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Performance, Nutrient Digestibility and Nutrient Balance in Weaned Pigs Fed Diets Supplemented with Antibiotics or Zinc Oxide

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Abstract: An issue with feeding pharmacological levels of zinc to pigs is that application of their manure to soil can negatively impact the environment and therefore, it would be desirable if the beneficial effects of feeding zinc oxide could be obtained at lower levels of zinc supplementation. Three experiments were conducted to determine the effects of feeding a basal diet fed without supplementation (negative control) or the basal diet supplemented with either an antibiotic combination (33 ppm tiamulin and 100 ppm chlortetracycline; positive control), as well as 1500 or 2500 ppm zinc on performance, nutrient digestibility and zinc balance in weaned pigs. Two growth trials demonstrated improved performance for pigs fed zinc supplemented diets compared with the negative control. In both experiments, the performance of pigs fed zinc supplemented diets was essentially equal to that of the antibiotic supplemented pigs indicating that zinc can substitute for antibiotics in diets fed to nursery pigs. In addition, our data indicate that feeding 1500 ppm zinc resulted in similar performance to feeding 2500 ppm zinc. There was no effect of dietary zinc or antibiotic addition on the digestibility of dry matter, crude protein, calcium, phosphorus or energy. The concentration of zinc in feces was significantly higher for the zinc supplemented pigs than for pigs fed either the negative control or the antibiotic supplemented diet. However, the concentration of zinc in the feces of pigs fed 1500 ppm zinc was approximately half that of pigs fed 2500 ppm zinc. Our finding that feeding 1500 ppm zinc supported a similar level of performance as 2500 ppm zinc, while significantly reducing fecal zinc excretion indicates that it may be possible to reduce the levels of zinc in nursery diets without having to sacrifice performance while, lessening the environmental impact of manure disposal.

Key words: Piglets, zinc, performance, digestibility, excretion, tissue

INTRODUCTION

Zinc is an essential nutrient for all swine (NRC, 1998). Zinc has a functional role in metalloenzymes such as zinc hydrolases, lyases, isomerases, transferases and ligases (Hill and Spears, 2001). Other roles for zinc include membrane and cytoskeletal stabilization (Hambidge *et al*., 1985), acid-base balance (Payne *et al*., 2006) and hormone structure (Hill and Spears, 2001). In rapidly growing tissues, zinc deficiency usually retards the synthesis of DNA, RNA and protein and hence, impairs growth (Sandstead and Evans, 1984). Dietary zinc deficiency also impairs overall immune function and resistance to infection by suppressing thymic function, T-lymphocyte development and lymphocyte proliferation (Prasad, 2007; Walker and Black, 2004).

Due to concerns about residues in animal products and the potential development of bacterial resistance to antibiotics, the possibility exists for the implementation of a complete ban in the use of antibiotics in animal feed. As a consequence, the development of alternatives to antibiotics is receiving considerable attention (Turner *et al*., 2001). Pharmacological concentrations of zinc in the form of zinc oxide are commonly added to nursery pig diets because they improve pig performance (Poulsen, 1995; Smith *et al*., 1997; Hill *et al*., 2000) and reduce the incidence of diarrhea after weaning (Kavanagh, 1992). These responses have been achieved at dietary concentrations of 2000-4000 ppm zinc.

An issue with feeding pharmacological levels of zinc to pigs is that application of their manure to soil can neg-atively impact the environment (Berenguer *et al*.,

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2008). Pigs fed 3000 ppm added zinc excreted almost four times more zinc in their feces as pigs fed 500 ppm zinc (Case and Carlson, 2002). Zinc accumulation in the soil has been implicated in reducing plant growth (Chaney, 1993), while leaching of zinc from soils treated with swine manure may lead to pollution of lakes, streams and costal waters (Li and Shuman, 1997; Hsu and Lo, 2001; Martinez and Motto, 2000). As a consequence, it would be desirable if the beneficial effects of feeding zinc oxide could be obtained at lower levels of zinc supplementation. Therefore, this study was conducted to determine the effects of feeding 1500 or 2500 ppm zinc on performance, nutrient digestibility and zinc balance in weaned pigs.

MATERIALS AND METHODS

Experiment 1: In experiment 1,144 crossbred barrows (Landrace × Yorkshire × Duroc; averaging 28±3 days of age and 7.21±1.00 kg BW) were blocked based on initial weight and litter of origin and allotted to 1 of 4 dietary treatments for a 28 days study. A basal diet was formulated based on corn (extruded and expanded), soybean meal (regular and fermented), milk based products (lactose, whey powder and milk powder complex) and spray dried porcine plasma. The basal diet contained 100 ppm zinc as $ZnSO_4$ (35.5% zinc) and 10 ppm copper as $CuSO_4$ (25.2% Cu).

The 4 dietary treatments consisted of the basal diet fed without supplementation (negative control) or the basal diet supplemented with either an antibiotic combination (33 ppm tiamulin and 100 ppm chlortetracycline; positive control), 1500 or 2500 ppm zinc (Table 1). Chlortetracycline has a broad spectrum of activity against respiratory and enteric bacteria and is one of the most commonly used antibiotics fed to swine (Burch, 2008). The activity of tiamulin is largely confined to gram-positive micro-organisms and mycoplasma and is used for the treatment of dysentery, pneumonia and mycoplasmal infections in pigs and poultry (Committee for Veterinary Medicinal Products, 2000). Prior to mixing in the diet, either the antibiotics or zinc was premixed with fiber powder and was then added to the feed mixer.

The experiment was conducted in 2 phases with the phase 1 (1-14 days) diet formulated to provide 1.71% lysine, 1.17% threonine and 1.04% methionine plus cystine, while the phase 2 (14-28 days) diet was formulated to provide 1.51% lysine, 1.09% threonine and 0.85% methionine plus cysteine. All diets were fed in meal form and all nutrient levels met or exceeded NRC (1998) requirements for the nursery pig.

The pigs were housed in an environmentally regulated container house in 1.2×1.5 m pens located over a slatted floor. Air temperature was controlled at 32°C during first 7 days and the temperature was decreased by 1°C every 4 days until it reached 25°C at the end of the experiment. There were with 12 pens/treatment and each pen housed three barrows. Each pen had a single feeder and a nipple waterer to provide free access to feed and water. Body weights and pen feed consumption were measured weekly to evaluate weight gain, feed intake and feed conversion.

Experiment 2: This experiment was conducted to evaluate the effects of zinc supplementation on nutrient digestibility, fecal excretion patterns and tissue mineral levels. Forty eight crossbred barrows (Landrace x Yorkshire x Duroc; averaging 21±3 days of age and 5.28±0.41 kg BW) were blocked based on initial body weight and litter of origin and allotted to 1 of 4 dietary treatments for a 20 days study. The diets fed were the same as those used in experiment 1 modified only by the addition of 1.0% Celite 545 (Fluka, Switzerland) to all diets as a digestibility marker.

For this experiment, the pigs were housed in pairs in 1.2×2.0 m stainless steel cages with 6 replications per treatment. Each cage had a single feeder and a nipple waterer to provide free access to feed and water. Air temperature in the house was controlled at 30°C during first 7 days and the temperature was decreased by 1°C every 4 days until it reached 26°C at the end of the experiment.

The pigs were fed the phase 1 diet for the first 10 days of the trial and the phase 2 diet for the remaining 10 days. Fecal samples were collected from each pen on 8-10 days and on 19-21 days with the accumulation of the 3 days fecal collection subsequently being pooled. All fecal samples were stored in sealed plastic bags at -25°C. The fecal samples were freeze dried for 72 h, allowed to equilibrate for 24 h at room temperature and then ground through a 1.0 mm screen with a Cycotec Grinder (Model 1093, FOSS, Denmark). Digestibility coefficients for nutrients were calculated using the equations for the indicator method described by Schneider and Flatt (1975).

On day 20, 3 pigs/treatment were killed using a lethal injection of acepromazine acetate (10 mg mL^{-1} at 0.10 mL/10.0 kg BW) into the jugular vein. The abdominal cavity was opened and the entire liver, kidney and spleen were removed. Collected tissues were weighed and stored in a deep freezer (-60°C) for later analysis of minerals. Tissue samples were homogenized and freeze-dried prior to analysis.

Experiment 3: This trial utilized 360 crossbred pigs (Landrace x Yorkshire x Duroc; 28±3 days of age and

6.94±0.82 kg BW) housed in 4 commercial pig farms located in the provinces of Hallim (850 sows), Icheon (350 sows), Pocheon (1000 sows) and Illzug (280 sows) in Korea. The pigs were blocked based on initial weight, sex and litter of origin and allotted to 1 of 3 dietary treatments for a 28 days study. Three dietary treatments were created by supplementation of the basal diet with either antibiotics or 1,500 ppm zinc. The negative control consisted of the basal diet with no supplementation.

This trial was conducted in 3 phases with phase 1 from day 1-7, phase 2 from day 7-21 and phase 3 from day 21-28. The nutrient content of the phase 1 and 2 diets was the same as for experiment 1, while the phase 3 diet was formulated to provide 1.45% lysine, 0.95% threonine and 0.76% methionine plus cystine. All diets were fed in meal form and all nutrient levels met or exceeded NRC (1998) recommendations for the nursery pig.

The pigs in all 4 stations were housed in environmentally controlled rooms with the air temperature set at 30°C during the first 7 days and then the temperature was lowered by 1°C every 5 days until it reached 25°C at the end of the experiment. There were 24 replications per treatment with 4 (Icheion and Illzug) or 6 (Hallim and Pocheon) pigs per pen. Each research station contributed 6 replicates each. The pens measured 1.0×1.5 m with 50% of the floor area being slatted and 50% solid. Each pen had a single feeder and a nipple waterer to provide free access to feed and water. Body weights and pen feed consumption were measured weekly to evaluate weight gain, feed intake and feed conversion.

Chemical analysis: Samples of the diets and feces were analyzed in triplicate according to the methods of the AOAC (1990). Analyses were conducted for moisture (AOAC method 930.15), crude protein (AOAC method 984.13), ash (AOAC method 942.05), crude fiber (AOAC 978.10) and ether extract (AOAC method 920.39). Calcium was determined by a Shimazu AA625 Atomic Absorption Spectrophoto-meter (Shimazu, Kyoto, Japan) and phosphorus was analyzed using a UV-vis. Spectrophotometer (Hitachi, Tokyo, Japan). An amino acid analysis of the feed and feces was performed using a L8500-Hitachi Amino Acid Analyzer (Hitachi, Tokyo, Japan) after hydrolysis for 24 h in 6 N HCl. Performic acid hydrolysis was performed for analysis of sulfur-containing amino acids. The analyzed chemical composition of the experimental diets is shown in Table 2.

Zinc, copper and iron analysis of the feed, feces and tissues was performed using Inductively-Coupled Plasma Emission Spectroscopy (Leeman Labs, Hudson, NH) after predigestion with 70% nitric acid. Gross energy was measured using an Adiabatic Oxygen Bomb Calorimeter (Model 1241, Parr Instrument Co., Molin, IL). Celite (HCL-Insoluble Ash) analysis was conducted according to the description provided by Prabucki *et al.* (1975).

Table 1: Ingredient composition of the basal diet used for all experiments to determine the effects of pharmacological levels of zinc oxide on performance, nutrient digestibility and nutrient balance in weaned pigs

Ingredients (% as fed)	Phase 1	Phase 2	Phase 3
Yellow corn, extruded	11.00	0.00	0.00
Yellow corn, expanded	3.50	36.28	47.78
Bakery by-product	5.00	7.00	9.00
Lactose	10.00	0.00	0.00
Soybean meal (48%)	8.00	0.00	0.00
Soybean meal (44%)	0.00	16.50	30.00
Soybean meal, fermented	10.00	3.75	0.00
Whey powder	20.76	10.00	5.00
Milk powder	10.00	7.50	0.00
Spray dried plasma	5.00	2.50	0.00
Fishmeal	2.50	0.00	0.00
Lard	0.00	2.00	2.50
Soy oil	4.50	3.00	0.00
Limestone	0.00	0.30	0.13
Salt	0.00	0.20	0.30
Tricalcium phosphate	0.00	0.00	0.60
Monocalcium phosphate	1.32	0.64	0.00
Calprona	1.05	0.73	1.25
Fine sugar	3.00	3.00	0.00
DL-Methionine	0.26	0.16	0.18
L-Lysine-HCL	0.06	0.25	0.31
Threonine	0.04	0.00	0.12
Choline chloride (50%)	0.20	0.20	0.20
Vitamin premix[a]	0.10	0.10	0.10
Mineral premix	0.20	0.20	0.20
Fiber powder + treatment[b]	3.51	3.19	2.33

[a]The vitamin and trace mineral premix for the experimental diet provided the following diet kg^{-1}: Fe, 100 mg; Cu, 10 mg; Mn, 20 mg; Zn, 100 mg; I, 0.35 mg; Se, 0.20 mg; vitamin A, 20,000 IU; vitamin D3, 2,000 IU; vitamin E, 100 mg; vitamin K, 3 mg; thiamin, 4 mg; riboflavin, 7.0 mg; pyridoxine, 5 mg; vitamin B12, 0.05 mg; pantothenic acid, 16 mg; niacin, 35 mg; biotin, 0.18 mg; folic acid 1.3 mg; choline, 350 mg; [b]Fiber powder was mixed with antibiotics (33 ppm tiamulin + 100 ppm chlortetracycline) or zinc oxide

Table 2: Analyzed composition of the experimental diets fed to determine the effects of pharmacological levels of zinc oxide on performance, nutrient digestibility and nutrient balance in weaned pigs

Ingredients (% as fed)	Phase 1	Phase 2	Phase 3
Crude protein (%)	25.160	23.260	22.840
Crude fiber (%)	1.490	2.790	3.210
Ether extract (%)	6.470	6.900	6.650
Ash (%)	6.660	6.760	6.550
Calcium (%)	0.930	0.850	0.860
Phosphorus (%)	0.660	0.680	0.630
Gross energy (kcal kg^{-1})	4.594	4.551	4.528
Essential amino acids			
Arginine (%)	1.340	1.190	1.050
Histidine (%)	0.690	0.550	0.540
Isoleucine (%)	1.030	0.930	0.820
Leucine (%)	2.050	1.910	1.820
Lysine (%)	1.710	1.510	1.450
Methionine + Cystine (%)	1.040	0.850	0.760
Phenylalanine (%)	1.120	1.070	1.020
Threonine (%)	1.170	1.090	0.950
Valine (%)	1.210	1.060	0.910

[1]Diets were fed either unsupplemented or supplemented with antibiotics (33 ppm tiamulin + 100 ppm chlortetracycline) as well as 1500 or 2500 ppm zinc oxide

Statistical analysis: The performance and digestibility data were analyzed as a randomized block design. Using the general linear model procedure (General AOV/AOCV) of the Statistix (1996). Pigs were blocked on the basis of initial body weight and the pen was considered the experimental unit for analyses of performance and digestibility data. The animal was considered the experimental unit for analyses of tissue data. The model included the effects of replication (i.e., block), treatment and replication × treatment (error). The significance of differences between means was determined by the Least Significant Difference (LSD) method for performance and tissue data, by Tukey's method for digestibility data at the level of $\alpha = 0.05$.

RESULTS

In experiment 1, weight gain from day 0-14 was significantly lower for pigs fed the negative control than for pigs fed the diets supplemented with antibiotics or 1500 and 2500 ppm zinc (Table 3). Weight gain did not differ between pigs fed antibiotics or the 2 zinc supplemented diets ($p>0.05$) and there was also no difference in weight gain between pigs fed diets containing 1500 or 2500 ppm zinc. Feed intake tended to be lower for pigs fed the negative control than for the other three treatments ($p = 0.12$). There was no difference in intake between pigs fed the antibiotic supplemented diet and the 2 zinc supplemented diets and there was also no difference in feed intake between pigs fed diets containing 1500 or 2500 ppm zinc. Feed conversion was poorest for pigs fed the negative control, while feed conversion was highest for pigs fed the antibiotic supplemented diet and pigs fed the diet containing 2500 ppm zinc. Feed conversion for pigs fed 1500 ppm zinc was intermediate to that of the negative control and the antibiotic supplemented diet.

From day 14-28 and over the entire experimental period (day 0-28), there was no difference in weight gain or feed intake between treatments (Table 3). Over the 28 days period, pigs fed antibiotics had lower feed conversion ($p<0.05$) than pigs fed the control diet or those receiving zinc.

The apparent fecal digestibilities of the various nutrients contained in the experimental diets are shown in Table 4 and 5. There was no effect of dietary zinc or antibiotic addition on the digestibility of dry matter, crude protein, calcium, phosphorus or energy during either phase 1 or 2. During phase 1, the digestibility of histidine, cysteine and methionine was significantly ($p<0.05$) lower for pigs fed the antibiotic supplemented diet than for pigs fed the other 3 diets. During phase 2, the digestibility of

Table 3: Effect of pharmacological levels of zinc or antibiotics in the diet on the performance of weanling pigs (Exp.1)[*a]

			Zinc (ppm)			
Diet	Control	Antibiotics	1500	2500	SEM	p-value
Day 0-14						
Weight gain (g day^{-1})	279[a]	347[b]	350[b]	341[b]	20.5	0.05
Feed intake (g day^{-1})	396	422	476	431	23.4	0.12
Feed conversion	1.45[a]	1.25[b]	1.39[ab]	1.27[b]	0.06	0.05
Day 14-28						
Weight gain (g day^{-1})	422	415	439	427	28.3	0.95
Feed intake (g day^{-1})	645	618	689	694	38.2	0.45
Feed conversion	1.55	1.53	1.58	1.63	0.04	0.38
Day 0-28						
Weight gain (g day^{-1})	351	381	394	384	19.4	0.43
Feed intake (g day^{-1})	521	520	583	562	25.1	0.22
Feed conversion	1.50[a]	1.37[b]	1.48[a]	1.47[a]	0.03	0.02

*Twelve replicate pens of 3 pigs pen^{-1} for the performance data; [a,b]Means in the same row with same or no superscript do not differ ($p>0.05$)

Table 4: Effect of pharmacological levels of zinc or antibiotics in diet on nutrition digestibility (Exp. 2, Phase 1)

			Zinc (ppm)		
Diet	Control	Antibiotics	1500	2500	SEM
Dry matter	92.61	92.87	93.87	93.67	0.68
Crude protein	81.36	77.56	79.94	82.01	1.45
Calcium	41.96	45.60	50.64	48.50	4.01
Phosphorus	49.52	42.80	49.27	48.32	2.17
Energy	83.99	82.78	84.43	85.78	1.53
Essential amino acids					
Arginine	87.25	84.53	86.46	87.71	1.08
Cysteine	84.71[ab]	79.71[b]	82.47[ab]	86.86[a]	1.50
Histidine	87.99[a]	83.42[b]	85.28[ab]	86.70[ab]	1.01
Isoleucine	81.12	78.20	81.09	82.16	1.45
Leucine	83.30	80.43	83.28	84.10	1.28
Lysine	86.23	82.42	84.53	86.05	1.16
Methionine	81.22[b]	81.66[b]	85.28[ab]	88.80[a]	1.69
Phenylalanine	82.04	79.30	81.97	83.04	1.36
Threonine	84.25	79.96	82.57	83.85	1.26
Valine	82.41	78.71	81.74	82.86	1.38

*Six replicate pens of three pigs-pen for the digestibility data; [a,b]Means in the same row with the same or no superscript do not differ ($p>0.05$)

Table 5: Effect of pharmacological levels of zinc or antibiotics in diet on nutrition digestibility (Exp 2, Phase II)

			Zinc (ppm)		
Diet	Control	Antibiotics	1500	2500	SEM
Dry matter	92.26	91.74	92.25	91.93	0.17
Crude protein	85.02	83.71	84.48	84.22	0.46
Calcium	56.05	54.02	56.99	53.38	1.17
Phosphorus	64.52	62.02	65.91	63.71	1.41
Energy	87.92	86.04	87.94	87.70	0.50
Essential amino acids					
Arginine	88.53[ab]	87.25[b]	89.33[a]	89.42[a]	0.43
Cysteine	87.37[ab]	85.26[b]	87.81[a]	88.24[a]	0.64
Histidine	88.24	87.59	88.68	88.77	0.42
Isoleucine	86.36	82.85	86.29	86.31	0.93
Leucine	86.88	86.07	87.52	87.18	0.45
Lysine	87.81	87.12	88.65	88.83	0.54
Methionine	89.24[a]	87.36[b]	88.45[ab]	89.65[a]	0.47
Phenylalanine	85.46	84.30	86.35	85.86	0.88
Threonine	86.53	85.15	87.59	87.98	0.82
Valine	85.24	84.06	86.53	85.84	0.80

*Six replicate pens of 3 pigs pen^{-1} for the digestibility data; [a,b]Means in the same row with the same or no superscript do not differ ($p>0.05$)

Table 6: Effect of dietary zinc concentration on daily zinc and copper excretion in feces (Exp. 2)*

			Zinc (ppm)		
Diet	Control	Antibiotics	1500	2500	SEM
Daily zinc excretion (Phase 1)					
Intake (mg day^{-1})	50^{c}	65^{c}	305^{b}	501^{a}	34
Feces (mg day^{-1})	45^{c}	60^{c}	342^{b}	555^{a}	60
Daily copper excretion (Phase 1)					
Intake (mg day^{-1})	25	32	25	25	3
Feces (mg day^{-1})	20	19	27	23	3
Daily zinc excretion (Phase 2)					
Intake (mg day^{-1})	143^{c}	154^{c}	426^{b}	745^{a}	58
Feces (mg day^{-1})	143^{c}	126^{c}	365^{b}	676^{a}	73
Daily copper excretion (Phase 2)					
Intake (mg day^{-1})	79	83	84	81	2
Feces (mg day^{-1})	74	72	74	70	3

*Six replicate pens of 2 pigs pen^{-1} for the excretion data; ^{a,b}Means in the same row with same or no superscript do not differ (p>0.05)

arginine, cysteine and methionine was significantly (p<0.05) lower for pigs fed the antibiotic supplemented diet than for pigs fed the other 3 diets.

During both phase 1 and 2, pigs zinc supplemented diets excreted more (p<0.05) zinc in their feces than pigs fed the negative control or the antibiotic supplemented diet (Table 6). However, zinc excretion was significantly lower (p<0.05) for pigs fed 1500 ppm zinc than for those fed 2500 ppm zinc. Daily copper excretion in the feces was not different between treatments during either phase 1 and 2.

Pigs fed either 1500 or 2500 ppm zinc had significantly higher (p<0.05) liver and spleen zinc concentrations than pigs fed the negative control or the antibiotic supplemented diet (Table 7). Liver zinc concentration was significantly higher for pigs fed 2500 ppm zinc than for pigs fed 1500 ppm zinc. Pigs fed 2500 ppm added zinc had significantly lower (p<0.05) spleen iron concentrations than pigs on the control. There was no effect of dietary zinc or antibiotic addition on the kidney zinc, liver and kidney iron and copper concentration in tissue.

In experiment 3, weight gain was significantly (p<0.05) lower for pigs fed the negative control than for pigs fed diets supplemented with antibiotics or 1500 ppm zinc during phases 1-3 as well as for the overall experiment (Table 8). Weight gain did not differ between pigs fed the antibiotic treatment or pigs fed 1500 ppm zinc during any phase of the experiment. Feed intake was lower for pigs fed the negative control than for pigs fed pigs fed 1500 dietary zinc or antibiotic treatments However, there was no difference in feed intake between pigs fed either antibiotic or zinc diets. Feed conversion was poorer (p<0.05) for pigs fed the negative control than for pigs fed either antibiotic or zinc supplemented diets during day 0-7 and for the overall experiment. Feed conversion was not significantly different between pigs fed the antibiotic or zinc supplemented diet during any phase of the experiment.

Table 7: Effect of dietary zinc concentration on tissue zinc, iron and copper concentrations (Exp. 2)*

			Zinc (ppm)		
Diet	Control	Antibiotics	1500	2500	SEM
Zinc concentration (μg g^{-1})					
Liver	174^{d}	191^{c}	809^{b}	1449^{a}	14.2
Spleen	170^{b}	176^{b}	184^{ab}	228^{a}	15.1
Kidney	135	145	161	175	12.5
Iron concentration (μg g^{-1})					
Liver	147	123	124	127	8.8
Spleen	177^{a}	146^{ab}	146^{ab}	130^{b}	9.5
Kidney	140	117	114	112	17.8
Copper concentration (μg g^{-1})					
Liver	15	16	14	14	1.1
Spleen	16	10	14	14	1.8
Kidney	40	41	14	9	16.0

*Pig was used as experimental unit. Means are based on 3 pigs/treatment; ^{a,b,c}Means in the same row with same or no superscript do not differ (p>0.05)

Table 8: Effect of additional zinc or antibiotics in the diet on performance of weanling pigs (Exp. 3)*

			1500 ppm		
Diet	Control	Antibiotics	Zinc	SEM	p-value
Day 0-7					
Weight gain (g day^{-1})	174^{b}	220^{a}	237^{a}	13.8	0.01
Feed intake (g day^{-1})	249	269	273	13.0	0.40
Feed conversion	1.50^{a}	1.31^{b}	1.20^{b}	0.065	0.01
Day 7-21					
Weight gain (g day^{-1})	304^{b}	349^{a}	359^{a}	15.1	0.03
Feed intake (g day^{-1})	445^{b}	510^{a}	535^{a}	18.9	0.01
Feed conversion	1.52	1.49	1.49	0.037	0.78
Day 21-28					
Weight gain (g day^{-1})	376^{b}	453^{a}	440^{a}	20.8	0.02
Feed intake (g day^{-1})	658^{b}	756^{a}	737^{a}	26.6	0.03
Feed conversion	658^{b}	756^{a}	737^{a}	26.6	0.03
Day 0-28					
Weight gain (g day^{-1})	290^{b}	343^{a}	349^{a}	9.6	0.01
Feed intake (g day^{-1})	455^{b}	511^{a}	520^{a}	13.1	0.01
Feed conversion	1.58^{a}	1.50^{b}	1.49^{b}	0.022	0.02

*Twenty four replicate pens of 4 or 6 pigs pen^{-1} for the performance data; ^{a,b}Means in the same row with same or no superscript do not differ (p>0.05)

DISCUSSION

The pig performance data obtained in experiments 1 and 3 demonstrated improved performance for pigs fed zinc supplemented diets compared with the negative control. In both experiments, pig performance was essentially equal to that of the antibiotic supplemented pigs indicating that zinc can substitute for antibiotics in diets fed to nursery pigs. In addition, our data indicate that feeding 1500 ppm zinc resulted in similar performance to feeding 2500 ppm zinc and that the younger the pig, the greater the response to zinc supplementation.

Previous studies have indicated that pharmacological doses of zinc oxide stimulate performance in weaned pigs (Hahn and Baker, 1993; Carlson *et al*., 1999; Hill *et al*., 2000), although, there are some reports in which no growth-promoting benefits were observed (Fryer *et al*., 1992; Tokach *et al*., 1992; Schell and Kornegay, 1996). Our results support the findings of Hill *et al*. (2001) who observed that responses to zinc oxide reached a plateau at 1500 ppm zinc.

Our data indicate that the improvements in weight gain due to zinc supplementation were primary the result of increased voluntary feed intake. In a recent study by Yin *et al*. (2008), it was observed that zinc supplementation stimulates ghrelin secretion from the stomach of young pigs and ghrelin has been shown to act on the small intestine and brain to stimulate feed intake via an unknown mechanism. Therefore, increased ghrelin secretion may explain the increased feed intake of the zinc supplemented pigs in the present study.

It has previously been suggested that zinc oxide promotes the growth of weaned pigs by controlling pathogenic bacterial scours (Holm and Poulsen, 1996; Katouli *et al*., 1999, Huang *et al*., 1999). However, other work has indicated that zinc oxide promotes growth in early and conventionally weaned pigs regardless of diarrhea incidence or effect on intestinal microbial numbers (Hahn and Baker, 1993; Li *et al*., 2001). The pigs used in our experiment exhibited improved performance but did not exhibit diarrhea, suggesting that mechanisms other than the antimicrobial effects of zinc oxide supplementation are responsible for the improvements in pig performance.

The results of the present experiment demonstrated no change in nutrient digestibility as a result of feeding either 1500 or 2500 ppm zinc. This finding was somewhat surprising given the fact that Li *et al*. (2001, 2006) have shown that zinc supplementation improves gut morphology by increasing villous height and reducing crypt depth in the small intestine thus, potentially increasing the absorptive capacity of the small intestine. In addition, Hedemann *et al*. (2006) reported that high dietary zinc increased the activity of several enzymes in the pancreatic tissue (amylase, carboxypeptidase, chymotrypsin, trypsin and lipase) and it might reasonably be expected that such an increase would result in improvements in nutrient digestibility. However, such was not the case with the present experiment.

It has been suggested that one potential mechanism through, which antibiotics stimulate growth is through enhanced efficiency of absorption and utilization of nutrients because the wall of the intestinal tract is thinner (Visek, 1978). It was therefore, somewhat surprising that antibiotic supplementation reduced the digestibility of some specific amino acids in both phase 1 and 2. An explanation for this anomaly is not readily apparent.

The concentration of zinc in feces was significantly higher for the zinc supplemented pigs than for pigs fed either the negative control or the antibiotic supplemented diet. This supports previous research in which pigs fed 3000 ppm added zinc excreted almost four times more zinc in their feces as pigs fed 500 ppm zinc (Case and Carlson, 2002). Hill *et al*. (2001) observed that pigs fed 2,000 ppm zinc excreted 14 times more zinc in the feces than pigs that were fed 150 ppm zinc, thus, supporting the findings in the present study that fecal zinc concentrations are reflective of the dietary zinc concentration fed to weanling pigs during the nursery phase.

The finding of high fecal zinc concentrations resulting from the feeding of pharmacological levels of zinc has serious implications as fertilization of crops with swine manure is a common practice throughout the world. Application of swine manure from pigs fed high levels of zinc increases the concentration of zinc in the soil (Berenguer *et al*., 2008) and zinc accumulation in the soil has been implicated in reducing plant growth (Chaney, 1993), while, leaching of zinc from soils treated with swine manure may lead to pollution of lakes, streams and costal waters (Li and Shuman, 1997; Hsu and Lo, 2001; Martinez and Motto, 2000). Our finding that feeding 1500 ppm zinc supported a similar level of performance as 2500 ppm zinc while significantly reducing fecal zinc excretion indicates that it may be possible to reduce the levels of zinc in nursery diets without having to sacrifice performance while lessening the environmental impact of manure disposal.

Our results show that during phase 1, pigs fed 1500 and 2500 ppm added zinc were excreting more zinc than they were consuming on a daily basis indicating that they were in a negative zinc balance. This result is in agreement with results reported by Case and Carlson (2002), who also reported a negative zinc balance in zinc supple-mented pigs.

Feeding high levels of zinc increased the concentration of zinc in the liver and spleen of supplemented pigs supporting the findings of Case and Carlson (2002). O'Dell (1989) reported that a high dietary intake of zinc can reduce the copper status. However, in the present study, copper absorption and retention were not varied when pigs were fed high dietary zinc concentrations.

CONCLUSION

Feeding either 1500 or 2500 ppm zinc supported a similar level of nursery pig performance as did antibiotic supplementation indicating that it may be possible to substitute pharmacological levels of zinc for antibiotics in swine nursery rations minimizing the potential for antibiotic residues to appear in pork products. In addition, 1500 ppm zinc supported equal performance to 2500 ppm zinc but fecal zinc concentrations were significantly lower thereby lessening the environmental impact of spreading swine manure.

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