, R.D., Tokach, M.D., Owen, K.Q., Nelssen, J.L., Blum, S.A., Campbell, R.G., Smits, R., Dritz, Civis, C.A., 1999a. Effects of L-carnitine fed during lactation on sow and litter performance. J. Anim. Sci. 77, 3296–3303.

Musser, R.E., Goodband, R.D., Tokach, M.D., Owen, K.Q., Nelssen, Blum, S.A., Dritz, S.S., Civis, C.A., 1999b. Effects of L-carnitine fed during gestation and lactation on sow and litter performance. J. Anim. Sci. 77, 3289–3295.

Owen, K.Q., Weeden, T.L., Nelssen, J.L., Blum, S.A., Goodband, R.D., 1993. The effect of L-carnitine additions on performance and carcass characteristics of growing–finishing swine. J. Anim. Sci. 71 (Suppl. 1), 62 (Abstr.).

Owen, K.Q., Nelssen, J.L., Goodband, R.D., Weeden, T.L., Blum, S.A., 1996. Effect of L-carnitine and soybean oil on growth performance and body composition of early-weaned pigs. J. Anim. Sci. 74, 1612–1619.

Owen, K.Q., Ji, H., Maxwell, C.V., Nelssen, J.L., Goodband, R.D., Tokach, Tremblay, G.C., Koo, S.I., 2001. Dietary L-carnitine suppresses mitochondrial branched-chain keto acid dehydrogenase activity, and enhances protein accretion and carcass characteristics of swine. J. Anim. Sci. 79, 3104–3112.

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.

Real, D.E., Steidinger, M.U., Nelssen, J.L., Tokach, M.D., Goodband, R.D., Dritz, S.S., DeRouchey, J.M., Woodworth, J.C., Owen, K.Q., 2001. Effects of dietary L-carnitine on growth performance of nursery pigs. J. Anim. Sci. 79 (Suppl. 2), 82 (Abstr.).

Rincker, M.J., Carter, S.D., Real, D.E., Nelssen, J.L., Tokach, M.D., Goodband, R.D., Dritz, S.S., Senne, B.W., Fent, R.W., Pettey, L.A., Owen, K.Q., 2003. Effects of increasing dietary L-carnitine on growth performance of weanling pigs. J. Anim Sci. 81, 2259–2269.

Woodworth, J.C., Minton, J.E., Tokach, M.D., Nelssen, J.L., Goodband, R.D., Dritz, S.S., Koo, S.I., Owen, K.Q., 2004. Dietary L-carnitine increases plasma leptin concentrations of gestating sows fed one meal per day. Domest. Anim. Endocrinol. 26, 1–9.

Woodworth, J.C., Tokach, M.D., Nelssen, J.L., Goodband, R.D., Dritz, S.S., Koo, S.I., Minton, J.E., Owen, K.Q., in press. Influence of dietary L-carnitine and(or) chromium picolinate on blood hormones and metabolites of gestating sows fed one meal per day. J. Anim. Sci. doi:10.2527/jas.2006-284.