Effect of standardized ileal digestible lysine and added copper on growth performance, carcass characteristics, and fat quality of finishing pigs[1]

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ABSTRACT: Two, 120-d, experiments were conducted to determine the effects of standardized ileal digestible (**SID**) lysine (**Lys**), added Cu (tribasic copper chloride, Intellibond C; Micronutrients, Inc., Indianapolis, IN), and duration of Cu supplementation on growth performance, carcass characteristics, and fat quality in finishing pigs. In Exp. 1, 1,248 pigs (PIC 337 × 1050; initially 29.0 kg) were allotted to one of six dietary treatments, balanced on average pen weight in a randomized complete-block design with 26 pigs per pen and eight replications per treatment. Treatments were arranged in a 3 × 2 factorial with main effects of SID Lys (85, 92.5, and 100% of the estimated requirement) and added Cu (0 or 150 mg/kg). There were no Cu × SID Lys interactions observed for growth performance or liver Cu concentrations. Increasing SID Lys increased (linear, $P < 0.05$) ADG, feed efficiency (G:F), final weight, and HCW. Pigs fed 150 mg/kg added Cu had marginally increased ($P < 0.10$) ADG, G:F, and final weight. Liver Cu concentrations were greater ($P = 0.001$) in pigs fed added Cu. A marginal Cu × Lys interaction ($P = 0.052$) was observed for jowl fat iodine value (IV) as increasing SID Lys in pigs fed added Cu increased IV, but decreased IV in pigs not fed added Cu. For Exp. 2, 1,267 pigs (PIC 337 × 1,050; initially 26.4 kg) were allotted to one of eight dietary treatments arranged in a split-plot design. Whole-plot treatments included SID Lys (92.5 or 100% of the estimated requirement) and within each Lys level, there was a 2 × 2 factorial arrangement of treatments with either 0 or 150 mg/kg added Cu and two feeding durations (60 or 120 d). Added Cu did not affect growth performance. Pigs fed 100% of the SID Lys requirement had increased ($P < 0.05$) ADG, G:F, and final weight compared with those fed 92.5%. A Cu × SID Lys interaction ($P < 0.05$) was observed for carcass yield and backfat depth. Pigs fed 92.5% SID Lys had increased carcass yield and decreased backfat depth with added Cu; however, pigs fed 100% SID Lys had decreased carcass yield and increased backfat depth with added Cu. Hot carcass weight was increased ($P < 0.05$) by feeding 100% SID Lys and was marginally ($P < 0.10$) increased by adding Cu to the diets. In summary, the growth response to added Cu was inconsistent between experiments; however, increasing SID Lys improved growth performance and carcass characteristics.

Key words: copper chloride, fat quality, growth, lysine, pigs

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INTRODUCTION

Adding pharmalogical levels of Cu to finishing diets has shown increased ADG and ADFI during the early finishing periods, but this response has been less consistent when fed during late finishing periods (Davis et al., 2002; Hastad, 2002; Carpenter et al., 2017). Hastad (2002) reported that adding 200 mg/kg Cu did not promote growth performance past 61 kg. However, Davis et al. (2002) observed improvements in ADG and feed efficiency (G:F) beyond 68 kg BW.

Coble et al. (2017) observed that Cu fed in the form of copper sulfate (**$CuSO_4$**) or tribasic copper chloride (**TBCC**; Intellibond C; Micronutrients, Inc., Indianapolis, IN) potentially offered growth benefits longer into the finishing period, increasing ADFI and G:F in pigs heavier than 88 kg BW. However, this improvement was observed in pigs fed diets formulated 0.05 percentage unit below the estimated standardized ileal digestible (**SID**) Lysine (**Lys**) requirement. Previous research evaluating the effect of SID Lys level on the response to added Cu in finishing pigs is not available. Rochell et al. (2017) observed that broilers fed a low digestible Lys diet (1.00%) had greater improvements in ADFI and ADG with 200 mg/kg of added Cu from TBCC compared with broilers fed a high digestible Lys diet (1.20%). They also observed that nitrogen digestibility was increased in chicks fed the low Lys diet with TBCC, but not in the high Lys diet. Other studies have observed improvements in fat and energy digestibility with added Cu in nursery pigs (Luo and Dove, 1996; Gonzales-Eguia et al., 2009), as well as increased nitrogen digestibility in finishing pigs (Kim et al., 2006). Thus, it is important to understand if adding Cu allows for using lower SID Lys in finishing diets without compromising pig growth performance and how feeding duration of Cu may affect the growth response. Therefore, these experiments were designed to investigate the effects of dietary SID Lys with or without 150 mg/kg added Cu from TBCC, and the duration of feeding added Cu, on finishing pig growth performance, carcass characteristics, and fat quality.

MATERIALS AND METHODS

All experimental procedures and animal care were approved by the Kansas State University Institutional Animal Care and Use Committee.

General

Two, separate, 120-d experiments were conducted in a commercial research facility in southwestern Minnesota. The facility was double-curtain sided with completely slatted concrete flooring. The barn contained 48 pens (3.05 × 5.49 m) equipped with a five-hole conventional dry self-feeder (Thorp Equipment, Thorp, WI) and a cup waterer providing ad libitum access to feed and water. The facility was equipped with a computerized feeding system (FeedPro; Feedlogic Corp., Willmar, MN) that delivered and recorded daily feed additions of the diets to each pen.

Before day 0, pigs were fed a common diet for 7 d containing 205 and 188 mg/kg Cu from TBCC (Intellibond C; Micronutrients Inc.) in Exp. 1 and 2, respectively. Samples of experimental diets were obtained by collecting samples at the feeder 2 d after initiating and 2 d prior to completing each dietary phase. Samples were combined for a composite sample of each treatment diet during each phase. Samples were analyzed in duplicate for total Cu (985.01, AOAC International, 2000; Cumberland Valley Analytical Services, Hagerstown, MD), and total amino acids (method 994.12; AOAC Int., 2012), and CP (method 990.03; AOAC Int., 2012) at Ajinomoto Heartland, Inc. (Eddyville, IA). On day 0, pens of pigs were weighed and allotted to dietary treatments in a randomized complete-block design, with initial pen weight serving as the blocking factor.

Pens of pigs were weighed and feed disappearance was recorded approximately every 3 wk to determine ADG, ADFI, G:F, and metabolizable and net energy caloric efficiency. In Exp. 1, the heaviest three pigs in each pen were weighed and marketed on day 97 according to standard farm protocol. In Exp. 2, the heaviest five pigs were weighed and marketed on day 101. These pigs were used in calculation of pen growth performance, but not carcass characteristics. The remaining pigs were marketed on day 120 in each experiment. Before marketing, final pen weights were taken and pigs were individually tattooed with a pen identification number to allow for carcass measurements to be recorded on a pen basis. Pigs were then transported to a commercial processing packing plant in southwestern Minnesota (JBS Swift and Company, Worthington, MN) for processing and carcass data collection. Twelve hours after final pen weights were taken, HCW was measured immediately after evisceration and each carcass evaluated for carcass yield, backfat depth, loin depth, and percentage lean. Carcass yield was calculated by dividing the HCW at the plant by the live weight at the farm prior to transport to the plant. Fat depth and loin depth were measured with an optical probe inserted between the third and fourth last rib (counting from the ham end of the carcass) at a distance approximately 7 cm from the dorsal midline. Hot carcass weight ADG was calculated by subtracting initial HCW (assumed to be 75% of live weight) from the final HCW obtained at the plant, then divided by the 120 d on test. Hot carcass weight G:F was calculated by dividing HCW gain by feed intake over the 120 d experiments.

Experiment 1

A total of 1,248 pigs (PIC 337 × 1,050, Hendersonville, TN; initially 29.0 kg) were allotted to one of six dietary treatments with 26 pigs (similar numbers of barrows and gilts) per pen and eight replications per treatment. Treatments were arranged in a 2 × 3 factorial with main effects of added Cu from TBCC (0 or 150 mg/kg) and SID Lys (85, 92.5, or 100% of the estimated requirement based on modeled response to Lys from previous experiments in this facility (Main et al., 2008; Shelton et al., 2012, Goncalves et al., 2015). All diets were corn–soybean meal-based with 30% distillers dried grains with solubles (**DDGS**) and 15% bakery meal and contained 17 mg/kg of Cu from $CuSO_4$ provided by the trace mineral premix. Treatment diets were fed in five phases (Tables 1 and 2). During the last phase, all diets contained 10 mg/kg ractopamine HCl (Paylean; Elanco Animal Health, Inc., Greenfield, IN).

On day 120 when pigs were marketed, three individual pigs per pen were identified to represent the mean individual pig weight of the pen and transported to a small commercial packing plant in northwestern Iowa (Natural Foods Holdings, Inc., Sioux City, IA) for measuring liver mineral concentrations along with backfat and jowl fat samples. Pigs were slaughtered 12 h after final pen weights were taken at the farm. The entire liver was obtained from the pluck for sampling and objective color scoring. Prior to sampling, a MiniScan EZ (Model 4500L; Hunter Associates Laboratory, Reston, VA) was used to determine L*, a*, and b* color values to indicate lightness, redness, and yellowness, respectively, by taking three scans of each liver and obtaining and average for each color value. From these values, hue angle and chroma were calculated to describe the blemish or taint of color and saturation of color, respectively. Samples of the liver were then collected from the top left lobe immediately after pigs were eviscerated, placed on dry ice, and shipped to Michigan State University for analysis. At Michigan State University, liver samples were microwave digested (MARS 5; CEM Corp., Matthews, NC) in 10 mL of HNO_3 and then in an addition 2 mL of H_2O_2. Samples were then brought to the desired volume for analysis by flame atomic absorption spectrophotometry according (Shaw et al., 2002; UNICAM 989 Solar AA Spectrometer, Thermo Elemental Corp., Franklin, MA). Fat samples were taken from pigs 1 h after slaughter from the jowl and 10th rib (all three layers), placed on dry ice, and shipped to the University of Georgia for complete fatty acid analysis. Fatty acid analysis was determined by gas chromatography (model 14 A, Shimadzu, Tokyo, Japan) described by Cromwell et al. (2011). Iodine value was calculated for the fat samples using the following equation (AOAC, 1998): IV = [C16:1] × 0.950 + [C18:1] × 0.860 + [C18:2] × 1.732 + [C18:3] × 2.616 + [C20:1] × 0.785 + [C20:4] × 3.201 + [C22:1] × 0.723 + [C22:5] × 3.697 + [C22:6] × 4.463, where brackets indicate concentration (%).

Experiment 2

A total of 1,267 pigs (PIC 337 × 1,050 PIC, Hendersonville, TN; initially 26.4 kg) were allotted to one of eight dietary treatments with 26 to 27 pigs (similar numbers of barrows and gilts) per pen with six replications per treatment. Treatments were arranged in a split-plot design with whole-plot treatments of SID Lys (92.5 or 100% of estimated requirement). Within each level of Lys, there was a 2 × 2 factorial arrangement with main effects of Cu (0 or 150 mg/kg from TBCC) and duration (60 or 120 d). All diets were corn–soybean meal-based with 30% DDGS and contained 17 mg/kg Cu from $CuSO_4$ provided by the trace mineral premix. Treatment diets were fed in five phases (Tables 3 and 4). During the last phase, all diets contained 5 mg/kg ractopamine HCl (Paylean; Elanco Animal Health, Inc.).

Statistical Analysis

Data from both Exp. 1 and 2 were analyzed separately using the MIXED procedure of SAS (SAS Institute, Inc., Cary, NC) as a randomized complete-block design with pen serving as the experimental unit. Weight block was included in both models as a random effect. Residual assumptions were checked using standard diagnostics on studentized residuals. The assumptions were reasonably met in both experiments. For Exp. 1, linear and quadratic contrasts were tested to determine if SID Lys affected the response to added Cu. When Lys × Cu interaction

Table 1. Composition of diets for phases 1 and 2, Exp. 1 (as-fed basis)[1,2]

	Phase 1 SID Lys,[3] %			Phase 2 SID Lys, %		
Item	85.0	92.5	100.0	85.0	92.5	100.0
Ingredient, %						
Corn	39.42	36.82	34.23	43.31	41.07	38.82
Soybean meal, 46.5% CP	13.02	15.59	18.15	9.42	11.64	13.86
Distillers dried grains with solubles	30.00	30.00	30.00	30.00	30.00	30.00
Bakery meal	15.00	15.00	15.00	15.00	15.00	15.00
Monocalcium P, 21 %	0.25	0.25	0.25	—	—	—
Dicalcium P, 18.5%	—	—	—	0.13	0.13	0.13
Limestone	1.25	1.25	1.25	1.15	1.15	1.15
Salt	0.35	0.35	0.35	0.35	0.35	0.35
Vitamin premix[4]	0.08	0.08	0.08	0.08	0.08	0.08
Trace mineral premix[5]	0.10	0.10	0.10	0.10	0.10	0.10
Lysine sulfate[6]	0.505	0.535	0.565	0.460	0.488	0.515
L-Thr	0.025	0.025	0.025	—	—	—
Phytase[7]	0.005	0.005	0.005	0.005	0.005	0.005
TBCC[8]	±	±	±	±	±	±
Total	100.0	100.0	100.0	100.0	100.0	100.0
Calculated analysis						
Standard ileal digestible (SID) amino acids, %						
Lys	0.88	0.96	1.04	0.77	0.84	0.91
Ile:Lys	74	72	71	77	75	73
Meth:Lys	34	33	31	37	35	34
Met + Cys:Lys	63	61	58	69	65	63
Thr:Lys	65	63	62	64	63	61
Trp:Lys	18.2	18.2	18.2	18.2	18.2	18.2
Val:Lys	87	84	82	91	88	86
Total lysine, %	1.07	1.16	1.24	0.95	1.03	1.10
SID lysine:ME, g/Mcal	2.61	2.84	3.08	2.28	2.48	2.68
ME, kcal/kg	3,387	3,384	3,382	3,397	3,395	3,393
NE, kcal/kg	2,492	2,477	2,462	2,518	2,506	2,493
CP, %	19.9	20.9	22.0	18.5	19.4	20.3
Ca, %	0.59	0.59	0.60	0.53	0.53	0.54
P, %	0.47	0.48	0.49	0.42	0.43	0.44
Available P, %	0.32	0.32	0.33	0.28	0.28	0.29

[1]Phase 1 diets fed from day 0 to 23 and phase 2 diets fed from day 23 to 38.

[2]Each diet was fed in meal form.

[3]Standardized ileal digestible; SID Lys values (NRC, 2012) are expressed as the percentage of estimated SID Lys requirement for these pigs in this environment and production phase.

[4]Provided per kilogram of premix: 7,054,720 IU vitamin A; 1,102,300 IU vitamin D_3; 35,274 IU vitamin E; 3,527 mg vitamin K; 6,173 mg riboflavin; 22,046 mg pantothenic acid; 39,683 mg niacin; and 26 mg vitamin B_{12}.

[5]Provided per kilogram of premix: 17 g Mn from manganese oxide, 110 g Fe from ferrous sulfate, 110 g Zn from zinc oxide, 17 g Cu from copper sulfate, 331 mg I from ethylenediamine dihydroiodide, and 300 mg Se from sodium selenite.

[6]Biolys (Evonik, Inc., Kennesaw, GA).

[7]Optiphos 2000 (Huvepharma, Inc., Peachtree City, GA) provided 200 phytase units (FTU)/kg, with a release of 0.05% available P.

[8]Tribasic copper chloride (Intellibond C; Micronutrients, Inc.) provided 150 mg/kg Cu and was added at the expense of corn.

was significant, pairwise comparisons for added Cu within SID Lys were determined to describe the interaction. The main effect of Cu and linear and quadratic effects of SID Lys were also tested.

For Exp. 2, the three-way interaction of early Cu (0 or 150 mg/kg Cu from day 0 to 60) × Late Cu (0 or 150 mg/kg Cu from day 60 to 120) × SID Lys and two-way interactions of Early Cu × SID Lys, Late Cu × SID Lys, and Early Cu × Late Cu were tested but were not significant ($P > 0.10$). Therefore, the interaction of Cu × SID Lys, main effect of Cu, and main effect of SID Lys for the overall period were tested and reported.

For Exp. 1 and 2, backfat depth, loin depth, and lean percentage were adjusted to a common HCW for analysis. Results from the experiments were considered significant at $P \leq 0.050$ and marginally significant at $P > 0.050$ and $P \leq 0.100$.

Table 2. Composition of diets for phases 3 to 5, Exp. 1 (as-fed basis)[1]

	Phase 3 SID Lys,[2] %			Phase 4 SID Lys,[2] %			Phase 5 SID Lys,[2] %		
Item	85	92.5	100	85	92.5	100	85	92.5	100
Ingredient, %									
Corn	46.59	44.58	42.57	48.8	46.98	45.17	41.81	39.39	36.97
Soybean meal, 46.5% CP	6.31	8.3	10.28	4.15	5.95	7.74	11.04	13.4	15.79
Distillers dried grains with solubles	30.00	30.00	30.00	30.00	30.00	30.00	30.00	30.00	30.00
Bakery meal	15.00	15.00	15.00	15.00	15.00	15.00	15.00	15.00	15.00
Limestone	1.15	1.15	1.15	1.13	1.13	1.13	1.15	1.15	1.15
Salt	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
Vitamin premix[3]	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08
Trace mineral premix[4]	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Lysine sulfate[5]	0.425	0.448	0.47	0.395	0.415	0.435	0.45	0.475	0.5
L-Thr	—	—	—	—	—	—	0.03	0.03	0.03
Phytase[6]	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005
Ractopamine HCl[7]	—	—	—	—	—	—	0.025	0.025	0.025
TBCC[8]	±	±	±	±	±	±	±	±	±
Total	100	100	100	100	100	100	100	100	100
Calculated analysis									
Standard ileal digestible (SID) amino acids, %									
Lys	0.68	0.74	0.80	0.61	0.67	0.72	0.81	0.88	0.95
Ile:Lys	80	78	76	83	81	79	77	75	74
Meth:Lys	74	70	67	79	75	72	36	35	33
Met + Cys:Lys	74	70	67	79	75	72	67	64	62
Thr:Lys	67	65	64	70	68	66	68	66	65
Trp:Lys	18.2	18.2	18.2	18.3	18.3	18.3	18.6	18.6	18.6
Val:Lys	97	93	90	102	98	95	91	88	85
Total lysine, %	0.85	0.92	0.98	0.85	0.92	0.98	0.99	1.07	1.14
SID lysine:ME, g/Mcal	2	2.17	2.35	1.8	1.96	2.12	2.38	2.59	2.8
ME, kcal/kg	3,401	3,403	3,405	3,407	3,406	3,404	3,399	3,397	3,395
NE, kcal/kg	2,517	2,528	2,540	2,553	2,543	2,532	2,511	2,498	2,485
CP, %	17.2	18	18.8	16.4	17.1	17.8	19.1	20.1	21
Ca, %	0.49	0.49	0.5	0.47	0.48	0.48	0.5	0.51	0.52
P, %	0.38	0.39	0.4	0.37	0.38	0.39	0.41	0.42	0.43
Available P, %	0.25	0.26	0.26	0.25	0.25	0.26	0.26	0.27	0.28

[1]Phase 3 diets fed from day 38 to 70, phase 4 diets fed from day 70 to 97, and phase 5 diets fed from day 97 to 120. All diets were fed in meal form.

[2]Standardized ileal digestible; SID Lys values (NRC, 2012) are expressed as the percentage of estimated SID Lys requirement for these pigs in this environment and production phase.

[3]Provided per kilogram of premix: 7,054,720 IU vitamin A; 1,102,300 IU vitamin D3; 35,274 IU vitamin E; 3,527 mg vitamin K; 6,173 mg riboflavin; 22,046 mg pantothenic acid; 39,683 mg niacin; and 26 mg vitamin B12.

[4]Provided per kilogram of premix: 17 g Mn from manganese oxide, 110 g Fe from ferrous sulfate, 110 g Zn from zinc oxide, 17 g Cu from copper sulfate, 331 mg I from ethylenediamine dihydroiodide, and 300 mg Se from sodium selenite.

[5]Biolys (Evonik, Inc., Kennesaw, GA).

[6]Optiphos 2000 (Huvepharma, Inc., Peachtree City, GA) provided 200 phytase units (FTU)/kg, with a release of 0.05% available P.

[7]Paylean 9 (Elanco Animal Health, Inc.) provided 5 mg/kg ractopamine HCl.

[8]Tribasic copper chloride (Intellibond C; Micronutrients, Inc.) provided 150 mg/kg Cu and was added at the expense of corn.

RESULTS

Diet and Ingredient Analysis

In both Exp. 1 and 2, the analyzed total Cu concentrations were similar to expected values and within acceptable limits, given the Cu level provided by the trace mineral premix and the exogenous copper from the ingredients (AAFCO, 2014; Tables 5 and 6). For Exp. 1, diets with no additional Cu, ranged from 25 to 56 mg/kg total Cu. Diets with 150 mg/kg added Cu ranged from 178 to 246 mg/kg total Cu. For Exp. 2, diets with no additional Cu, ranged from 28 to 42 mg/kg total Cu and 201 to 272 mg/kg total Cu when 150 mg/kg Cu was included. Phase 5 diets for Exp. 2 were not available for analysis. For amino acid analysis, diets had analyzed amino acid values similar to expected

Table 3. Composition of diets for phase 1 and 2, Exp. 2 (as-fed basis)[1,2]

	Phase 1 SID Lys,[3] %		Phase 2 SID Lys, %	
Item	92.5	100.0	92.5	100.0
Ingredient, %				
Corn	56.06	52.94	59.94	57.20
Soybean meal, 46.5% CP	11.23	14.33	7.56	10.29
Distillers dried grains with solubles	30.00	30.00	30.00	30.00
Limestone	1.60	1.60	1.45	1.45
Salt	0.35	0.35	0.35	0.35
Vitamin premix[4]	0.08	0.08	0.08	0.08
Trace mineral premix[5]	0.10	0.10	0.10	0.10
L-Lys HCl	0.475	0.475	0.450	0.450
DL-Meth	0.005	0.025	—	—
L-Thr	0.050	0.050	0.030	0.035
L-Trp	0.043	0.040	0.041	0.039
Phytase[6]	0.005	0.005	0.005	0.005
TBCC[7]	±	±	±	±
Total	100.0	100.0	100.0	100.0
Calculated analysis				
Standard ileal digestible (SID) amino acids, %				
Lys	0.95	1.03	0.84	0.91
Ile:Lys	62	62	63	63
Meth:Lys	31	32	32	31
Met + Cys:Lys	58	58	61	59
Thr:Lys	62	62	62	62
Trp:Lys	19	19	19	19
Val:Lys	71	70	73	73
Total lysine, %	1.14	1.22	1.02	1.09
SID lysine:ME, g/Mcal	2.87	3.11	2.53	2.74
ME, kcal/kg	3,318	3,314	3,327	3,322
NE, kcal/kg	2,456	2,436	2,480	2,465
CP, %	19.3	20.5	17.7	18.8
Ca, %	0.65	0.66	0.58	0.59
P, %	0.42	0.42	0.39	0.40
Available P, %	0.28	0.28	0.26	0.27

[1]Phase 1 diets fed from day 0 to 21 and phase 2 diets fed from day 21 to 38.

[2]Each diet was fed in meal form.

[3]Standardized ileal digestible; SID Lys values (NRC, 2012) are expressed as the percentage of estimated SID Lys requirement for these pigs in this environment and production phase.

[4]Provided per kilogram of premix: 7,054,720 IU vitamin A; 1,102,300 IU vitamin D_3; 35,274 IU vitamin E; 3,527 mg vitamin K; 6,173 mg riboflavin; 22,046 mg pantothenic acid; 39,683 mg niacin; and 26 mg vitamin B_{12}.

[5]Provided per kilogram of premix: 17 g Mn from manganese oxide, 110 g Fe from ferrous sulfate, 110 g Zn from zinc oxide, 17 g Cu from copper sulfate, 331 mg I from ethylenediamine dihydroiodide, and 300 mg Se from sodium selenite.

[6]Optiphos 2000 (Huvepharma, Inc., Peachtree City, GA) provided 200 phytase units (FTU)/kg, with a release of 0.05% available P.

[7]Tribasic copper chloride (Intellibond C; Micronutrients, Inc.) provided 150 mg/kg Cu and was added at the expense of corn.

when observed across all phases within treatment for both Exp. 1 and 2. As SID Lys increased, total Lys concentrations increased, as well as the other amino acids as expected; suggesting that the diet formulation successfully created the Lys gradient intended by the design of the experiment.

Experiment 1

From day 0 to 70, SID Lys affected the response to Cu for ADG (Cu × Lys interaction, linear, $P = 0.034$; Table 7). This was due to the significant increase ($P = 0.003$) in ADG with added Cu when pigs were fed 100% of the estimated SID Lys requirement, while there was no Cu response within the 85 or 92.5% SID Lys treatments. Similarly, SID Lys marginally affected the ADFI response to Cu (Cu × Lys interaction, quadratic, $P = 0.095$) as pigs fed added Cu and 100% SID Lys had increased ADFI ($P = 0.019$) compared with those not fed added Cu. As expected, G:F improved as SID Lys increased (linear, $P = 0.001$). From day 70 to 120, neither Cu or SID Lys affected ADG, ADFI, or G:F.

Table 4. Composition of diets for phase 3 to 5, Exp. 2 (as-fed basis)[1]

	Phase 3 SID Lys,[2] %		Phase 4 SID Lys,[2] %		Phase 5 SID Lys,[2] %	
Item	92.5	100	92.5	100	92.5	100
Ingredient, %						
Corn	62.61	60.2	64.14	61.98	60.63	57.92
Soybean meal, 46.5% CP	5.04	7.45	3.65	5.81	7.16	9.87
Distillers dried grains with solubles	30.00	30.00	30.00	30.00	30.00	30.00
Limestone	1.38	1.38	1.30	1.30	1.10	1.10
Salt	0.35	0.35	0.35	0.35	0.35	0.35
Vitamin premix[3]	0.08	0.08	0.08	0.08	0.08	0.08
Trace mineral premix[4]	0.10	0.10	0.10	0.10	0.10	0.10
L-Lys HCl	0.40	0.40	0.35	0.35	0.45	0.45
L-Thr	—	0.005	—	—	0.055	0.06
L-Trp	0.039	0.038	0.031	0.03	0.045	0.044
Ractopamine HCl[5]					0.025	0.025
Phytase[6]	0.005	0.005	0.005	0.005	0.005	0.005
TBCC[7]	±	±	±	±	±	±
Total	100	100	100	100	100	100
Calculated analysis						
Standard ileal digestible (SID) amino acids, %						
Lys	0.74	0.80	0.67	0.72	0.83	0.9
Ile:Lys	65	66	69	69	63	63
Meth:Lys	35	34	38	36	32	31
Met + Cys:Lys	66	64	71	69	61	59
Thr:Lys	62	62	66	65	65	65
Trp:Lys	19.5	19.5	19.5	19.5	19.5	19.5
Val:Lys	78	77	83	82	73	73
Total lysine, %	0.91	0.97	0.83	0.89	1.01	1.08
SID lysine:ME, g/Mcal	2.22	2.4	2	2.16	2.49	2.7
ME, kcal/kg	3,311	3,329	3,333	3,331	3,338	3,336
NE, kcal/kg	2,496	2,482	2,507	2,493	2,491	2,476
CP, %	16.7	17.6	16	16.9	17.6	18.7
Ca, %	0.55	0.55	0.52	0.52	0.46	0.46
P, %	0.38	0.39	0.37	0.38	0.39	0.4
Available P, %	0.25	0.25	0.23	0.24	0.23	0.24

[1] Phase 3 diets fed from day 38 to 60, phase 4 diets from day 60 to 95, and phase 5 diets fed from day 95 to 120. All diets were fed in meal form.

[2]Standardized ileal digestible; SID Lys values are expressed as the percentage of estimated SID Lys requirement for these pigs in this environment and production phase.

[3]Provided per kilogram of premix: 7,054,720 IU vitamin A; 1,102,300 IU vitamin D3; 35,274 IU vitamin E; 3,527 mg vitamin K; 6,173 mg riboflavin; 22,046 mg pantothenic acid; 39,683 mg niacin; and 26 mg vitamin B12.

[4]Provided per kilogram of premix: 17 g Mn from manganese oxide, 110 g Fe from ferrous sulfate, 110 g Zn from zinc oxide, 17 g Cu from copper sulfate, 331 mg I from ethylenediamine dihydroiodide, and 300 mg Se from sodium selenite.

[5]Paylean 9 (Elanco Animal Health, Inc.) provided 5 mg/kg ractopamine HCl.

[6]Optiphos 2000 (Huvepharma, Inc., Peachtree City, GA) provided 200 phytase units (FTU)/kg, with a release of 0.05% available P.

[7]Tribasic copper chloride (Intellibond C; Micronutrients, Inc.) provided 150 mg/kg Cu and was added at the expense of corn.

Overall (day 0 to 120), adding Cu to the diet marginally increased ($P < 0.10$) ADG and G:F. Average daily gain and G:F increased as SID Lys increased (linear, $P = 0.001$). These differences led to an increase in final weight with added Cu ($P = 0.006$) and increasing SID Lys (linear, $P = 0.001$). Caloric efficiency on both a metabolizable and net energy basis marginally improved ($P < 0.05$) when Cu was added to the diet and improved ($P < 0.001$) as SID Lys increased.

For carcass characteristics, increasing SID Lys increased (linear, $P = 0.007$) HCW by over 2 kg, or almost 3%, in pigs fed 100% of their estimated SID Lys requirement compared with those fed only 85% (Table 8). The Cu response for loin depth was marginally influenced by SID Lys (Cu × Lys linear; $P = 0.068$) as pigs fed increasing SID Lys with added Cu had an increase in loin depth, whereas pigs not fed supplemental Cu did not. Standardized ileal digestible Lys also marginally affected percentage lean only when Cu was included in the diet (Cu × Lys quadratic, $P = 0.057$), specifically within the 92.5% SID Lys treatment. Evaluating performance on a

Table 5. Chemical analysis of complete diets, Exp. 1 (as-fed basis)[1]

Added Cu,[2] mg/kg:	0			150		
SID lysine,[3] %:	85.0	92.5	100.0	85.0	92.5	100.0
Total Cu, mg/kg						
Phase 1	45	38	28	217	218	218
Phase 2	34	25	29	188	178	215
Phase 3	30	29	41	182	219	196
Phase 4	42	39	56	222	246	232
Phase 5	34	39	33	187	225	221
Amino acids and CP, %						
Phase 1						
CP	20.06	20.65	21.42	19.72	20.62	21.22
Lys	1.03	1.13	1.23	1.10	1.11	1.15
Met + Cys	0.72	0.71	0.75	0.73	0.73	0.74
Thr	0.78	0.79	0.81	0.78	0.79	0.81
Trp	0.20	0.21	0.22	0.19	0.21	0.22
Val	0.95	0.97	1.00	0.93	0.97	0.99
Phase 2						
CP	19.06	19.05	20.58	19.72	20.38	21.72
Lys	0.93	1.02	1.17	1.05	1.02	1.20
Met + Cys	0.70	0.71	0.73	0.72	0.72	0.75
Thr	0.71	0.73	0.76	0.76	0.74	0.82
Trp	0.18	0.19	0.21	0.20	0.20	0.22
Val	0.89	0.92	0.96	0.93	0.83	1.01
Phase 3						
CP	17.88	20.40	22.27	17.50	19.12	18.67
Lys	0.88	1.23	1.26	0.75	0.90	0.81
Met + Cys	0.68	0.71	0.78	0.65	0.66	0.66
Thr	0.68	0.79	0.86	0.65	0.69	0.67
Trp	0.17	0.21	0.23	0.16	0.18	0.17
Val	0.86	0.95	1.03	0.80	0.85	0.83
Phase 4						
CP	17.20	16.69	17.58	16.78	17.23	20.92
Lys	0.79	0.82	0.83	0.81	0.74	1.10
Met + Cys	0.63	0.62	0.64	0.61	0.64	0.72
Thr	0.63	0.62	0.65	0.60	0.62	0.78
Trp	0.15	0.15	0.16	0.14	0.15	0.21
Val	0.77	0.75	0.79	0.75	0.77	0.93
Phase 5						
CP	18.65	20.87	20.73	20.08	20.36	20.87
Lys	1.04	1.12	1.11	1.05	1.05	1.15
Met + Cys	0.67	0.73	0.72	0.69	0.70	0.73
Thr	0.73	0.79	0.78	0.75	0.78	0.81
Trp	0.19	0.20	0.21	0.19	0.20	0.21
Val	0.88	0.95	0.93	0.90	0.91	0.96

[1]Values represent means from one composite sample, analyzed in duplicate.

[2]Tribasic copper chloride (Intellibond C; Micronutrients, Inc.).

[3]Standardized ileal digestible; SID Lys values are expressed as the percentage of estimated SID Lys requirement for these pigs in this environment and production stage.

HCW-basis showed that hot carcass ADG and G:F improved (linear, $P < 0.05$) as the SID Lys increased.

For liver color, added Cu led to a decrease ($P = 0.027$) in a*, suggesting that Cu decreased the redness of the liver (Table 8). The a* value also marginally decreased (linear, $P = 0.097$) as SID Lys increased. Furthermore, Cu marginally decreased ($P = 0.071$) chroma, or the intensity of the liver color. Adding 150 mg/kg Cu increased liver Cu concentrations ($P = 0.001$) by 19 mg/kg, and marginally decreased liver Zn concentrations ($P = 0.095$; Table 8). As SID Lys increased, liver concentrations of Cu (quadratic, $P = 0.092$) and Zn (linear, $P = 0.099$) marginally decreased.

Table 6. Chemical analysis of complete diets, Exp. 2 (as-fed basis)[1]

Added Cu,[2] mg/kg:	0		150	
SID lysine,[3] %:	92.5	100.0	92.5	100.0
Total Cu, mg/kg				
Phase 1	37	31	249	201
Phase 2	31	28	272	214
Phase 3	38	42	246	210
Phase 4	34	32	246	219
Phase 5[4]	—	—	—	—
Amino acids and CP, %				
Phase 1				
CP	19.70	20.96	19.82	20.49
Lys	1.10	1.20	1.12	1.21
Met + Cys	0.69	0.74	0.70	0.73
Thr	0.74	0.77	0.75	0.79
Trp	0.22	0.23	0.22	0.23
Val	0.91	0.96	0.91	0.93
Phase 2				
CP	18.30	19.38	17.34	19.34
Lys	1.07	1.03	0.94	1.02
Met + Cys	0.68	0.70	0.64	0.68
Thr	0.70	0.77	0.65	0.69
Trp	0.19	0.19	0.18	0.20
Val	0.86	0.90	0.81	0.85
Phase 3				
CP	16.41	17.46	16.07	16.20
Lys	0.83	0.97	0.85	0.87
Met + Cys	0.59	0.60	0.59	0.61
Thr	0.58	0.62	0.57	0.60
Trp	0.17	0.18	0.16	0.17
Val	0.74	0.79	0.75	0.77
Phase 4				
CP	15.50	15.64	15.65	15.73
Lys	0.72	0.82	0.81	0.83
Met + Cys	0.60	0.60	0.61	0.62
Thr	0.57	0.57	0.59	0.59
Trp	0.34	0.34	0.34	0.37
Val	0.16	0.16	0.16	0.16
Phase 5[4]	—	—	—	—

[1]Values represent means from one composite sample, analyzed in duplicate.

[2]Tribasic copper chloride (Intellibond C; Micronutrients, Inc.).

[3]Standardized ileal digestible (SID) lysine values are expressed as the percentage of estimated SID Lys requirement finishing pigs within this production system.

[4]Phase 5 diets were not available for analysis.

For backfat fatty acid profile, no evidence of main effects of Cu, Lys, or their interaction ($P > 0.10$) was observed for major fatty acids, specifically palmitic acid (C16:0), palmitoleic acid (C16:1), stearic acid (C18:0), oleic acid (C18:1 *cis*-9), and linoleic acid (C18:2n-6; data not shown). To this, these small changes in fatty acid composition did not influence the backfat IV (Table 8). As a result, IV of the 10th rib backfat samples was not affected by treatment.

For fatty acid concentrations of jowl samples, total saturated fatty acids decreased in pigs fed added Cu as SID Lys increased but were relatively unchanged in pigs fed no added Cu (Cu × Lys linear, $P = 0.019$; data not shown). These were the results of decreasing stearic acid (C18:0) concentration as SID Lys increased with added Cu compared with no added Cu. These differences are also partly responsible for the tendency for jowl IV to increase in pigs fed added Cu and increasing SID Lys (Cu × Lys linear, $P = 0.052$) compared with the reduction in jowl IV with increasing SID Lys in pigs fed no added Cu (Table 8).

Experiment 2

For any of the measured responses, no three-way interactions for early Cu × late, Cu × SID Lys, or two-way interactions for early Cu × SID Lys, late Cu × SID Lys, or early Cu × late Cu were observed ($P > 0.10$).

For growth performance during the early finishing period (day 0 to 60), there was a Cu × SID Lys interaction for ADFI ($P = 0.023$; Table 9). This was the result of pigs fed 100% of the estimated SID Lys requirement having increased ADFI with added Cu, whereas pigs fed 92.5% of the estimated SID Lys requirement had decreased ADFI with added Cu. For the main effect of SID Lys from day 0 to 60, pigs fed 100% of the estimated SID Lys requirement had increased ($P < 0.05$) ADG compared with pigs only fed 92.5% of the estimated SID Lys requirement. During the late finishing period (day 60 to 120), pigs fed 100% of the estimated SID Lys requirement had increased ($P < 0.05$) ADG, final BW, and G:F compared with pigs fed 92.5% of the estimated SID Lys requirement.

Overall (day 0 to 120), there were no Cu × SID Lys interactions for growth performance or caloric efficiency. Pigs fed 100% of the estimated SID Lys requirement had increased ($P < 0.05$) ADG and G:F compared to pigs fed 92.5% of the estimated SID Lys requirement. Furthermore, pigs fed 100% of the estimated SID Lys requirement had improved ($P < 0.05$) caloric efficiency on both an ME and NE basis.

For carcass characteristics, there was a Cu × SID Lys interaction ($P < 0.022$) for carcass yield and backfat (Table 10). This was the result of pigs fed 100% of the estimated SID Lys requirement having increased backfat and a moderate reduction in carcass yield with added Cu, whereas pigs fed 92.5% of the estimated SID Lys requirement had an increase in carcass yield and reduction in backfat with added Cu. Furthermore, Cu tended to

Table 7. Effect of standardized ileal digestible (SID) lysine (Lys) and added Cu on growth performance of finishing pigs, Exp. 1[1]

								Probability, $P <$				
Added Cu,[2] mg/kg:	0			150				Cu × Lys			SID Lys	
SID Lys,[3] %:	85.0	92.5	100.0	85.0	92.5	100.0	SEM	Linear	Quadratic	Cu	Linear	Quadratic
BW, kg												
Day 0	29.0	29.0	29.0	29.0	28.9	29.0	0.93	0.896	0.940	0.915	0.930	0.840
Day 70	84.2	86.6	86.6	84.5	86.3	88.7	1.50	0.089[5]	0.124	0.089	0.001	0.325
Day 120	122.8	125.4	126.1	123.7	125.8	130.0	1.38	0.110	0.169	0.006	0.001	0.636
Day 0 to 70												
ADG, kg	0.79	0.82	0.82	0.79	0.82	0.85	0.010	0.034[6]	0.222	0.057	0.001	0.236
ADFI, kg	1.96	2.00	1.97	1.97	1.98	2.04	0.039	0.172	0.095[7]	0.184	0.053	0.765
G:F	0.402	0.410	0.415	0.400	0.414	0.418	0.005	0.392	0.470	0.494	0.001	0.299
Day 70 to 120												
ADG, kg	0.81	0.81	0.82	0.82	0.82	0.83	0.012	0.772	0.956	0.514	0.339	0.519
ADFI, kg	2.52	2.51	2.52	2.51	2.50	2.51	0.031	0.897	0.997	0.599	0.979	0.752
G:F	0.322	0.322	0.325	0.325	0.326	0.331	0.004	0.532	0.925	0.110	0.168	0.597
Day 0 to 120												
ADG, kg	0.80	0.82	0.82	0.80	0.82	0.84	0.007	0.109	0.414	0.095	0.001	0.740
ADFI, kg	2.19	2.20	2.19	2.19	2.19	2.23	0.032	0.414	0.333	0.654	0.227	0.949
G:F	0.365	0.370	0.373	0.366	0.374	0.379	0.004	0.276	0.786	0.090	0.001	0.582
Caloric efficiency, Mcal/kg[4]												
ME	9.32	9.19	9.11	9.31	9.10	8.97	42.9	0.278	0.837	0.087	0.001	0.541
NE	6.93	6.81	6.71	6.92	6.74	6.61	31.7	0.276	0.831	0.085	0.001	0.535

[1]A total of 1,248 pigs (PIC 337 × 1050 PIC, Hendersonville, TN; initial BW = 29.0 ± 0.1 kg) were used in a 120 d study; 8 pens per treatment and 26 pigs per pen.

[2]Tribasic copper chloride (Intellibond C; Micronutrients, Inc.).

[3]SID Lys values are expressed as the percentage of estimated SID Lys requirement for these pigs in this environment and production stage.

[4]Caloric efficiencies were calculated by the following equation: sum of (ADFI × Mcal) ÷ (ADG) for each period.

[5]Effect of Cu within 100 % SID Lys: $P = 0.007$.

[6]Effect of Cu within 100% SID Lys: $P = 0.003$.

[7]Effect of Cu within 100% SID Lys: $P = 0.019$.

influence the response to SID Lys for hot carcass G:F ($P = 0.071$) as pigs fed 100% of the estimated SID Lys requirement had no change in hot carcass G:F with added Cu; however, pigs fed 92.5% of the estimate SID Lys requirement had a 3.5% increase in hot carcass G:F with added Cu. For the main effect of SID Lys, pigs fed 100% of the estimated SID Lys requirement had increased ($P < 0.05$) HCW and hot carcass ADG compared to pigs fed 92.5% of the estimated SID Lys requirement. Pigs fed added Cu had reduced carcass yield ($P = 0.048$) but tended to have increased ($P < 0.10$) HCW as well as hot carcass ADG, and G:F compared to pigs fed no added Cu.

DISCUSSION

The purpose of these two experiments were to first, determine if SID Lys could be reduced in diets containing added Cu without negatively affecting growth performance, and second, determine the duration of added Cu supplementation that results in the maximum response. The estimated SID Lys requirements used in the present study were based on the results of a previous study that was completed in the same facility with pigs of a similar genotype. This is supported by the improvement in pig growth performance as dietary SID Lys increased. While the current study was successful at reporting improvements in growth performance with increasing SID Lys, added Cu did not provide a response when SID Lys was limiting. Furthermore, added Cu did not influence growth in Exp. 2, when efforts were focused on determining the optimal duration of feeding added Cu.

To our knowledge, the first research to evaluate dietary amino acid by TBCC interactions was completed by Rochell et al. (2017) in broilers. They fed broilers diets containing two concentrations of digestible Lys (1.00 or 1.20%) and two levels of added Cu (0 or 200 mg/kg) from TBCC. They reported that broilers fed the low digestible Lys had greater improvements in ADG and ADFI in response to 200 mg/kg added Cu from TBCC compared with

Table 8. Effect of standardized ileal digestible (SID) lysine and added Cu on carcass characteristics of finishing pigs, Exp. 1[1]

								Probability, $P <$				
Added Cu,[2] mg/kg:	0			150				Cu × Lys			SID Lys	
SID Lys,[3] %:	85.0	92.5	100.0	85.0	92.5	100.0	SEM	Linear	Quadratic	Cu	Linear	Quadratic
Carcass characteristics[4]												
HCW, kg	92.6	94.7	94.3	93.3	94.6	96.7	1.15	0.346	0.290	0.170	0.007	0.619
Carcass yield,[5] %	75.45	75.51	74.76	75.47	75.16	74.97	0.464	0.838	0.557	0.921	0.203	0.666
Backfat,[6] mm.	16.3	16.8	15.7	16.0	16.3	16.0	0.43	0.745	0.509	0.765	0.553	0.215
Loin depth,[6] mm.	69.6	68.8	68.8	68.8	69.6	70.6	0.66	0.068[7]	0.930	0.260	0.340	0.601
Lean,[6] %	57.42	57.31	58.12	57.59	58.04	57.87	0.222	0.342	0.057[8]	0.249	0.040	0.696
Carcass performance												
HCW ADG,[9] kg	0.591	0.608	0.605	0.597	0.607	0.625	0.007	0.321	0.276	0.151	0.006	0.591
HCW G:F[10]	0.271	0.276	0.276	0.273	0.278	0.281	0.004	0.581	0.642	0.137	0.012	0.412
Liver color[11]												
Lightness, L*[12]	32.55	31.18	32.24	31.48	31.05	32.08	0.594	0.431	0.888	0.160	0.800	0.191
Redness, a*[13]	14.86	15.01	14.71	14.77	14.09	13.71	0.359	0.206	0.537	0.027	0.097	0.912
Yellowness, b*[14]	6.42	5.59	6.19	6.75	5.61	5.68	0.461	0.357	0.271	0.303	0.163	0.695
Hue Angle, °[15]	0.399	0.409	0.389	0.424	0.370	0.379	0.199	0.376	0.186	0.647	0.170	0.639
Chroma[16]	16.24	16.43	16.02	16.28	15.23	14.98	0.488	0.266	0.404	0.071	0.125	0.908
Liver mineral concentration,[11] mg/kg												
Cu	13	13	12	33	39	26	3.27	0.393	0.105	0.001	0.182	0.092
Fe	196	221	211	200	203	205	11.43	0.654	0.368	0.437	0.344	0.322
Zn	62	59	59	59	57	55	2.29	0.566	0.806	0.095	0.099	0.841
Iodine value,[11,17] g/100g												
Backfat	82.63	81.75	82.21	82.64	82.44	83.36	0.901	0.530	0.942	0.406	0.869	0.433
Jowl fat	84.20	84.62	83.61	82.73	83.61	85.48	0.861	0.052	0.402	0.769	0.202	0.882

[1]A total of 1,248 pigs [PIC 337 × 1050, PIC (Hendersonville, TN); initial BW = 29.0 ± 0.1 kg] were used in a 120 d study; 8 pens per treatment and 26 pigs per pen.

[2]Tribasic copper chloride (Intellibond C; Micronutrients, Inc.).

[3]SID Lys values are expressed as the percentage of estimated SID Lys requirement for these pigs in this environment and production stage.

[4]1,069 pigs (19 to 23 pigs/pen) were transported to a commercial packing plant for processing and data collection (Swift and Company, Worthington, MN) and 144 pigs (three pigs/pen) visually assumed to represent the mean live weight of the pen were subsampled and shipped to a separate processing facility for further carcass measurements (Natural Foods Holdings, Inc., Sioux Center, IA). The weighted average of the two plants were used for HCW, farm yield, and backfat.

[5]Carcass yield determined by dividing HCW at the plant by live BW at the farm prior to transport.

[6]HCW was used as a covariate.

[7]Effect of Cu within 100% SID Lys: $P = 0.063$.

[8]Effect of Cu within 92.5% SID Lys: $P = 0.062$.

[9]HCW ADG = (HCW – (day 0 wt × 75% yield)) ÷ 120 d.

[10]HCW G:F = (HCW – (day 0 wt × 75% yield)) ÷ (ADFI × 120).

[11]Samples were collected from three pigs from each pen.

[12]L*, 0 = black, 100 = white.

[13]a* − values = green; + values = red.

[14]b* − values = blue; + values = yellow.

[15]Hue angle = $\tan^{-1}(b^*/a^*)$.

[16]Chroma = $(\sqrt{a^*+b^*})/L^*$.

[17]Calculated as iodine value = [C16:1] × 0.950 + [C18:1] × 0.860 + [C18:2] × 1.732 + [C18:3] × 2.616 + [C20:1] × 0.785 + [C20:4] × 3.201 + [C22:1] × 0.723 + [C22:5] × 3.697 + [C22:6] × 4.463; brackets indicate concentration. No evidence of main effects of Cu, Lys, or their interaction ($P > 0.10$) was observed for major FA, such as C16:0, C18:1, and C18:2 etc.; therefore, individual FA data were not shown.

broilers fed high digestible Lys. In addition to the improvements in growth, they also reported that nitrogen and DM digestibility were each increased by nearly 4% in broilers fed 200 mg/kg of added Cu in the low Lys diet. Furthermore, they observed that the amino acid digestibility for various essential amino acids was improved in the low Lys diet with added Cu, but not in high Lys diet. Specifically, apparent ileal digestibility of most of the indispensable amino acids was increased by at least 1.5%.

While Rochell et al. (2017), to our knowledge, currently has the only published data to investigate

Table 9. Effects of standardized ileal digestible (SID) lysine (Lys) and duration of feeding Cu on growth performance of finishing pigs, Exp. 2[1]

SID Lys,[2] %	92.5				100.0							
Early added Cu[3]:	−	+	−	+	−	+	−	+				
Late added Cu[4]:	−	−	+	+	−	−	+	+		Probability, [5]$P <$		
Treatment:	A	B	C	D	E	F	G	H	SEM	Cu × SID Lys[6]	Cu[7]	SID Lys[8]
Weight, kg												
Day 0	26.4	26.4	26.4	26.4	26.4	26.4	26.4	26.4	0.662	0.913	0.998	0.987
Day 60	78.1	78.5	78.2	78.3	79.1	79.7	79.1	79.5	1.002	0.833	0.567	0.031
Day 120	129.4	129.8	130.8	129.2	132.3	132.4	132.1	133.4	1.202	0.428	0.527	0.001
Day 0 to 60												
ADG, kg	0.86	0.86	0.86	0.86	0.88	0.88	0.87	0.88	0.009	0.463	0.681	0.018
ADFI, kg	2.08	2.12	2.06	2.05	2.05	2.06	2.08	2.12	0.031	0.023	0.391	0.461
G:F	0.413	0.408	0.416	0.418	0.427	0.429	0.418	0.418	0.005	0.098	0.592	0.109
Day 60 to 120												
ADG, kg	0.90	0.92	0.92	0.90	0.93	0.93	0.94	0.93	0.010	0.951	0.931	0.007
ADFI, kg	2.77	2.78	2.77	2.79	2.82	2.75	2.83	2.78	0.025	0.283	0.576	0.326
G:F	0.326	0.329	0.332	0.325	0.331	0.337	0.333	0.336	0.004	0.338	0.591	0.032
Day 0 to 120												
ADG, kg	0.88	0.89	0.89	0.88	0.90	0.91	0.90	0.91	0.007	0.566	0.732	0.001
ADFI, kg	2.42	2.43	2.40	2.40	2.42	2.39	2.44	2.44	0.022	0.365	0.900	0.235
G:F	0.365	0.365	0.369	0.366	0.373	0.378	0.371	0.373	0.003	0.735	0.870	0.009
Caloric efficiency[9]												
ME	9.13	9.13	9.02	9.10	8.93	8.81	8.98	8.93	0.067	0.754	0.832	0.007
NE	6.83	6.83	6.74	6.80	6.64	6.55	6.68	6.65	0.050	0.740	0.829	0.001

[1]A total of 1,267 pigs (PIC 337 × 1,050 PIC, Hendersonville, TN; initially 26.4 kg) were used in a 120 d study; six pens per treatment and 26 to 27 pigs per pen.

[2]SID Lys values are expressed as the percentage of estimated SID Lys requirement for these pigs in this environment and production stage.

[3]150 mg/kg copper from tribasic copper chloride (TBCC; Intellibond C; Micronutrients, Inc.) fed from day 0 to 60.

[4]150 mg/kg copper from TBCC fed from day 60 to 120.

[5]No Early Cu × Late Cu × SID Lys, Early Cu × SID Ly, Late Cu × SID Lys, or Early Cu × Late Cu interactions, or early Cu vs. late Cu main effects, were observed.

[6]Contrast between Treatments A and H vs. D and E.

[7]Contrast between Treatments A and E vs. D and H.

[8]Contrast between Treatments A and D vs. E and H.

[9]Caloric efficiencies were calculated by the following equation: sum of (ADFI × Mcal) ÷ (ADG) for each period.

the interaction between Cu and Lys, others have investigated the effects of Cu on digestibly in diets formulated to the pigs Lys requirement. Gonzales-Eguia et al. (2009) investigated the effects of 50 mg/kg of Cu from nanoCu ($CuSO_4$ and SiO_2 processed and ground to particle size <200 µ; 37.38% Cu) and $CuSO_4$ (400 to 1,000 µ; 25.4% Cu) on nutrient digestibility in growing pigs (30 to 65 kg). They reported that DM, CP, and mineral digestibility were not affected by added Cu or Cu source. However, crude fat and GE digestibility was increased by at least 3.5% for either copper source. They further reported that nanoCu increased crude fat digestibility more than $CuSO_4$, but suggested this was due to particle size. In contrast, Kim et al. (2006) reported that 60 mg/kg added Cu from $CuSO_4$ decreased DM digestibility by 3% and increased nitrogen digestibility by at least 2.5%. One difference between Gonzales-Eguia et al. (2009) and Kim et al. (2006) was that the latter observed their responses in pigs greater than 65 kg BW, whereas Gonzales-Eguia et al. (2009) used pigs between 30 and 65 kg.

Based on the results of Rochell et al. (2017), Coble et al. (2017) investigated the effects $CuSO_4$ and TBCC in diets containing high amounts of DDGS and wheat middlings formulated to 0.05% unit below the estimated SID Lys requirement in growing and finishing pigs. They observed that adding supplemental Cu in the form of TBCC or $CuSO_4$ improved growth into the finishing phase than previously reported Hastad, 2002. Thus, it was important to determine if there was an interaction between SID Lys and added Cu, and the duration of feeding. This was of scientific importance and economic importance, as the potential to decrease amino acid concentrations in diets without negatively affecting performance has benefits for swine producers and decreasing N excretion.

Table 10. Effect of standardized ileal digestible (SID) lysine (Lys) and duration of feeding Cu on carcass characteristics of finishing pigs, Exp. 2[1]

SID Lys,[2] %	92.5				100.0							
Early added Cu[3]:	−	+	−	+	−	+	−	+				
Late added Cu[4]:	−	−	+	+	−	−	+	+		Probability,[5] $P <$		
Treatment:	A	B	C	D	E	F	G	H	SEM	Cu × SID Lys[6]	Cu[7]	SID Lys[8]
Carcass characteristics												
HCW, kg	97.8	99.1	99.9	100.3	100.5	100.8	100.2	101.1	0.99	0.244	0.076	0.043
Carcass yield,[9] %	75.06	76.11	75.74	76.74	75.89	75.35	75.60	75.76	0.383	0.022	0.048	0.847
Backfat,[10] mm.	18.4	18.0	17.2	17.3	16.9	17.1	18.2	18.1	0.48	0.011	0.780	0.279
Loin depth,[10] mm.	56.0	55.7	56.5	56.5	56.9	56.2	55.4	56.2	0.45	0.117	0.953	0.289
Lean,[10] %	55.78	55.56	56.53	56.51	56.97	56.26	55.42	56.29	0.450	0.115	0.953	0.286
Carcass performance												
HCW ADG,[11] kg	0.649	0.661	0.667	0.671	0.672	0.675	0.670	0.677	0.007	0.232	0.064	0.035
HCW G:F[12]	0.269	0.272	0.278	0.279	0.278	0.282	0.275	0.278	0.003	0.071	0.086	0.198

[1]A total of 1,267 pigs (PIC 337 × 1050 PIC, Hendersonville, TN; initial BW = 26.4 ± 0.1 kg) were used in a 120 d study; 6 pens per treatment and 26 to 27 pigs per pen.

[2]SID Lys values are expressed as the percentage of estimated SID Lys requirement for these pigs in this environment and production stage.

[3]150 mg/kg copper from tribasic copper chloride (TBCC; Intellibond C; Micronutrients, Inc.) fed from day 0 to 60.

[4]150 mg/kg copper from TBCC fed from day 60 to 120.

[5]No Early Cu × Late Cu × SID Lys, Early Cu × SID Ly, Late Cu × SID Lys, or Early Cu × Late Cu interactions, or early Cu vs. late Cu main effects, were observed.

[6]Contrast between Treatments A and H vs. D and E.

[7]Contrast between Treatments A and E vs. D and H.

[8]Contrast between Treatments A and D vs. E and H.

[9]Carcass yield determined by dividing HCW at the plant by live BW at the farm prior to transport.

[10]HCW was used as a covariate.

[11]HCW ADG = (HCW − (day 0 wt. × 75% yield)) ÷ 120 d.

[12]HCW G:F = (HCW − (day 0 wt. × 75% yield)) ÷ (ADFI × 120 d).

Although we did not measure nutrient digestibility in the current studies, the growth data suggest that digestibility of neither nitrogen nor energy was likely improved with added Cu as Rochell et al. (2017) and Gonzales-Eguia et al. (2009) suggested. Differences between the current study and those previously mentioned do exist which could explain why the results are not similar. The current study was completed in older, heavier pigs, and utilized a diet with high amounts of byproduct ingredients. Rochell et al. (2017) used diets for broilers with low amounts of DDGS and 2.6 to 3.8% soybean oil. Gonzales-Eguia et al. (2009) fed diets containing 2.4% soybean oil, did not include byproduct ingredients, and utilized younger pigs than in the present study. However, our results that adding Cu does not interact with SID Lys concentration of the diet.

The lack of an overall growth response to added Cu in Exp. 2 is in agreement with other studies when feeding additional Cu does not always affect growth rate or feed efficiency during the late finishing period (Davis et al., 2002; Hastad, 2002; Carpenter et al., 2017); further challenging the ability to determine an optimal duration of supplementation. Hastad (2002) reported that 200 mg/kg added Cu only improved growth performance until pigs were only 61 kg, whereas Davis et al. (2002) observed improvements in ADG and G:F beyond 69 kg BW. The elongated Cu response reported by Davis et al. (2002) might be related to fat digestibility. They utilized diets that contained 5% added fat, in addition to 175 mg/kg of added Cu. Luo and Dove (1996) reported that adding 250 mg/kg of Cu increased fat digestibility in nursery pigs when 5% added fat was included in the diet. However, more research is needed to understand how diet ingredient and nutrient composition may affect the response to added Cu throughout the finishing period. Although the growth performance in Exp. 2 did not provide the intended answers for determining the optimal duration of feeding, the observed improvement in carcass performance with 150 mg/kg added Cu is consistent with the other research that demonstrated improvements with added Cu (Zhao et al., 2014; Coble et al., 2017).

As expected, increasing SID Lys improved ADG, G:F, and HCW in both experiments. Overall across experiments, ADG and G:F were increased by 3.3 and 2.5%, respectively. During the early finish period from 26 to 78 kg, the relative change between the low and high SID Lys treatments were similar to the results reported by Main et al. (2008). However, during the late finishing period, Main et al. (2008) reported more significant changes in ADG and G:F to increasing SID Lys (over 6% reduction). One possible reason for this difference is, unlike Main et al. (2008), pigs in the present studies were fed ractopamine HCl in the last phase of production.

As TBCC is green in color, determining the potential for TBCC to affect internal body tissue color, such as the liver where Cu is stored, and negatively impact offal value is important. While adding Cu in the form of TBCC did decrease the redness and color saturation of the livers, the current study suggests that liver color is only minimally impacted and should not decrease the potential value. In our study, increasing SID Lys reduced liver redness which would be similar to the response Apple et al. (2004) observed in other tissues. Ultimately, the small changes in liver color that we observed would not be detectable by the human eye, even though instrumentally there are differences (T. Houser, Kansas State University, Manhattan, personal communication).

The liver stores about 8 to 10% of the total Cu in tissue and serves as a sink for Cu (Luza and Speisky, 1996; Hill and Spears, 2001). Feeding high levels of Cu can increase liver Cu concentrations. The slight increase in liver Cu concentrations (approximately 20 mg/kg) for pigs fed 150 mg/kg added Cu from TBCC is consistent with others who fed higher levels of TBCC (Cromwell et al., 1998; Miles et al., 1998).

Lastly, the current experiment also measured the differences in carcass fatty acid composition in both jowl and backfat. Earlier published research suggested that increasing dietary Cu increased the amount of unsaturated fatty acids (primarily C16:1 and C18:1) while decreasing the amount of saturated fatty acids (C16:0 and C18:0; Elliot and Bowland, 1968). Although recently published literature is scarce, determining if carcass fat quality is influenced by dietary Cu is important as many packers have quality requirements related to IV. Surprisingly, backfat IV increased with increasing SID Lys and added Cu, but that response was not observed when diets did not contain added Cu. This was the result of a reduction in C18:0 with added Cu, decreasing the concentration of saturated fatty acids, which is consistent with Elliot and Bowland (1968). As a result of increasing SID Lys, CP content of the diet increased, which has also been shown to decrease the amount of saturated fatty acids and increase polyunsaturated fatty acids (Tous et al., 2014), consistent with the results observed in the present study. While these changes are important, the carcass IV for both depots measured were relatively high, likely related to the amount of byproduct ingredients used in formulation that contain high amounts of unsaturated fatty acids (Salyer et al., 2012; Asmus et al., 2014; Wu et al., 2016).

In conclusion, feeding an additional 150 mg/kg Cu from TBCC in diets for finishing pigs did not result in improved performance when fed in diets deficient in SID Lys. However, feeding added Cu in diets at the estimated SID Lys requirement, improved growth performance in Exp. 1, and increased hot carcass ADG and G:F were observed in Exp. 2. Together, these data showed inconsistencies in the growth response to added dietary Cu, similar to other published research. Additionally, more data are needed to understand the impacts of Cu supplementation on nutrient digestibility in growing-finishing pigs, and if the response is potentially impacted by diet type. More data are needed to investigate the effects of adding high levels of Cu in finishing pig diets, especially for its mode of action.

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